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Report

The impact of protection systems on power system reliability

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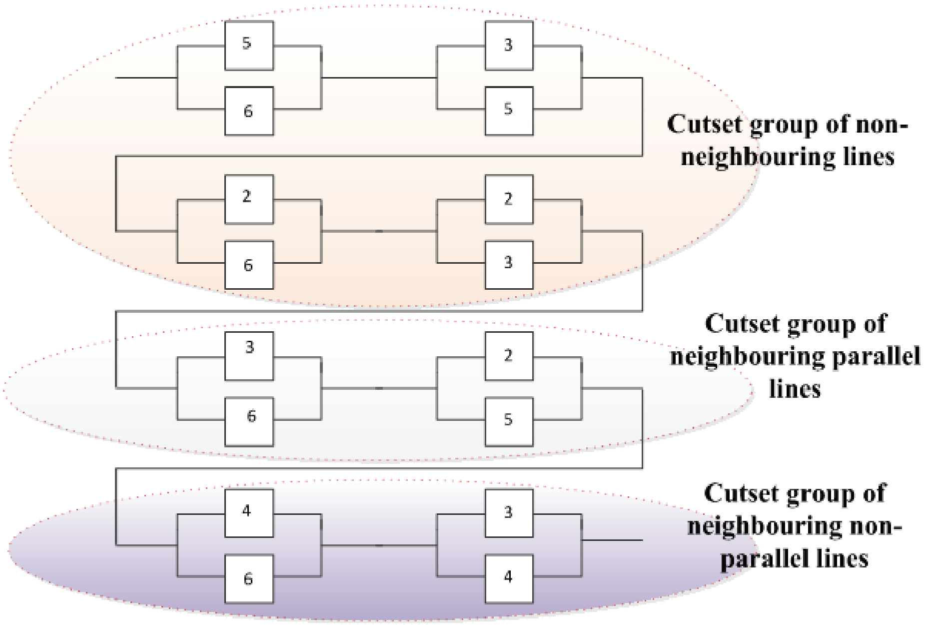

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ABSTRACT

This report is a collection of memos written to describe the methodology for quantifying the impact of protection systems on power system reliability.

Including the effect of protection system response scenarios on a transmission system is vital for a realistic appraisal of the reliability attributes of electricity supply. This is usually accomplished by resorting to Markov models. As a viable alternative, a new procedure based on approximate methods of system reliability evaluation is proposed in this work. This is used in conjunction with the OPAL methodology for reliability analysis of power systems. The overall reliability model is thus based on minimal cutsets for each delivery point, which are obtained from an analytical contingency enumeration approach. The results are first demonstrated on the four bus OPAL test network. Additional dependent failure considerations in the modeling are then illustrated on a Modified OPAL (MOPAL) test network. Further, the impact of substation configuration arrangement (breaker-and-a-half scheme) has been investigated, on the transmission protection system failure dependency propagation and the consequent effect on reliability of supply. The results are presented for the MOPAL test network.

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Project memo

Incorporation of various protection system failure modes in composite power system reliability studies in the OPAL framework - Part I

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ABSTRACT

The aim of this memo is to present the results of investigation carried out to improve the existing module on protection system reliability considerations in the OPAL methodology for reliability analysis of power systems. Quantifying the impact of protection system imperfections on power system reliability entails the identification of multiple failure modes of transmission lines arising out of the various protection system response scenarios. Analytical methods for the same were initially developed as part of the SINTEF technical report TR A6429 on the requirement specification for reliability analysis in meshed power networks. Building on this reported conceptual foundation, the methodology outlined in this memo retains the uniqueness of capturing the impact of protection system failure modes in composite power system reliability studies without the need for complex Markov models, while accounting in detail for the constituent complex dependency effects. The classification of protection system faults to be considered for the reliability analysis has been expanded, and their detailed mathematical modelling for further analysis has been presented. The memo has been written in a way that is mostly self-explanatory, starting from the first principles and followed by gradual development of the pertinent derivations. A simple case study involving the calculation of basic delivery point reliability indices, with and without the consideration of protection system failures, is illustrated on the four-bus OPAL test network.

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1 Introduction

Research on composite power system reliability is well documented in literature. Numerous analytical and simulation methods to assess the reliability of supply are in vogue, based on mathematical models of varying degrees of complexity [1, 2]. Several assumptions underline these methods with a view to tractability, depending on the specific goals of such studies. The generic assumption of perfectly reliable transmission protection systems is no longer valid, as seen from the studies on fault statistics of power systems across the world that point to failures in protection systems as being one of the major contributors to unreliability of power systems [3-5]. The North American Electric Reliability Corporation (NERC) System Protection and Control Task Force recently outlined protection system reliability requirements for bulk electric systems that ensure adequate levels of bulk system reliability [6]. However, relatively fewer studies have been conducted on incorporating the impact of protection system failures on power system reliability. Those reported in literature thus far have mainly relied on extensive and complex Markov models [7] or fault trees combined with event trees [8]. The latest development in this field includes an elaborate Markov model-based composite power system reliability evaluation [9], where the impact of two main types of hidden protection failures, namely, undesired-tripping mode and fail-to-operating tripping mode, on system reliability has been investigated.

At SINTEF, a new methodology for reliability of supply assessment, termed as OPAL [10], has been initiated and is currently being improvised to provide inputs for long term planning purposes [11, 12, 13]. The basic objective is to *"determine the reliability of supply indices for the delivery points under study, i.e., to estimate the frequency and duration of interruptions (or reduced supply), energy not supplied, and the corresponding cost of energy not supplied"*. The reliability model is based on the minimal cutsets for each delivery point. It takes into account both interruptions due to faults on the power system components and protection system faults that render isolation of the faulted power system components ineffective.

In this memo, building on the initial conceptualizations of [10] and [13], a generic procedure of including the impact of protection system imperfections on supply reliability is put forward. Norwegian fault statistics form the basis for the identification of key failure modes of transmission line protection failures [14]. Thus, four uniquely identified fault types that result on account of the various protection system response scenarios are presented in this memo. The uniqueness of the proposed approach lies in its ability to model the impacts of transmission protection system failures on power system reliability without the need for complex Markov models, while accounting in detail for the dependency effects. It is shown how this feature can be incorporated in the general minimal cutset structure of the OPAL methodology. It can be tailored to develop different standard expressions for different protection coordination schemes, though emphasis is laid only on the distance protection scheme in this memo. Sample results are illustrated on a four-bus OPAL test network.

Case-specific simple analytical expressions were developed in [10] and [13] to gauge the impact of reliability of the protection system on the reliability of supply by taking into account four uniquely identified fault types (failure modes). In this memo, based on the single-circuit meshed transmission system – the OPAL network – as a reference case, generic expressions for failure rates are developed for similar meshed systems. These account for the four revised and comprehensively *expanded* fault types that a transmission line could experience because of the various associated protection system response scenarios. The task of obtaining generic expressions that can capture the more complex effects of back-up protection coordination schemes of multi-circuit meshed transmission configurations will be addressed in a later memo (Part II).

1.1 Assumptions

The following are the important underlying assumptions that establish the scope of the research carried out:

- A circuit breaker and its associated relay and communication units (fault clearance system) together constitute a protection system unit. Each line is protected by a protection system unit at both its ends; this arrangement as a whole is referred to as protection system of the line.

- A simple bus configuration is assumed for the single circuit meshed transmission system considered initially. A distance protection scheme is assumed.

- Repair of protection systems is faster than that of the corresponding protected components.

- All circuit breakers have similar switching times; all protection system units have similar repair times.

- Neighbouring lines are defined as transmission lines connected to the common bus bar.
- Misoperations of backup protection system units occur one at a time.

2 Mathematical Modeling for Expanded Failures Modes of Protection Systems

2.1 First principles: Basic failure modes of protection systems

Say, protection system of line 'X' is PT_X. PT_X is a system composed of two sub-systems: two protection system units – $PT_{A[X]}$ and $PT_{B[X]}$, each at one end of the line.

The primary responsibility of PT_X is to protect line 'X'. i.e., PT_X acts if there is a fault on line 'X', and isolates it.

PT_X also has a secondary responsibility (depending upon the way backup protection coordination scheme is designed for a system) – to protect adjacent lines when their corresponding protection systems fail.

If 'Y' and 'Z' are lines adjacent to 'X', PT_X also serves as a back-up for lines 'Y' and 'Z'.

The unsuccessful operation of a protection system is on account of its unwanted operation or missing operation. An unwanted operation is said to occur if a protection system acts in response to the conditions it is not designed to react to. A missing operation is said to occur if a protection system fails to act in response to the conditions it is designed to react to. In this connection, a brief description of the two significant failure modes of protection system as given in [15] is quoted below:

> *"**Failure to Operate**: Protection systems generally do not operate unless a fault occurs. The failure in a protection system may, therefore, remain undetected until the next inspection or until the protection system is called upon to clear a fault.*
>
> ***Undesired Trippings**: A failure in a protection system may generate a spurious response and cause undesired opening of the associated circuit breakers. This could be either spontaneous, in the absence of a fault, or could be due to faults outside the protection zone."*

Failure-to-operate state is also termed as state of unreadiness. Undesired trippings are also termed as mal-trippings. Unreadiness and mal-trippings are grouped as 'misoperations'. A fault tree diagram-based depiction of a line's failure on account of the line's basic protection system failure modes is shown in Fig. 1. The dotted lines in the fault tree in Fig. 1 refer to all possible basic events.

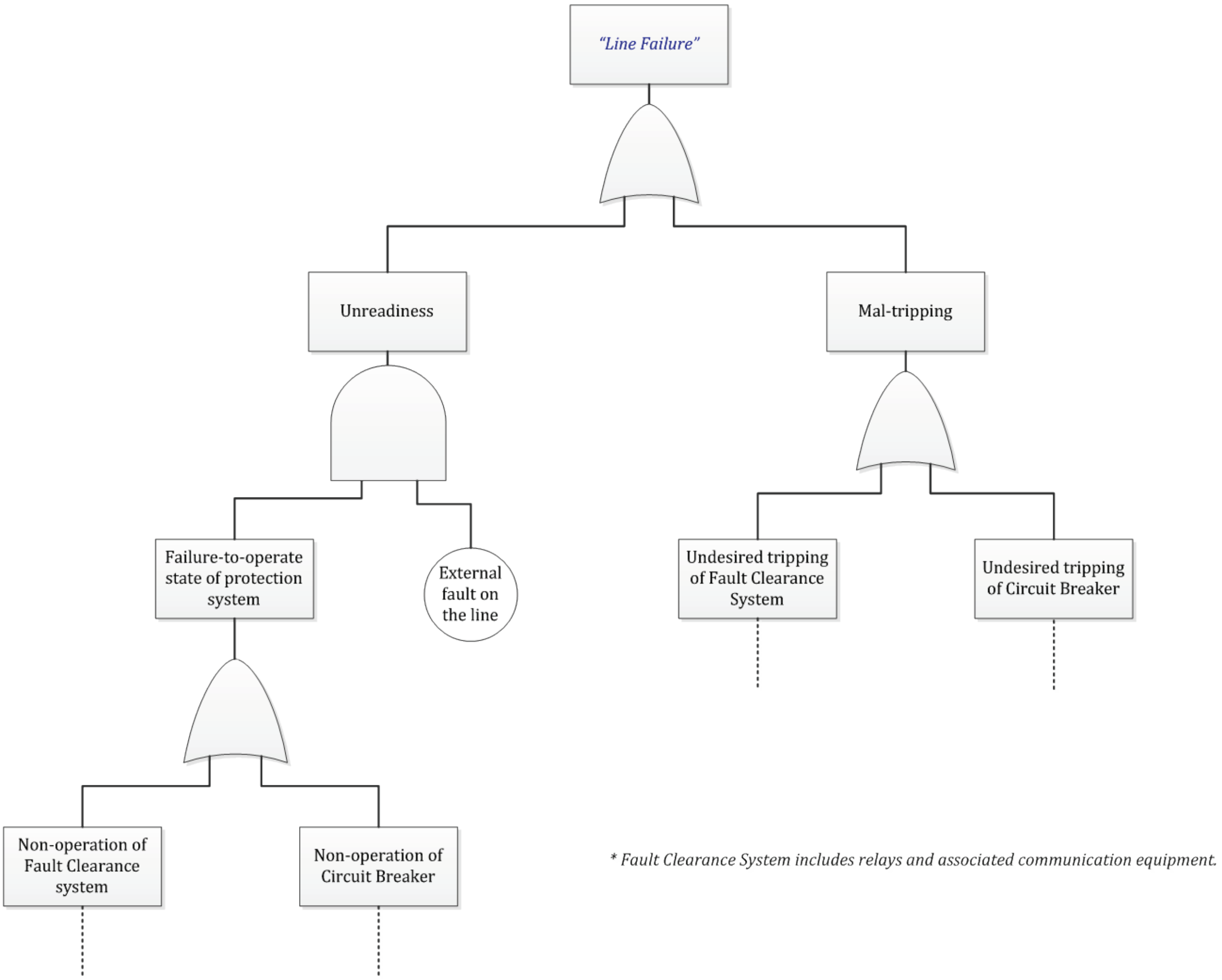


Fig. 1. Fault tree of line failure due to protection system response scenarios

Theoretically, the summation of probability of unwanted operation, probability of missing operation and probability of successful operation is unity. These events are considered to be exhaustive. Whether the consequence of a possible delayed response is the same as that of a missing response is a question of statistical benchmarking in the data collection.

$$P_{\mathrm{unwanted(PTx)}} + P_{\mathrm{missing(PTx)}} + P_{\mathrm{successful(PTx)}} = 1 \qquad (1)$$

$$P_{\mathrm{successful(PTx)}} = 1- [P_{\mathrm{unwanted(PTx)}} + P_{\mathrm{missing(PTx)}}] \qquad (2a)$$

where

$P_{\mathrm{unwanted(PTx)}}$ is the probability of unwanted operation of protection system 'X',

$P_{\mathrm{missing(PTx)}}$ is the probability of missing operation of protection system 'X', and

$P_{\mathrm{successful(PTx)}}$ is the probability of successful operation of protection system 'X'.

The failure probabilities – $P_{\mathrm{unwanted(PTx)}}$ and $P_{\mathrm{missing(PTx)}}$, can be obtained from the historical operating data of protection systems. However, for a detailed analysis, it is advantageous to estimate these probability values for the individual units of a protection system rather than the protection system itself.

If $P_{unwanted(PTx)} = 0$ and $P_{missing(PTx)} = 0$, the condition pertains to a perfect protection system.

The conditional probability of successful operation of a line's protection system unit upon the occurrence of a fault on the line is given as follows:

$$P\left(Successful\ operation\ of\ PT_X\ \ on\ line\ i \mid Fault\ on\ line\ i\right) = \left[1 - P_{missing(PT_X)}\right] \tag{2b}$$

2.2 Terms and Definitions

Line i is protected by two protection system units, each at either end of the line. One end of the line is termed as A-end, and the other end as B-end. The unit at the A-end of line i is denoted by $PT_{A[i]}$, and the unit at the B-end of line i is denoted by $PT_{B[i]}$. Both the protection units together constitute primary protection system of the line. The subscript A or B for a parameter (e.g., failure rate, probability) refers to the end at which the protection system unit is located on the line.

$P_{missing(PT_{A[i]})}$ and $P_{missing(PT_{B[i]})}$ are the probabilities of missing operation of protection system units $PT_{A[i]}$ and $PT_{B[i]}$, respectively, of line i;

According to [15]:

$$Unreadiness\ Probability = \frac{Number\ of\ times\ breakers\ fail\ to\ trip}{Number\ of\ trip\ commands} \tag{2c}$$

Unwanted operations of a line's protection system unit are further classified into two categories, based on the originating 'source' responsible for such operations.

Unwanted non-selective operations: Such operations are a result of 'over-reach' feature of the protection system unit, which has its manifestations primarily in the relay component of the unit. 'Probability' is deemed to be a better quantifier of this category of unwanted operations.

- Probability of unwanted non-selective operations of a protection system unit (conditional upon faults in neighbouring lines) - $P_{unwanted-Ns.(PT_{A[i]})}$ and $P_{unwanted-Ns.(PT_{B[i]})}$.

Unwanted spontaneous operations: It is assumed that such operations occur on account of maltripping of the associated circuit breakers. 'Failure rate' is deemed to be a better quantifier of this category of unwanted operations. According to the APM Task Force Report [7], based on field-data observations, unnecessary (unwanted) operation rate is defined as follows:

$$Unnecessary\ Operation\ Rate = \frac{Number\ of\ unnecessary\ operations}{Number\ of\ years\ of\ operation\ (In\text{-}service\ time)} \tag{2d}$$

$\lambda_{BE_{A[i]}}$ and $\lambda_{BE_{B[i]}}$ are the failure rates of unwanted spontaneous tripping of the circuit breakers of A-end, and B-end of line i's protection system, respectively.

Theoretically speaking, if one were interested solely in compiling all possible statistical parameters related to the functional aspects of protection systems, the following parameters could be of interest:

$P_{unwanted(PT_{A[i]})}$ and $P_{unwanted(PT_{B[i]})}$ are the probabilities of cumulative unwanted operations of protection system units $PT_{A[i]}$ and $PT_{B[i]}$, respectively, of line i.

$P_{unwanted-Sp.(PT_{A[i]})}$ and $P_{unwanted-Sp.(PT_{B[i]})}$ are the probabilities of unwanted spontaneous operations (i.e., independent of faults in neighbouring lines) of protection system units $PT_{A[i]}$ and $PT_{B[i]}$, respectively, of line i. -

The 'overall' failure rate $\lambda_{PT_{A[i]}}$ or $\lambda_{PT_{B[i]}}$ is a record of all kinds of failure events associated with the phenomena of unreadiness and mal-trips (including spontaneous and non-selective tripping.

$\lambda_{PT_{A[i]}}$ and $\lambda_{PT_{B[i]}}$ are the failure rates of protection system units $PT_{A[i]}$ and $PT_{B[i]}$, respectively, of line i, which could be defined on the lines of Eqn. (2d), with the numerator including operations resulting from unreadiness and mal-trips.

A single-circuit meshed transmission system structure is considered for the analysis. Every line is assumed to have two neighbouring lines: line i is the focus line, with two neighbouring lines j and k. Transmission lines are labeled in the single line diagram of the OPAL test network (as shown in Fig. 2) in such a manner that similar ends (A-ends or B-ends) of neighbouring lines are connected to the common bus. The validity of the expressions derived in this memo is contingent upon deploying this notation for the OPAL test network.

Lines adjacent to line i (neighbouring lines) are classified into two sets: Set J and Set K.

- J_i is the set of lines connected to the bus nearest to the A-end of line i. A generic notation of any element of J_i is j.
- K_i is the set of lines connected to the bus nearest to the B-end of line i. A generic notation of any element of K_i is k.

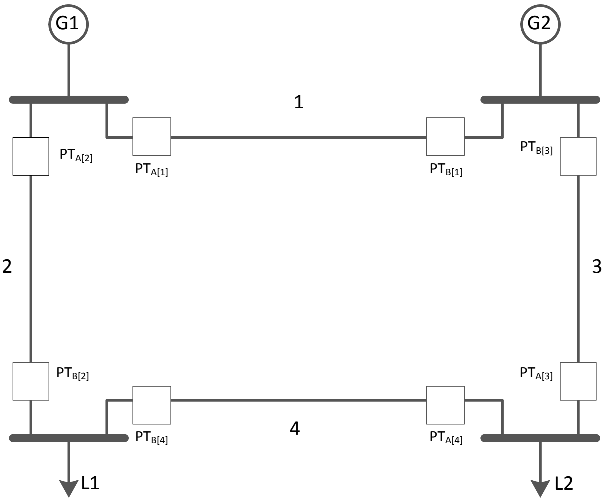


Fig. 2. Single line diagram of OPAL network [10]

For the OPAL network shown in Fig. 2, the classification of neighbouring lines into sets J and K is displayed in Table 1.

Table 1. Classification of neighbouring lines for the OPAL network

Line i	Set of all neighbouring lines	Set J_i	Set K_i
1	{2, 3}	{2}	{3}
2	{1, 4}	{1}	{4}
3	{1, 4}	{4}	{1}
4	{2, 3}	{3}	{2}

2.3 Nomenclature for the explanation of protection system response scenarios in terms of *events*

Let PT_i be the event that protection system of line i is operational (fully effective).

Let PT_{A-i} be the event that protection system unit at the A end of line i at is operational (fully effective).

Let PT_{B-i} be the event that protection system unit at the B end of line i is operational (fully effective).

Let $\overline{PT_{A-i}}$ be the event that protection system unit at the A end of line i is non-operational (ineffective).

Let $\overline{PT_{B-i}}$ be the event that protection system unit at the B end of line i is non-operational (ineffective).

Let X_i be the event that line i is unfaulted.

Let $\overline{X}_i$ be the event that line i is faulted.

Let $\widetilde{X}_i$ be the event that line i is isolated.

Then, the following expressions hold good:

$$P(PT_i) = P[(PT_{A-i}) \bigcap (PT_{B-i})] = P(PT_{A-i}) * P(PT_{B-i}) \tag{3}$$

i.e., the protection system of a line is effective only when protection system units at both ends of the line are effective.

(or)

$$P(\overline{PT}_i) = P[(\overline{PT_{A-i}}) \bigcup (\overline{PT_{B-i}})] = P(\overline{PT_{A-i}}) + P(\overline{PT_{B-i}}) - P[(\overline{PT_{A-i}}) \bigcap (\overline{PT_{B-i}})] \tag{4}$$

$$\Rightarrow P(\overline{PT}_i) = P(\overline{PT_{A-i}}) + P(\overline{PT_{B-i}}) - \left[P(\overline{PT_{A-i}}) * P(\overline{PT_{B-i}}) \right] \tag{5}$$

Equation (5) follows Equation (4) since the assumption of independence is considered to be reasonable in this case.

$$P(PT_i) + P(\overline{PT}_i) = 1 \Rightarrow P(PT_i) = 1 - P(\overline{PT}_i) \tag{6}$$

However, based on Equation (2a), $P(PT^*_{A-i}) = [1 - P_{missing(PT_{A[i]})} - P_{unwanted(PT_{A[i]})}]$ (7)

Similarly, $P(PT^*_{B-i}) = [1 - P_{missing(PT_{B[i]})} - P_{unwanted(PT_{B[i]})}]$ (8)

However, the above two probability parameters $P(PT^*_{A-i})$ and $P(PT^*_{B-i})$ of a protection system unit are of theoretical interest. Of practical interest is the corresponding conditional probability upon the occurrence of a fault, which from Equation (2b) is as follows:

$$P(PT_{A-i}) = P\left(\overline{PT}_{A-i} \Big/ \overline{X}_i \right) = [1 - P_{missing(PT_{A[i]})}]$$

A new term known as 'successful fault clearance rate' of a protection system unit is now introduced: It is defined as the failure rate of a line multiplied by the conditional probability of successful operation of a line's protection system unit in clearing a fault. For example, for a line i whose failure rate is λ_i, the protection system unit at the A-end of the line having a conditional probability of successful operation as $P(PT_{A-i})$, the successful fault clearance rate of the protection system unit is given as $\lambda_i * P(PT_{A-i})$.

2.4 Analysis of transmission line failure modes (fault types) due to protection system response scenarios

Based on the Norwegian fault statistics, the following dominant failure modes of transmission lines due to the various protection system response scenarios could be identified and analyzed. These modes are assumed to be representative of a vast majority of practical occurrences, in general. Additional failure modes can be included if necessary. The objective is to deduce equivalent failure rates corresponding to the various identified fault types, so that Approximate Methods of system reliabililty evaluation [1, 16] could be applied for the reliability analysis.

Fault Type 1 (FT1): A fault occurs on the transmission line i, upon which there could be two consequent scenarios:

Consequent Scenario 1 (CS1): Because of the readiness of line i's primary protection system, the fault is cleared correctly. The line remains isolated from the system until its repair is complete.

Consequent Scenario 2 (CS2): Because of the unreadiness of line i's primary protection system, the fault cannot be cleared, and protection system unit(s) of the neighbouring lines must act to isolate the faulted line.

The fault on line i cannot be cleared by the line's primary protection system on account of the one of the following conditions:

- *Unreadiness of protection system at one end of the line.*
- *Unreadiness of protection system at the other end of the line.*
- *Unreadiness of protection systems at both ends of the line. (Note that the assumption on misoperations taking place one at a time is valid for backup protection system actions only. In a later memo, it will be shown how this scenario is ruled out in the case of a substation configuration.)*

Explanation of the Fault Type in terms of *events*: CS2 of FT1 is the occurrence of event $\overline{X}_i$ and its persistence because of ineffectiveness of *either* $PT_{A[i]}$ *or* $PT_{B[i]}$ *or both*. The sequential event $\tilde{X}_i$, whose occurrence is important for the preservation of system security, occurs only when the neighboring protection system(s) act to isolate line i. In such a case, failure is propagated to the neighbouring line(s) through the dependency effect.

$$P\left(\overline{X}_i\right) = P\left(\left(\overline{PT}_{A-i} / \overline{X}_i\right) \cup \left(\overline{PT}_{B-i} / \overline{X}_i\right)\right) \tag{9}$$

The equivalent failure rate pertaining to CS2 of FT1 is thus the failure rate of the line weighted by a probability figure, which is the probability of failure of the primary protection system of the line (consisting of protection system units at both ends) due to missing operations.

Probability of failure of the primary protection system of line i due to missing operations is given as:

P[(missing operation of $PT_{A[i]}$) ∪ (missing operation of $PT_{B[i]}$)] =

P(missing operation of $PT_{A[i]}$) + P(missing operation of $PT_{B[i]}$) – P[(missing operation of $PT_{A[i]}$) ∩ (missing operation of $PT_{B[i]}$)]

$= P_{missing(PT_{A[i]})} + P_{missing(PT_{B[i]})} - [P_{missing(PT_{A[i]})} * P_{missing(PT_{B[i]})}]$

Missing operations of the protection system end-units of a line are independent events but not mutually exclusive.

Thus, the equivalent failure rate of CS2 of FT1 is:

$$\lambda_{\mathrm{CS2FT1(i)}} = \lambda_{\mathrm{i}}[\mathrm{P}_{\mathrm{missing(PT_{A[i]})}} + \mathrm{P}_{\mathrm{missing(PT_{B[i]})}} - (\mathrm{P}_{\mathrm{missing(PT_{A[i]})}} * \mathrm{P}_{\mathrm{missing(PT_{B[i]})}})] \qquad (10)$$

Irrespective of the consequent scenarios, the expression for equivalent failure rate of line i due to FT1, $\lambda_{FT1(i)}$, is merely its original failure rate. Thus,

$$\lambda_{FT1(i)} = \lambda_i \qquad (11)$$

The outage time associated with FT1 of line i, $r_{FT1(i)}$, is the same as the line's repair time.

Fault Type 2 (FT2): The transmission line i is fault-free, but because of faulty operation of the line's primary protection system, unwanted spontaneous tripping of the circuit breaker(s) occurs. This results in isolation of the healthy line i. This situation can be remedied by auto-reclosure of the breaker associated with the corresponding protection system unit.

Explanation of the Fault Type in terms of *events*: This Fault Type occurs when the conditional event ${}^{\tilde{X}_i}\!/_{X_i}$ occurs on account of the line's own protection system.

In order to obtain the equivalent failure rate pertaining to FT2, the failure rate of the series connected (reliability-logic wise) protection system units at both ends of the line is multiplied by a weightage probability, which is the probability of failure of the primary protection system of line i due to unwanted operations. Failure rate of reliability-logic wise series connected protection system ends is obtained as $[\lambda_{PT_{A[i]}} + \lambda_{PT_{B[i]}}]$.

(Again, it must be noted that the assumption on misoperations taking place one at a time is valid for backup protection system actions only. In a later memo, it will be shown how this scenario is ruled out in the case of a substation configuration.)

The unwanted operations of $PT_{A[i]}$ and $PT_{B[i]}$ are independent but not mutually exclusive. Thus, the probability of failure of the primary protection system of line i due to unwanted operations is given as:

P[(unwanted operation of $PT_{A[i]}$) ∪ (unwanted operation of $PT_{B[i]}$)] =

$$[P_{unwanted-Sp.(PT_{A[i]})} + P_{unwanted-Sp.(PT_{B[i]})} - [P_{unwanted-Sp.(PT_{A[i]})} * P_{unwanted-Sp.(PT_{B[i]})}]]$$

Thus, the expression for equivalent failure rate of line i due to FT2, $\lambda_{FT2(i)}$, is given as:

$$\lambda_{FT2(i)} = \begin{pmatrix} [\lambda_{PT_{A[i]}} + \lambda_{PT_{B[i]}}]* \\ [P_{unwanted-Sp.(PT_{A[i]})} + P_{unwanted-Sp.(PT_{B[i]})} - [P_{unwanted-Sp.(PT_{A[i]})} * P_{unwanted-Sp.(PT_{B[i]})}]] \end{pmatrix} \tag{12a}$$

However, depending upon the data collection schemes in place, this formula can be replaced by simple arithmetic on the statistic of unwanted spontaneous tripping-failure rate of the fault clearance system when available. If there is access to data for determining the failure rate for unwanted spontaneous tripping of the fault clearance system of a protection system unit, the failure rate for FT2 is given as:

$$\lambda_{FT2(i)} = [\lambda_{BE_{A[i]}} + \lambda_{BE_{B[i]}}] \tag{12b}$$

The outage time associated with FT2 of line i, $r_{FT2(i)}$, is the same as the switching time.

Fault Type 3 (FT3): A fault occurs on one of the neighbouring transmission lines, but because of the faulty operation of a protection system assembly of the neighbouring line, its corresponding circuit breaker fails to act. This results in missing operation of a circuit breaker, because of which the faulted neighbouring line cannot be isolated by its own circuit breakers. In such a case, a protection system assembly of line i, the focus line, acts as backup to isolate the faulted neighbouring line. This also results in isolation of the healthy line i.

<u>Explanation of the Fault Type in terms of *events*</u>: Fault Type 3 is the occurrence of conditional event $\tilde{X}_i / X_i$ (i.e., line 'i' is isolated given that it is unfaulted). This is a consequence of one of the following:

(i) Tripping of PTA[i] due to the initiating event: $\overline{PT}_{A-j}/\overline{X}_j$ (i.e., protection system unit at the A end of adjoining line j is ineffective, given line j is faulted).

(ii) Tripping of PTB[i] of line 'i' due to the initiating event: $\overline{PT}_{B-k}/\overline{X}_k$ (i.e., protection system unit at the B end of adjoining line k is ineffective, given line k is faulted).

Thus,

$$P\left(\tilde{X}_i/X_i\right)=P\left(\left(\overline{PT}_{A-j}/\overline{X}_j\right)\cup\left(\overline{PT}_{B-k}/\overline{X}_k\right)\right) \tag{13}$$

The two conditional events are considered to be mutually exclusive because of the assumption of non-overlapping protection system failures.

Theoretically speaking, when appropriate historical operational data collection schemes of protection systems are in place, probability of conditional events can be evaluated from the expression for conditional probability:

$$P\left(E_2/E_1\right)=\frac{P(E_2\cap E_1)}{P(E_1)} \tag{14}$$

However, the probability figure in itself is not of interest per se in this context. The aim is to derive an equivalent failure rate characterizing this fault type.

FT3 'may' occur whenever there is a fault on a neighbouring line. Considering one neighbouring line at a time, the rate at which FT3 occurs would be the same as the failure rate of the neighbouring line if and only if it occurs every time there is a fault on the neighbouring line. Instead, the rate at which FT3 occurs is characterized by the weighted failure rate of the neighbouring line, the weightage factor being the probability of missing operation of the protection system assembly of the neighbouring line nearest to the common bus. Thus, for multiple neighbouring lines,

$$\lambda_{FT3(i)}=\left(\sum_{\forall j\in J_i}(\lambda_j * P_{missing(PT_{A[j]})})\right)+\left(\sum_{\forall k\in K_i}(\lambda_k * P_{missing(PT_{B[k]})})\right) \tag{15}$$

This simplifies to the following expression when there is only one neighbouring line, say line j, adjacent to line i at one end; and also only one neighbouring line, say line k, adjacent to line i at its other end.

$$\lambda_{FT3(i)} = \lambda_j * P_{missing(PT_{A[j]})} + \lambda_k * P_{missing(PT_{B[k]})} \tag{16}$$

The outage time associated with FT3 of line i, $r_{FT3(i)}$, is the same as the switching time.

Fault Type 4 (FT4): A fault occurs on one of the neighbouring transmission lines, upon which the neighbouring line's primary protection system clears the fault correctly. However, because of faulty operation of either of the protection system units of line i or both protection system units of line i, unwanted non-selective tripping of line i's circuit breaker(s) occurs. This results in healthy line i's isolation. (*Though the general assumption is that the misoperations take place one at a time for backup protection system actions only, an exception arises here on account of the specific characteristic features of distance protection.)*

Explanation of the Fault Type in terms of *events*: Fault Type 4 is the occurrence of conditional event ${}^{\tilde{X}_i}/_{X_i}$ (i.e., line i is isolated given that it is unfaulted). This is a consequence of:

(i) Tripping of $PT_{A[i]}$ due to the initiating event: ${}^{\tilde{X}_j}/_{PT_{A-j}}$ (i.e., protection system unit at the A end of adjoining line j is effective, given line j is faulted).

(ii) Tripping of $PT_{B[i]}$ due to the initiating event: ${}^{\tilde{X}_k}/_{PT_{A-k}}$ (i.e., protection system unit at the B end of adjoining line k is effective, given line k is faulted).

$$P\left({}^{\tilde{X}_i}/_{X_i}\right) = P\left(\left({}^{\tilde{X}_j}/_{PT_{A-j}}\right) \cup \left({}^{\tilde{X}_k}/_{PT_{A-k}}\right)\right) \tag{17}$$

FT4 'may' occur on line i whenever there is a fault on a neighbouring line and is cleared successfully by the neighbouring line's primary protection system. The rate at which this FT occurs would be the same as the 'successful fault clearance rate' of the neighbouring line's protection unit if and only if it occurs every time there is successful fault clearance instance on the neighbouring line. Instead, the rate at which FT4 occurs is characterized by the successful fault clearance rate of the neighbouring line's nearest protection system unit (or summation of successful fault clearance rates of the nearest protection system units of neighbouring lines, in the case of more than one neighbouring line) weighted by the probability of unwanted non-selective operation of the primary protection system of line i. Thus,

$$\lambda_{FT4(i)} = \left(\left(\sum_{\forall j \in J_i} [\lambda_j * P(PT_{A-j})] + \sum_{\forall k \in K_i} [\lambda_k * P(PT_{B-k})] \right) * \left(P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} - P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \right) \right) \tag{18}$$

This simplifies to the following expression when there is only one neighbouring line, say line j, adjacent to line i at one end; and also only one neighbouring line, say line k, adjacent to line i at its other end:

$$\lambda_{FT4(i)} = \left(\left([\lambda_j * P(PT_{A-j})] + [\lambda_k * P(PT_{B-k})] \right) * \left(P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} - P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \right) \right) \tag{19}$$

where

$$P(PT_{A-j}) = [1 - P_{\text{missing}(PT_{A[j]})}] \tag{20}$$

and

$$P(PT_{B-k}) = [1 - P_{\text{missing}(PT_{B[k]})}] \tag{21}$$

$\lambda_j * P(PT_{A-j})$ is the successful fault clearance rate of protection system unit at the A-end of line j, and $\lambda_k * P(PT_{B-k})$ is the successful fault clearance rate of protection system unit at the B-end of line k. It must again be noted here that the convention used is such that line j is the neighbouring line connected to the bus nearest to the A-end of line i; line k is the neighbouring line connected to the bus nearest to the B-end of line i.

The outage time associated with FT4 of line i, $r_{FT4(i)}$, is the same as the switching time.

2.4.1 Equivalent failure rate for transmission line subjected to multiple failure modes

The equivalent failure rate of line i taking into account the significant transmission line failure modes due to the various protection system response scenarios is obtained as the summation of individual failure rates of all the above fault types. This is a valid logic since these failure mode states are mutually exclusive for line i, and elements exhibiting such multiple failure modes can be modeled using appropriate series/parallel logic. A system with a component consisting of four mutually exclusive failure modes is analogous to a four component series system. Thus,

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)} \tag{22}$$

where $\lambda_{FT1(i)}, \lambda_{FT2(i)}, \lambda_{FT3(i)}$ and $\lambda_{FT4(i)}$ are as described by Equations (11), (12), (15) and (18), respectively. Some of the important points to be noted about the various fault types are as follows:

- CS1 of FT1 on line i 'may' result in FT4 on a neighbouring line.
- CS2 of FT1 on line i 'will' result in FT3 on a neighbouring line.

Thus, both the consequent scenarios of FT1 could result in multiple transmission line isolations due to the dependency effects of back-up protection system coordination design. FT2 is the only fault type which is independent in that there is no failure propagation to the neighbouring lines at all times.

2.4.2 Input data requirements

To quantify the failure rates of FT1 and FT2 of line i, the needed input information, based on the proposed methodology, is the failure rate of transmission line i and the failure rates of individual units of its protection system. However, for FT3 and FT4, the needed input information also includes the failure rates of adjacent transmission lines (which are designed to have the protection system of line i as their backup protection) and the probability attributes of individual units of the corresponding protection systems.

Table 2. Input data requirements for line i

1	Failure rate of line i	λ_i
2	Probability attributes of the protection system units of line i	$P_{\text{missing}(PT_{A[i]})}$ $P_{\text{missing}(PT_{B[i]})}$ $P_{unwanted-Ns.(PT_{A[i]})}$ $P_{unwanted-Ns.(PT_{B[i]})}$
3	Failure rates of the protection system units of line i	$\lambda_{BE_{A[i]}}$
		$\lambda_{BE_{B[i]}}$

Ideally speaking, the probability attributes need to be computed from appropriate reliability models of the protection and control (P&C) system, which however is possible only if failure and repair rates of all the individual elements of P&C system are known. An alternative is to estimate the required attributes from field data. The basis for data used in [10] and this report is the FASIT scheme of data collection on Norwegian fault statistics.

3 Important Aspects of Approximate System Reliability Evaluation

3.1 Fundamental set of linear relationships

In approximate system reliability evaluation methods [16], mean time to repair (MTTR) is neglected, leading to the assumption of mean time to failure (MTTF) being the same as mean time between failures (MTBF). This further translates to failure rate being the same as failure frequency. The basic reliability parameters of interest for an engineering system (say, power system) are: interruption frequency (equivalent failure rate) $\lambda_{Eq.}$, annual interruption duration (expected annual outage time) U, and average interruption duration (equivalent outage time) r. Approximate methods yield the very popular set of linear relationships, for a system S consisting of i components following series reliability logic, as follows:

$$\begin{aligned} \lambda_s &= \sum \lambda_i \\ U_s &= \sum \lambda_i r_i \\ r_s &= \frac{U_s}{\lambda_s} \end{aligned} \tag{23}$$

In the above equations, the subscripts 's' and 'i' are used to refer to system and component reliability parameters, respectively. In general, U stands for unavailability, which is a probability figure if the units for failure and repair rates are identical. If the units are different, say, failure rate is in failures per year and repair time is in hours (per repair of a failure) as against years, the value of 'U' has dimensional units associated with it – hours/year. The dimensional form is a useful descriptive form as it represents the expected annual outage time, and is the one used in Approximate Methods [16]. The Approximate Methods for reliability computations are very convenient both in terms of algorithmic implementation and computational ease, and hence retain a popular appeal. A unique feature of the OPAL methodology is the employment of Approximate Methods in the reliability calculations.

Input parameters must retain consistency of units when used to verify the validity of Approximate Methods with the exact methods (e.g., Markov). An example is shown in the next subsection.

3.2 Example on interpretation of reliability parameters with different units

The failure rates of three components are 0.05 f/yr, 0.01 f/yr and 0.02 f/yr, respectively, and their average repair times are 20 hr, 15 hr and 25 hr, respectively.

Evaluate the system failure rate, average repair time and unavailability if all three components must operate for system success.

$\lambda_s = 0.05 + 0.01 + 0.02 = 0.08$ f/yr

$U_s = 0.05{*}20 + 0.01{*}15 + 0.02{*}25 = 1.65$ hr/yr

$r_s = 1.65/0.08 = 20.6$ hr

The above is a simple example from [16].

If failure rate is converted to f/hr,

$$U_s = \frac{0.05}{8760} * 20 + \frac{0.01}{8760} * 15 + \frac{0.02}{8760} * 25 = 1.88356 * 10^{-4}$$

If Unavailability is dimensionless (which is the case when calculated with consistent units), multiplying it with 8760 would give 'Annual outage time' in hours/year. In the above example, $1.88356 * 10^{-4} * 8760 = 1.65$ hr/yr.

If U_s is dimensionless, and λ_s is in f/hr, then r_s will be in hours (i.e. hours per repair of a failure).

$$r_s = \frac{1.88356 * 10^{-4}}{0.08 / 8760} = 20.6 \text{ hr}$$

This consistent way of using identical units for failure and repair rates is to be followed when working with Markov models.

3.3 Example on comparison of Approximate Methods with Exact Method

Consider an element which exhibits four different failure modes. Let the following input data be used: failure rates of failure modes 1, 2, 3 and 4 are 3 f/yr, 0.05 f/yr, 0.14 f/yr, and 0.049 f/yr, respectively; corresponding repair times are 15 hr, 2 hr, 0.5 hr, and 0.5 hr, respectively. As noted earlier, a system with a component consisting of four mutually exclusive failure modes is analogous to a four component series system. From the Markov model of a four component series system, solved using the exact frequency and duration methodology, the following set of exact equations is obtained.

$$U = \frac{(\mu_1+\lambda_1)(\mu_2+\lambda_2)(\mu_3+\lambda_3)(\mu_4+\lambda_4)-\mu_1\mu_2\mu_3\mu_4}{(\mu_1+\lambda_1)(\mu_2+\lambda_2)(\mu_3+\lambda_3)(\mu_4+\lambda_4)}$$

$$F = \frac{\mu_1\mu_2\mu_3\mu_4(\lambda_1+\lambda_2+\lambda_3+\lambda_4)}{(\mu_1+\lambda_1)(\mu_2+\lambda_2)(\mu_3+\lambda_3)(\mu_4+\lambda_4)} \tag{24}$$

$$MTTR = \frac{U}{F} = \frac{(\mu_1+\lambda_1)(\mu_2+\lambda_2)(\mu_3+\lambda_3)(\mu_4+\lambda_4)-\mu_1\mu_2\mu_3\mu_4}{\mu_1\mu_2\mu_3\mu_4(\lambda_1+\lambda_2+\lambda_3+\lambda_4)}$$

where F is the failure frequency, MTTR is the mean time to repair.

To employ the Exact Method, failure/repair data for the example element exhibiting four failure modes is transformed into data with consistent units as below

$\lambda_1 = 3f/yr = 3/8760 f/hr$

$\lambda_2 = 0.05f/yr = 0.05/8760 f/hr$

$\lambda_3 = 0.14f/yr = 0.14/8760 f/hr$

$\lambda_4 = 0.049f/yr = 0.049/8760 f/hr$

$r_1 = 15\ hr \Rightarrow \mu_1 = 1/15$ repairs/hr

$r_2 = 2\ hr \Rightarrow \mu_2 = 1/2$ repairs/hr

$r_3 = 0.5\ hr \Rightarrow \mu_3 = 1/0.5$ repairs/hr

$r_4 = 0.5\ hr \Rightarrow \mu_4 = 1/0.5$ repairs/hr

$$U = \frac{\left(\frac{1}{15}+\frac{3}{8760}\right)\left(\frac{1}{2}+\frac{0.05}{8760}\right)\left(\frac{1}{0.5}+\frac{0.14}{8760}\right)\left(\frac{1}{0.5}+\frac{0.049}{8760}\right)-\left(\frac{1}{15}*\frac{1}{2}*\frac{1}{0.5}*\frac{1}{0.5}\right)}{\left(\frac{1}{15}+\frac{3}{8760}\right)\left(\frac{1}{2}+\frac{0.05}{8760}\right)\left(\frac{1}{0.5}+\frac{0.14}{8760}\right)\left(\frac{1}{0.5}+\frac{0.049}{8760}\right)}$$

$\Rightarrow U = 5.13282*10^{-3}$

This Unavailability U is a probability figure. Multiplying it with 8760 gives the annual outage time in hours/year.

$U = 5.13282*10^{-3}*8760 = 44.9635\ hours/year$

$F = 3.678510034*10^{-4}\ failures/hour = 3.678510034*10^{-4}*8760 = 3.22237\ failures/year$

$$r = \frac{U}{F} = \frac{44.9635\ hours/year}{3.22237\ failures/year} = 13.9535\ hours/failure$$

Table 3. Reliability indices: Approximate Methods Vs. Exact Method

Index	Approximate Methods	Exact F&D Method
λ (F)	3.239 failures/year	3.22237 failures/year
U	45.1945 hours/year	44.9635 hours/year
r (MTTR)	13.9532 hours/failure	13.9535 hours/failure

Note that failure frequency F of the Exact Method corresponds to failure rate λ of the Approximate Methods. Mean Time to Repair MTTR of the Exact Method corresponds to the equivalent outage time r of the Approximate Methods.

3.4 Validity of Approximate Methods

The applicability of Approximate Methods must be evidenced by substantiation as not all cases will yield acceptable results. Approximate Methods are applicable only when individual component availabilities approach unity. Their usage in handling system cutsets in OPAL is in fact an acceptable study of mere 'upper bounds' of system failure probability and associated indices. Such upper bound approximate results in comparison with exact system reliability evaluation results are very much a function of the component reliabilities.

3.5 Mapping Approximate Methods with Markov Models

Mapping the results obtained from the Approximate Methods to obtain the parameters of a corresponding Markov model is perfectly valid, i.e., the reciprocal of the equivalent outage time obtained from the Approximate Methods can be directly used as the repair rate in corresponding Markov transitions. This circumvents the need to solve the multi-failure mode Markov model of a component for individual state probabilities to obtain the equivalent repair rate of the component. The Markov model for a transmission line in a transmission network with perfect protection systems is as shown in Fig. 3.

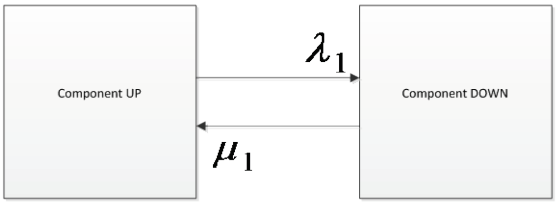


Fig. 3. Two-state representation of a transmission line in a network with perfect protection system. Only one failure mode is existent.

Due to imperfections in the protection system response, the Markov model for a transmission line with four different failure modes is as shown in Fig. 4.

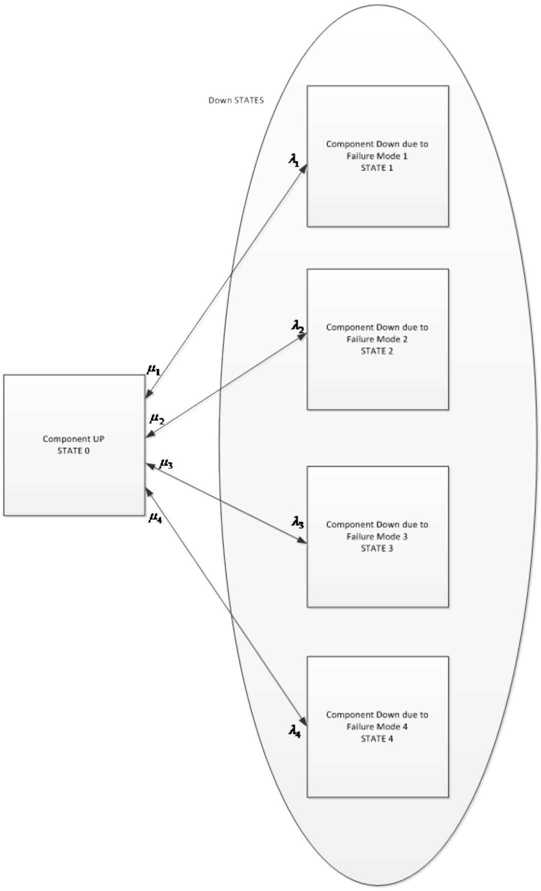


Fig. 4. Markov model for a transmission line with four failure modes

A simplified model of Fig. 4, obtained using the concept of 'merging of states', is as shown in Fig. 5.

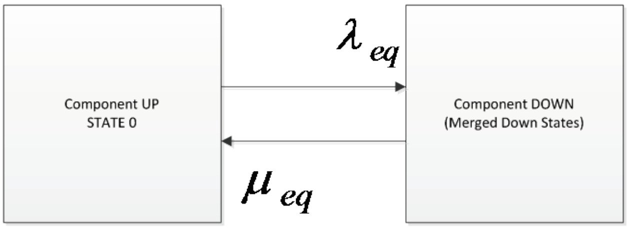


Fig. 5. Simplified Markov model of Fig. 4, using the concept of merging of states

If x and y are identical states to be combined and the resulting state is z, then according to the principle of merging [17], the following set of equations hold good. Fig. 6 is an illustration of the concept of merging of states.

$$
\begin{aligned}
P_z &= P_x + P_y \\
\lambda_{iz} &= \lambda_{ix} + \lambda_{iy} \\
\lambda_{zi} &= \frac{\lambda_{xi}.P_x + \lambda_{yi}.P_y}{P_x + P_y}
\end{aligned}
\tag{25}
$$

where z is a merged state; i is an individual state;

P_x is the probability of occurrence of state x,

P_y is the probability of occurrence of state y,

P_z is the probability of occurrence of state z;

λ_{iz} is the transition rate from state i to state z,

λ_{zi} is the transition rate from state z to state i,

λ_{ix} is the transition rate from state i to state x,

λ_{iy} is the transition rate from state i to state y,

λ_{xi} is the transition rate from state x to state i,

λ_{yi} is the transition rate from state y to state i.

Transition rate from state i to states x/y/z is, in essence, failure rate, and transition rate from states x/y/z to state i is repair rate. For Fig. 4, the following relations hold good:

$$
\begin{aligned}
\lambda_{eq} &= \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 \\
\mu_{eq} &= \frac{P_1\mu_1 + P_2\mu_2 + P_3\mu_3 + P_4\mu_4}{P_1 + P_2 + P_3 + P_4}
\end{aligned}
\tag{26}
$$

In order to obtain the values of P_1, P_2, P_3 and P_4, the Markov model of Fig. 4 needs to be solved. Accordingly, steady state transition probability matrix equations are given as shown in Equation (27).

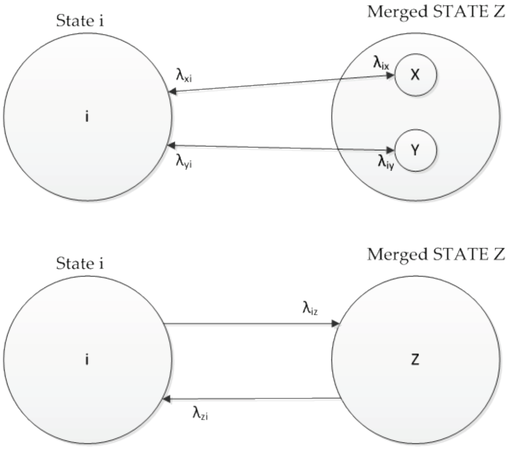


Fig. 6. Illustration of the concept of merging of states

$$\begin{bmatrix} -(\lambda_1+\lambda_2+\lambda_3+\lambda_4) & \mu_1 & \mu_2 & \mu_3 & \mu_4 \\ \lambda_1 & -\mu_1 & 0 & 0 & 0 \\ \lambda_2 & 0 & -\mu_2 & 0 & 0 \\ \lambda_3 & 0 & 0 & -\mu_3 & 0 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{27}$$

Using the example input data used in Section 3.3, where substituting the values of λ in failures/hour and μ in repairs/hour,

$$\begin{bmatrix} -(\frac{3}{8760}+\frac{0.05}{8760}+\frac{0.14}{8760}+\frac{0.049}{8760}) & \frac{1}{15} & \frac{1}{2} & \frac{1}{0.5} & \frac{1}{0.5} \\ \frac{3}{8760} & -\frac{1}{15} & 0 & 0 & 0 \\ \frac{0.05}{8760} & 0 & -\frac{1}{2} & 0 & 0 \\ \frac{0.14}{8760} & 0 & 0 & -\frac{1}{0.5} & 0 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Thus,

$P_0 = 0.9948672911$

$P_1 = 0.0051106196$

$P_2 = 0.0000113569$

$P_3 = 0.0000079498$

$P_4 = 0.0000027824$

$$\Rightarrow \mu_{eq} = \frac{P_1\mu_1 + P_2\mu_2 + P_3\mu_3 + P_4\mu_4}{P_1 + P_2 + P_3 + P_4} = 0.0716679\ repairs / hour$$

$$\Rightarrow \text{Equivalent repair time} = \frac{1}{0.0716679} = 13.9532 \text{ hr}$$

(Equivalent outage time)

$\lambda_{eq} = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 3.69863 * 10^{-4}\ failures / hour$

$= 3.69863 * 10^{-4} * 8760 = 3.2399\ failures / year$

Unavailability U as a probability figure is given by:

$\text{U} = \text{1-P}_0 = 1 - 0.9948672911 = 5.1327089 * 10^{-3}$

Multiplying this with 8760 gives the annual outage time in hours/year.

$5.1327089 * 10^{-3} * 8760 = 44.96252$ hours

Failure Frequency = $P_0 * \lambda_{eq}$ = 0.9948672911 * 3.24 = 3.22327 failures/year

Table 4. Reliability indices: Approximate Methods Vs. Markov Method

Index	Approximate Methods	Markov Method
λ (F)	3.239 failures/year	3.22327 failures/year
U	45.1945 hours/year	44.96252 hours/year
r (MTTR)	13.9532 hours/failure	13.9532 hours/failure

Thus, it can be seen that the reciprocal of the equivalent outage time obtained from the Approximate Methods can be directly used as the repair rate in corresponding Markov transitions. This has the implication that any number of protection system failure modes, as appropriately identified, for a comprehensive analysis of protection system contribution to overall system reliability, can be included in the Approximate Methods, and the results can be used to *map* the parameters of a corresponding Markov model in a simpler way.

Consider a 'sub system' consisting of two 'independent' components labeled 2 and 3, for which Markov model is required for the purpose of some analysis of interest. The Markov state space diagram, when each component has only a single failure mode, is as given in Fig. 7.

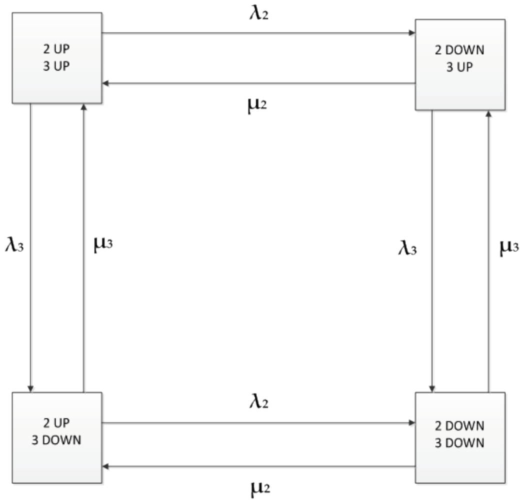


Fig. 7. State space diagram of a two-component system

Say, each component can fail in any of four different failure modes. For component labeled 'i':

For failure mode 1, let the corresponding failure rate be denoted as $\lambda_{f1,i}$, and the repair rate be denoted as $\mu_{f1,i}$;

For failure mode 2, let the corresponding failure rate be denoted as $\lambda_{f2,i}$, and the repair rate be denoted as $\mu_{f2,i}$;

For failure mode 3, let the corresponding failure rate be denoted as $\lambda_{f3,i}$, and the repair rate be denoted as $\mu_{f3,i}$;

For failure mode 4, let the corresponding failure rate be denoted as $\lambda_{f4,i}$, and the repair rate be denoted as $\mu_{f4,i}$. The Markov state space diagram, when each component has four possible failure modes, is as given in Fig. 8.

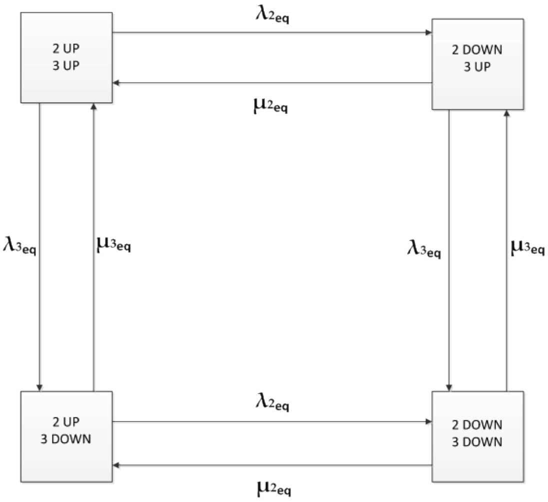


Fig. 8. State space diagram of a two-component system prone to multiple failure modes

The equivalent failure rates – λ_{2eq}, λ_{3eq} and the equivalent repair rates – μ_{2eq}, μ_{3eq}, using the mapping property as described in Section 3.5 and the basis of Equation (23) are as shown in Fig. 9.

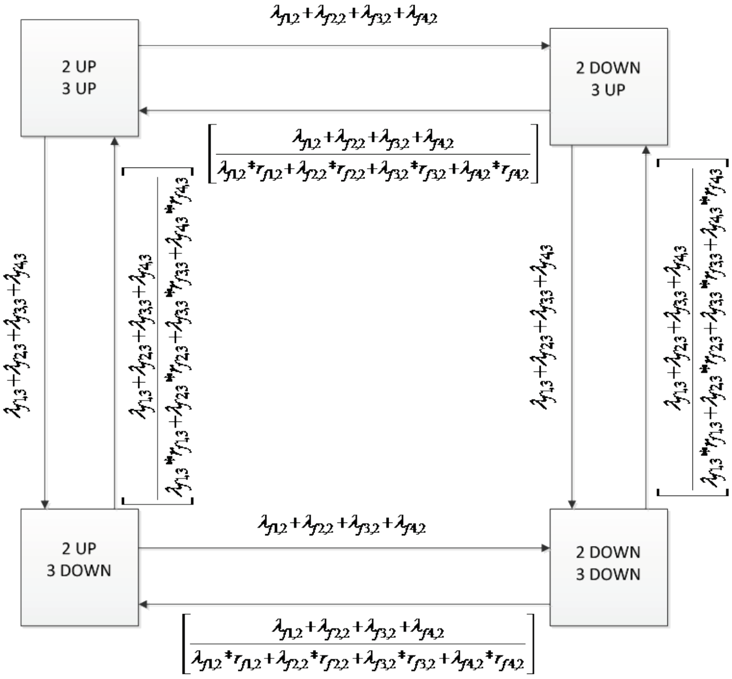


Fig. 9. Markov model parameters for two-component system prone to multiple failure modes as mapped from the Approximate Methods

4 Reliability Analysis

Based on results of the system contingency analysis phase [10, 13], minimal cutsets of lines whose contingency results in load interruptions at delivery points are identified. A good rule of thumb, generally accepted, is to consider minimal cutsets up to order n+1 where n is the lowest-order minimal cutset of the system [18]. The lowest possible order being 1 in general, it is mandatory to have a methodology in place that at least analyzes second order cutsets for reliability analysis.

Once the minimal cutsets are deduced, for every element (transmission line) of each of the cutsets, the equivalent failure rate as derived in Equation (22) is calculated. Further, a three-tiered analysis is carried out at the following levels with the application of Approximate Methods of reliability evaluation.

a) Element level
b) Cutset level
c) Delivery point level

The basic reliability parameters of interest – interruption frequency (equivalent failure rate) $\lambda_{Eq.}$, annual interruption duration (expected annual outage time) U, and average interruption duration (equivalent outage time) r – are calculated at each of these levels, as shown below. When the units for failure rates are in failures per year and repair times/switching times are in hours, $\lambda_{Eq.}$, U and r as given in the subsequent equations are obtained in terms of failures (interruptions) per year, hours per year and hours per failure (interruption), respectively.

a) Element level: Employing the logic of Approximate Methods of reliability evaluation as applied to series systems,

$$U_{(i)} = \lambda_{FT1(i)}r_{FT1(i)} + \lambda_{FT2(i)}r_{FT2(i)} + \lambda_{FT3(i)}r_{FT3(i)} + \lambda_{FT4(i)}r_{FT4(i)} \; h/yr \tag{28}$$

$$r_{(i)} = \frac{U_{(i)}}{\lambda_{Eq.(i)}} \; h \tag{29}$$

b) Cutset level: If the cutset is of first order, $\lambda_{Eq.}$, U and r are the same as obtained at the element level. The composition of second order cutset may be such that the two elements could be either non-neighbouring or neigbouring transmission lines.

Case (i): Cutset {x, y} where x and y are non-neighbouring lines: Employing the logic of Approximate Methods of reliability evaluation as applied to parallel systems,

$$\lambda_{Eq.\{x,y\}} = \frac{\lambda_{Eq.(x)} * \lambda_{Eq.(y)} (r_{(x)} + r_{(y)})}{8760} \; f/yr \tag{30}$$

$$r_{\{x,y\}} = \frac{r_{(x)} * r_{(y)}}{r_{(x)} + r_{(y)}} \; h \tag{31}$$

$$U_{\{x,y\}} = \lambda_{Eq.\{x,y\}} * r_{\{x,y\}} \; h/yr \tag{32}$$

Case (ii): Cutset {x, y} where x and y are neighbouring lines: Since the required resolution of minimal cutsets comprises second order, the dependency effects of consequent scenarios of FT1 between the two neighbouring lines in a minimal cutset could result in multiple transmission line isolations. This can be modeled the same way common-mode failures are modeled in the reliability block diagram of a two-component active parallel redundant system, where an additional 'component' characterizing the common-mode failure rate is connected in series with the parallel configuration of elements, for analysis purposes. Thus, employing the logic of Approximate Methods of reliability evaluation as applied to parallel-series systems,

$$\lambda_{Eq.\{x,y\}} = \frac{\lambda^{'}_{Eq.(x)} * \lambda^{'}_{Eq.(y)} (r^{'}_{(x)} + r^{'}_{(y)})}{8760} + \lambda_D \; f/yr \tag{33}$$

$$U_{\{x,y\}} = \left(\frac{\lambda^{'}_{Eq.(x)} * \lambda^{'}_{Eq.(y)} * r^{'}_{(x)} * r^{'}_{(y)}}{8760} \right) + (\lambda_D * r_D) \; h/yr \tag{34}$$

$$r_{\{x,y\}} = \frac{U_{\{x,y\}}}{\lambda_{Eq.\{x,y\}}} \; h \tag{35}$$

where

$$\lambda^{'}_{Eq.(x)} = \lambda_{FT1(x)} + \lambda_{FT2(x)} + \lambda^{'}_{FT3(x)} + \lambda^{'}_{FT4(x)} \tag{36}$$

$$\lambda^{'}_{Eq.(y)} = \lambda_{FT1(y)} + \lambda_{FT2(y)} + \lambda^{'}_{FT3(y)} + \lambda^{'}_{FT4(y)} \tag{37}$$

λ_D is the dependency-mode failure rate of cutset {x, y}, and r_D is the restoration time taken for the switching action (switching time).

$\lambda^{'}_{FT3(x)}$ is a portion of $\lambda_{FT3(x)}$ that does not contain parameters related to the neighbouring line y present in the cutset being analyzed. $\lambda^{'}_{FT4(x)}$ is a portion of $\lambda_{FT4(x)}$ that does not contain parameters related to the neighbouring line y present in the cutset being analyzed. These subtractions are done to avoid double counting when evaluating λ_D. $\lambda^{'}_{FT3(y)}$ and $\lambda^{'}_{FT4(y)}$ are defined on similar lines.

$$\begin{aligned}\lambda'_{FT3(x)} &= \lambda_{FT3(x)} - \lambda_y * P_{missing(PT_{A[y]})} \; if\, y \in J_x \\ &= \lambda_{FT3(x)} - \lambda_y * P_{missing(PT_{B[y]})} \; if\, y \in K_x\end{aligned} \tag{38}$$

$$\begin{aligned}\lambda'_{FT3(y)} &= \lambda_{FT3(y)} - \lambda_x * P_{missing(PT_{A[x]})} \; if\, x \in J_y \\ &= \lambda_{FT3(y)} - \lambda_x * P_{missing(PT_{B[x]})} \; if\, x \in K_y\end{aligned} \tag{39}$$

$$\begin{aligned}\lambda'_{FT4(x)} &= \lambda_{FT4(x)} - \left(\left(\lambda_y * P(PT_{A-y})\right) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{pmatrix} \right) \; if\, y \in J_x \\ &= \lambda_{FT4(x)} - \left(\left(\lambda_y * P(PT_{B-y})\right) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{pmatrix} \right) \; if\, y \in K_x\end{aligned} \tag{40}$$

$$\begin{aligned}\lambda'_{FT4(y)} &= \lambda_{FT4(y)} - \left(\left(\lambda_x * P(PT_{A-x})\right) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \right) \; if\, x \in J_y \\ &= \lambda_{FT4(y)} - \left(\left(\lambda_x * P(PT_{B-x})\right) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \right) \; if\, x \in K_y\end{aligned} \tag{41}$$

$r'_{(i)}$ is obtained on the lines of Equations (28) and (29) with $\lambda'_{FT3(i)}$ and $\lambda'_{FT4(i)}$ substituted for the existing $\lambda_{FT3(i)}$ and $\lambda_{FT4(i)}$, respectively therein.

Dependency-mode failure rate of cutset {x, y} can be quantified as explained below.
CS2 of FT1 on line x will result in FT3 on line y, and vice-versa (i.e., CS2 of FT1 on line y results in FT3 on line x). These two events are mutually exclusive.
In general, the rate of occurrence of CS2 of FT1 on line i, $\lambda_{CS2FT1(i)}$, can be expressed as:

$$\lambda_{CS2FT1(i)} = \lambda_i [P_{missing(PT_{A[i]})} + P_{missing(PT_{B[i]})} - [P_{missing(PT_{A[i]})} * P_{missing(PT_{B[i]})}]] \tag{42}$$

CS2 of FT1 on line x results in FT3 on all the neighbouring lines. What is of interest in the cutset analysis is only the proportion of CS2 of FT1 on line x which results in FT3 on only that neighbouring line which belongs to the cutset.
The proportional $\lambda_{CS2FT1(x)}$ of interest, $\lambda^*_{CS2FT1(x)}$ is given as:

$$\begin{aligned}\lambda^*_{CS2FT1(x)} &= \lambda_x * P_{missing(PT_{A[x]})} \; if\;\, y \in J_x \\ &= \lambda_x * P_{missing(PT_{B[x]})} \; if\;\, y \in K_x\end{aligned} \tag{43}$$

At this rate, there will be a common-cause failure of lines x and y on account of failure of line x. Similary, the rate at which the other mutually exclusive event – CS2 of FT1 on line y resulting in FT3 on line x – occurs can be expressed as:

$$\begin{aligned}\lambda^{*}_{CS2FT1(y)} &= \lambda_{y} * P_{missing(PT_{A[y]})} \;\; if \;\; x \in J_{y} \\ &= \lambda_{y} * P_{missing(PT_{B[y]})} \;\; if \;\; x \in K_{y}\end{aligned} \tag{44}$$

Thus, λ'_{D}, the dependency-mode failure rate of cutset {x, y} because of CS2 of FT1 on a line that will result in FT3 on the neighbouring line present in the cutset, is given as the summation of $\lambda^{*}_{CS2FT1(x)}$ and $\lambda^{*}_{CS2FT1(y)}$.

$$\lambda'_{D} = \lambda^{*}_{CS2FT1(x)} + \lambda^{*}_{CS2FT1(y)} \tag{45}$$

$\lambda^{*}_{CS2FT1(x)}$ is the same as $\lambda^{*}_{FT3(y)}$, where $\lambda^{*}_{FT3(y)}$ is only that part of the expression for $\lambda_{FT3(y)}$ which contains parameters (line/protection system) of line x. This is so because the dependency propagation from line x due to the failure of its primary protection system to neighbouring lines other than line y is inconsequential to the dependency-mode failure rate of cutset {x, y}. Similarly, $\lambda^{*}_{CS2FT1(y)}$ is the same as $\lambda^{*}_{FT3(x)}$, where $\lambda^{*}_{FT3(x)}$ is only that part of the expression for $\lambda_{FT3(x)}$ which contains parameters (line/protection system) of line y.

$$\lambda^{*}_{FT3(y)} = \lambda_{FT3(y)} - \left(\left(\sum_{\substack{\forall j \in J_i \\ j \neq x}} (\lambda_{j} * P_{missing(PT_{A[j]})}) \right) + \left(\sum_{\substack{\forall k \in K_i \\ k \neq x}} (\lambda_{k} * P_{missing(PT_{B[k]})}) \right) \right) \tag{46}$$

$$\lambda^{*}_{FT3(x)} = \lambda_{FT3(x)} - \left(\left(\sum_{\substack{\forall j \in J_i \\ j \neq y}} (\lambda_{j} * P_{missing(PT_{A[j]})}) \right) + \left(\sum_{\substack{\forall k \in K_i \\ k \neq y}} (\lambda_{k} * P_{missing(PT_{B[k]})}) \right) \right) \tag{47}$$

CS1 of FT1 on line x ‘may’ result in FT4 on line y, and vice-versa. (i.e., CS1 of FT1 on line y ‘may’ result in FT4 on line x). These two events are mutually exclusive. This is a ‘probable’ effect on the dependency-mode failure rate of the cutset as opposed to the ‘certain’ effect of CS2 of FT1 on a line resulting in FT3 on the neighbouring line in the cutset.

$\lambda^{*}_{CS1FT1(x)}$ is the successful fault clearance rate of the protection system unit of line x nearest to the neighbouring line y weighted by the probability of unwanted non-selective operation of the primary protection system of line y.

$$\begin{aligned}\lambda^{*}_{CS1FT1(x)} &= [\lambda_{x} * P(PT_{A-x})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \;\; if \;\; y \in J_{x} \\ &= [\lambda_{x} * P(PT_{B-x})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \;\; if \;\; y \in K_{x}\end{aligned} \tag{48}$$

$\lambda^{*}_{CS1FT1(y)}$ is the successful fault clearance rate of the protection system unit of line y nearest to the neighbouring line x weighted by the probability of unwanted non-selective operation of the primary protection system of line x.

$$\begin{aligned}\lambda^{*}_{CS1FT1(y)} &= [\lambda_y * P(PT_{A-y})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{pmatrix} \quad if\ x \in J_y \\ &= [\lambda_y * P(PT_{B-y})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{pmatrix} \quad if\ x \in K_y \end{aligned} \tag{49}$$

Thus, $\lambda^{"}_{D}$, the dependency-mode failure rate of cutset {x, y} because of CS1 of FT1 on a line that will result in FT4 on the neighbouring line present in the cutset, is given as the summation of $\lambda^{*}_{CS1FT1(x)}$ and $\lambda^{*}_{CS1FT1(y)}$.

$$\lambda^{"}_{D} = \lambda^{*}_{CS1FT1(x)} + \lambda^{*}_{CS1FT1(y)} \tag{50}$$

The net dependency-mode failure rate of cutset {x, y} is given as:

$$\lambda_D = \lambda^{'}_{D} + \lambda^{"}_{D} \tag{51}$$

c) Delivery point level: Based on results obtained at the cutset level, all minimal cutsets which lead to interruptions at delivery points are analyzed together using the logic of Approximate Methods of reliability evaluation as applied to series systems. The computation of Unavailability U for the series combination of minimal cutsets is on the lines of obtaining the upper bound for the probability of system failure using the inclusion-exclusion principle for minimal cutsets. The assumption of independence in evaluating the individual terms of the inclusion-exclusion based union of minimal cutsets can give quite close results for the dependent case if the component reliabilities are high enough.

If there are n minimal cutsets $\{x, y\}_1$, $\{x, y\}_2$, … $\{x, y\}_n$,

$$\lambda_{Eq.(Dp)} = \sum_{i=1}^{n} \lambda_{Eq.\{x,y\}_i}\ f/yr \tag{52}$$

$$U_{(Dp)} = \sum_{i=1}^{n} \left(\lambda_{Eq.\{x,y\}_i} * r_{\{x,y\}_i} \right)\ h/yr \tag{53}$$

$$r_{(Dp)} = \frac{U_{(Dp)}}{\lambda_{Eq.(Dp)}}\ h \tag{54}$$

According to the basic procedure set down in the OPAL methodology [10], [11], input to the reliability analysis phase consists of information about which delivery points will experience interruptions or reduced supply on account of critical contingencies. Minimal cutsets of up to second order are deduced from the contingency analysis phase. The following is the postulated algorithmic approach for obtaining the various reliability indices:

(i) Obtain MCs for each operating state of each load point from the contingency analysis phase.

(ii) Analyse every MC:

(a) For each MC, obtain the equivalent failure rate of each of its elements. It must be noted that the equivalent failure rate of an element is dependent upon the composition of the MC, i.e., whether there are neighbouring lines or non-neighbouring lines present in the MC.

(b) Analyse the combination of all elements of the MC using the approximate methods of system reliability evaluation for parallel systems.

(iii) Analyse the combination of all MCs for each operating state of each load point using the approximate methods of system reliability evaluation for series systems.

(iv) Accumulate the reliability indices for each operating state of each load point.

(v) Use relevant weightage factors (probabilities of occurrences of operating states) to obtain overall reliability indices for each load point.

Once the basic reliability indices λ, U and r are computed, subsequently, the annual power interrupted (PI), annual energy not supplied (ENS) and annual interruption costs (IC) can be computed, all based on a minimal cutset based approach [10]. A recap of the formulae used is as below. A consequence analysis of each contingency under specified operating conditions yields a system available capacity (SAC) for each delivery point due to the contingency. For each MC *j* for a given operating state,

$$\left.\begin{aligned} P_{IN,j} &= P - SAC_j \text{ MW/interruption} \\ ENS_j &= r_j * P_{IN,j} \text{ MWh/interruption} \\ IC_j &= C(r_j) * ENS_j \text{ NOK/interruption} \end{aligned}\right\} \tag{55}$$

where *C(r)* is the specific interruption cost in currency per kWh of energy not supplied, P_{IN} is the interrupted power, and P is the load demand. Each of the expressions above is multiplied by the equivalent failure rate of MC *j* to obtain the indices on an annual basis, i.e., MW/year, MWh/year and NOK (Norwegian Kroners)/year, respectively. For a given operating state, if there are n MCs, the corresponding n annual indices are summed up to get the net delivery point indices per operating state. If there are multiple operating states, a probability weighted equivalent failure rate of MC j is used as the basis for obtaining the above annual indices and summed up accordingly.

5 Case Study

OPAL is a four-bus network with two generators, two delivery points and four transmission lines, as shown in Fig. 2 [10]. The transmission network operates at 132 kV. The capacity of each of the transmission lines is 135 MW. The two generators are assumed to be 100% reliable. Delivery point 1, LP1, has industry customers; delivery point 2, LP2 has energy-intensive industry customers. The network data is given in Table 4.

Table 4. OPAL network data [10]

Line No.	Failure Rate (f/yr)	Repair Time (h)
1	2	20
2	3	15
3	4	12
4	5	10

Two uniform loading conditions are assumed to prevail throughout certain duration of a year at a delivery point. In a 'heavy' load condition (designated as Operating State 1 (OS1)), delivery point LP1 is assumed to have a constant load demand of 100 MW, and delivery point LP2 a constant demand of 75 MW. In a 'light' load condition (designated as Operating State 1 (OS2)), delivery point LP1 is assumed to have a constant load demand of 60 MW, and delivery point LP2 a constant demand of 30 MW. By assigning probability weightages, the effect of multiple operating states can be easily captured. For a twelve month period (December through November) OS2 is assumed to last for 9 months (March to November) a year. Hence, the probability of occurrence of light load condition is 9/12=0.75. OS1 is assumed to last for 3 months (December, January and February) and thus, the probability of occurrence of heavy load condition is 3/12=0.25. All the protection system units have the same repair time of 2 h. The missing and unwanted probabilities of all the protection system units are assumed to be 0.0205 and 0.007, respectively. Failure rate of unwanted spontaneous tripping of the circuit breakers of protection system unit is 0.025 f/yr. The switching time is 0.5 h. It must be noted that different operating states result in different minimal cutsets during the system contingency analysis.

The basic reliability indices are obtained for delivery point LP1, step-by-step, in the next section, to illustrate the application of the proposed methodology. Performing a contingency analysis to identify the interrupted power at delivery point LP1 for the heavy load condition (OS1) yields the following minimal cutsets: $\{x, y\}_1$:{2, 3} and $\{x, y\}_2$:{2, 4}as shown in Fig. 2.

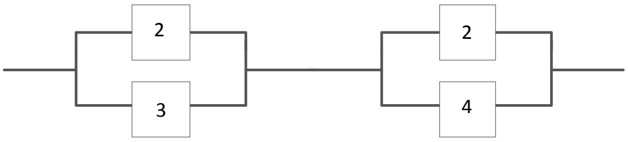


Fig. 10. Minimal cutsets for heavy load condition (OS1) at LP1

{2, 3} has non-neighbouring transmission lines as its constituent elements and {2, 4} has neighbouring transmission lines as its constituent elements. Employing the methodology proposed in Section 2.4, the following basic reliability indices as shown in Table 5 are obtained.

Table 5. Basic reliability indices for delivery point for OS1LP1

Reliability Parameter	Value
λ (f/yr)	0.358
U (h/yr)	0.644
r (h)	1.798

Table 6 provides an overview of the comparative analysis of methods that include the impact of protection and control (P&C) (i.e., circuit breakers and their associated fault clearance systems) in power system reliability assessment against the benchmark of delivery point reliability at LP1 with perfectly reliable P&C. Difference between the values of basic reliability indices obtained using the detailed mathematical modeling of the proposition in Section 4 of this memo and the methodology of the requirement specification document (RSD) [10] is brought forward. Clearly, there is a marked effect of the reliability of protection systems on the reliability of supply.

From the basic indices of Table 5, other indices such as annual interrupted power, annual energy not supplied and annual interruption costs could be obtained [10].

Table 6. Comparative analysis of different reliability evaluation methods for OS1LP1

Method	λ (f/yr)	r (h)	U (h/yr)	% Change in 'λ' w.r.t Perfect P&C	% Change in 'r' w.r.t Perfect P&C	% Change in 'U' w.r.t Perfect P&C
Perfect P&C	0.08	6.324	0.506	-	-	-
With P&C (RSD)	0.302	2.049	0.619	277.50	-67.60	22.32
Proposed Methodology	**0.358**	**1.798**	**0.644**	**347.50**	**-71.57**	**27.27**

A sample graphical depiction of comparative analysis of some indices is shown in Figs. 11 and 12.

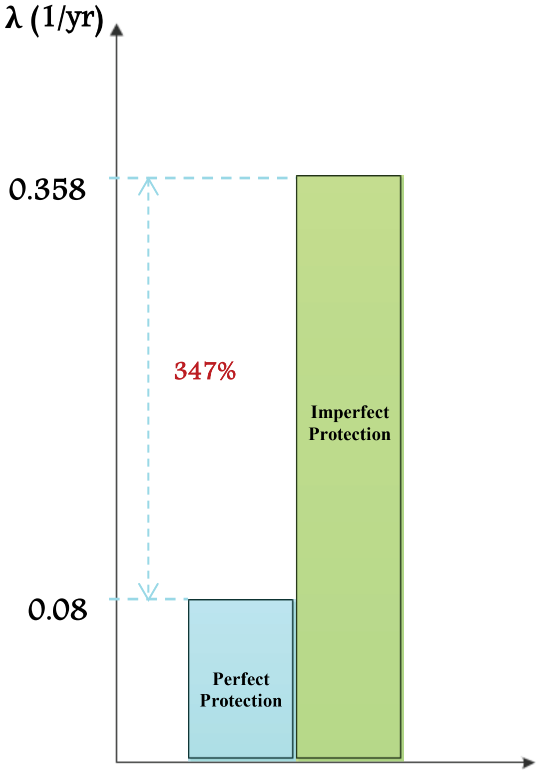


Fig. 11. Graphical depiction of comparative values of the interruption frequency index for OS1LP1

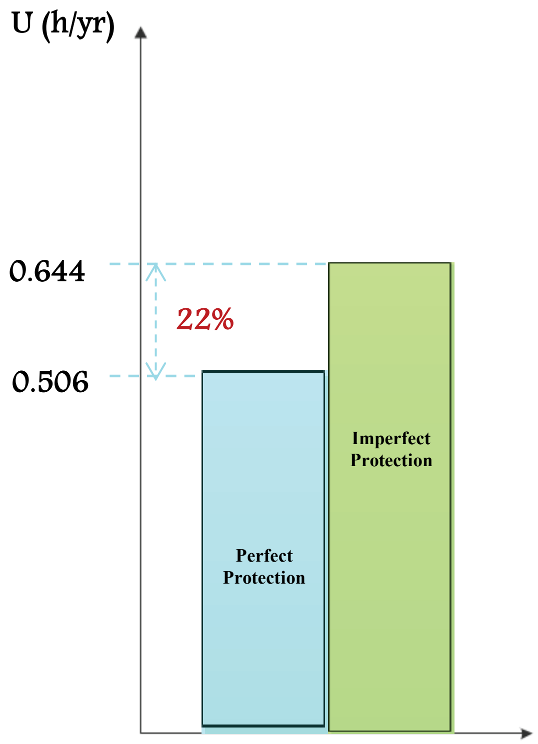
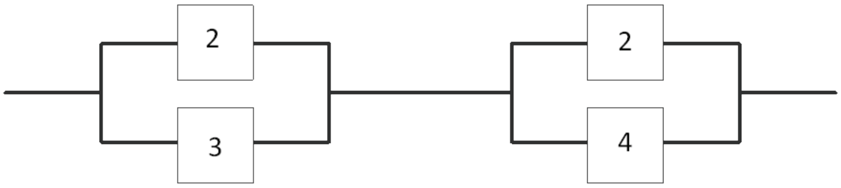
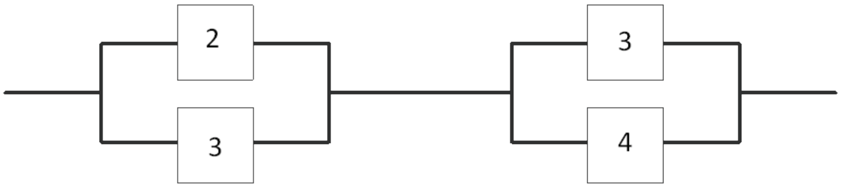


Fig. 12. Graphical depiction of comparative values of the annual interruption duration index for OS1LP1

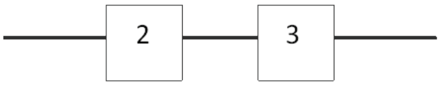
A summary depiction of the minimal cutsets for all the considered operating states (OS1 and OS2) for load points LP1 and LP2 is given in Fig. 13.



(a) Minimal cutsets for heavy load (OS1), and light load (OS2) conditions at LP1



(b) Minimal cutsets for light load (OS2) condition at LP2



(c) Minimal cutsets for heavy load (OS1) condition at LP2

Fig. 13. Minimal cutsets for the case study on OPAL test network

The remaining results are summarized in Tables 7 through 11.

Table 7. Comparative analysis for OS1LP2

Method	λ (f/yr)	r (h)	U (h/yr)
Perfect P&C	7	13.285	93
Proposed Methodology	7.482	12.482	93.39

Table 8. Comparative analysis for OS2LP1 (same for OS1LP1)

Method	λ (f/yr)	r (h)	U (h/yr)
Perfect P&C	0.08	6.324	0.506
Proposed Methodology	0.302	2.037	0.6162

Table 9. Comparative analysis for OS2LP2

Method	λ (f/yr)	r (h)	U (h/yr)
Perfect P&C	0.087	5.97	0.52
Proposed Methodology	0.337	1.919	0.647

Table 10. Additional reliability indices for LP1

Method	PI (MW/yr)	ENS (MWh/yr)	IC (million NOK/yr)
Perfect P&C	5.6	35.328	~1.779
Proposed Methodology	21.17	43.134	~2.137

Table 11. Additional reliability indices for LP2

Method	PI (MW/yr)	ENS (MWh/yr)	IC (million NOK/yr)
Perfect P&C	71.96	941.688	~14.737
Proposed Methodology	82.405	948.47	~14.842

There is an almost 20% increase in the values of ENS and IC for LP1 due to the various protection system response scenarios as against the case of a perfect response scenario. But for LP2, the corresponding increase is just under 1%. This is so because the reliability indices are dominated by higher order outages for LP1. There is no single contingency forming a minimal cutset for LP1, and hence the dependent double contingencies originating from protection system faults on neighbouring lines play an important role.

Though the proposed methodology of handling protection system imperfections in power system reliability calculations for the OPAL test system yields somewhat similar results as those of RSD [10], it must be pointed out that the algorithmic approach as outlined in detail here is comprehensive, and accounts for a more systematic way of handling dependencies. With respect to the RSD, definitions of the various fault types have been refined, and their standard expressions put forward.

Approximate Methods of reliability assessment are known to give pessimistic results. However, their application circumvents the need for complex Markov model-based solutions in incorporating the effects of protection system reliability on power system reliability.

6 Sample Calculations

For illustrative purposes, the basic reliability indices are obtained step-by-step for the delivery point LP1. The results here pertain to a certain operating state assumed to last the whole duration of a year.

Analysis of Minimal Cutset (MC) {2, 3}

(This minimal cutset group contains non-neighbouring lines)

Element 2 when part of (MC) {2, 3}:

$$P_{unwanted(PT_{A[2]})} = P_{unwanted(PT_{B[2]})} = 0.007$$

$$P_{unwanted-Ns.(PT_{A[2]})} = P_{unwanted-Ns.(PT_{B[2]})} = 0.007$$

$$P_{missing(PT_{A[2]})} = P_{missing(PT_{B[2]})} = 0.0205$$

$$\lambda_{BE_{A[2]}} = \lambda_{BE_{B[2]}} = 0.025\ f/yr$$

$$\lambda_2 = 3\ f/yr$$

From Equations (7) & (8),

$$P(PT_{A-i}) = [1 - P_{missing(PT_{A[i]})}]$$

$$P(PT_{B-i}) = [1 - P_{missing(PT_{B[i]})}]$$

$$\Rightarrow P(PT_{A-2}) = [1 - P_{missing(PT_{A[2]})}] = [1 - 0.0205] = 0.9795$$

$$P(PT_{B-2}) = [1 - P_{missing(PT_{B[2]})}] = [1 - 0.0205] = 0.9795$$

From Equation (11),

$$\lambda_{FT1(i)} = \lambda_i$$

$$\Rightarrow \lambda_{FT1(2)} = \lambda_2 = 3\ f/yr$$

From Equation (12b),

$$\lambda_{FT2(i)} = [\lambda_{BE_{A[i]}} + \lambda_{BE_{B[i]}}]$$

$$\Rightarrow \lambda_{FT2(2)} = [\lambda_{BE_{A[2]}} + \lambda_{BE_{B[2]}}]$$

$$\lambda_{FT2(2)} = [0.025 + 0.025] = 0.05\ f/yr$$

For element i=2, $J_i = \{1\}$; $K_i = \{4\}$. (From Table 1)

$$\lambda_1 = 2\ f/yr;\ \lambda_4 = 5\ f/yr$$

From Equation (15),

$$\lambda_{FT3(i)} = \left(\sum_{\forall j \in J_i} (\lambda_j * P_{missing(PT_{A[j]})}) \right) + \left(\sum_{\forall k \in K_i} (\lambda_k * P_{missing(PT_{B[k]})}) \right)$$

$$\Rightarrow \lambda_{FT3(2)} = \lambda_1 * P_{missing(PT_{A[1]})} + \lambda_4 * P_{missing(PT_{B[4]})}$$

$$P_{missing(PT_{A[1]})} = P_{missing(PT_{B[4]})} = 0.0205$$

$$Thus,\ \lambda_{FT3(2)} = 2*0.0205 + 5*0.0205 = 0.1435\ f/yr$$

From Equation (18),

$$\lambda_{FT4(i)} = \left(\left(\sum_{\forall j \in J_i} [\lambda_j * P(PT_{A-j})] + \sum_{\forall k \in K_i} [\lambda_k * P(PT_{B-k})] \right) * \left(P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} - P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \right) \right)$$

For element i=2, $J_i = \{1\}$; $K_i = \{4\}$. (From Table 1)

$$\lambda_{FT4(2)} = \left(([\lambda_1 * P(PT_{A-1})] + [\lambda_4 * P(PT_{B-4})]) * \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \right) \right)$$

From Equations (7) & (8),

$$P(PT_{A-1}) = [1 - P_{missing(PT_{A[1]})}] = [1 - 0.0205] = 0.9795$$

$$P(PT_{B-4}) = [1 - P_{missing(PT_{B[4]})}] = [1 - 0.0205] = 0.9795$$

$$\Rightarrow \lambda_{FT4(2)} = (2*0.9795 + 5*0.9795)*[0.007 + 0.007 - 0.007*0.007] = 0.095655\ f/yr$$

Failure rates (f/yr) on account of different failure modes for element 2 when it is a part of MC{2, 3}

$\lambda_{FT1(2)} = 3$
$\lambda_{FT2(2)} = 0.05$
$\lambda_{FT3(2)} = 0.1435$
$\lambda_{FT4(2)} = 0.095655$

From Equation (22),

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}$$

$$\Rightarrow \lambda_{Eq.(2)} = \lambda_{FT1(2)} + \lambda_{FT2(2)} + \lambda_{FT3(2)} + \lambda_{FT4(2)}$$

$$\Rightarrow \lambda_{Eq.(2)} = 3 + 0.05 + 0.1435 + 0.095655 = 3.289155\ f/yr$$

$$r_{FT1(2)} = 15\ h;\ r_{FT2(2)} = 2\ h;\ r_{FT3(2)} = 0.5\ h;\ r_{FT4(2)} = 0.5\ h$$

From Equation (28),

$$U_{(i)} = \lambda_{FT1(i)} r_{FT1(i)} + \lambda_{FT2(i)} r_{FT2(i)} + \lambda_{FT3(i)} r_{FT3(i)} + \lambda_{FT4(i)} r_{FT4(i)}\ \ h/yr$$

$$\Rightarrow U_{(2)} = \lambda_{FT1(2)} r_{FT1(2)} + \lambda_{FT2(2)} r_{FT2(2)} + \lambda_{FT3(2)} r_{FT3(2)} + \lambda_{FT4(2)} r_{FT4(2)}\ \ h/yr$$

$$\Rightarrow U_{(2)} = (3*15) + (0.05*2) + (0.1435*0.5) + (0.095655*0.5) = 45.2195775\ h/yr$$

From Equation (29),

$$r_{(i)} = \frac{U_{(i)}}{\lambda_{Eq.(i)}} \ h$$

$$\Rightarrow r_{(2)} = \frac{U_{(2)}}{\lambda_{Eq.(2)}} = \frac{45.2195775}{3.289155} = 13.74808347 \ h$$

Reliability parameters of element 2 when it is a part of MC{2, 3}

$\lambda_{Eq.(2)} = 3.289155 \ f/yr$
$U_{(2)} = 45.2195775 \ h/yr$
$r_{(2)} = 13.74808347 \ h$

Element 3 when part of (MC) {2, 3}:

$$P_{unwanted(PT_{A[3]})} = P_{unwanted(PT_{B[3]})} = 0.007$$

$$P_{unwanted-Ns.(PT_{A[3]})} = P_{unwanted-Ns.(PT_{B[3]})} = 0.007$$

$$P_{missing(PT_{A[3]})} = P_{missing(PT_{B[3]})} = 0.0205$$

$$\lambda_{BE_{A[3]}} = \lambda_{BE_{B[3]}} = 0.025 \ f/yr$$

$$\lambda_3 = 4 \ f/yr$$

From Equations (7) & (8),

$$P(PT_{A-i}) = [1 - P_{missing(PT_{A[i]})}]$$

$$P(PT_{B-i}) = [1 - P_{missing(PT_{B[i]})}]$$

$$\Rightarrow P(PT_{A-3}) = [1 - P_{missing(PT_{A[3]})}] = [1 - 0.0205] = 0.9795$$

$$P(PT_{B-3}) = [1 - P_{missing(PT_{B[3]})}] = [1 - 0.0205] = 0.9795$$

From Equation (11),

$$\lambda_{FT1(i)} = \lambda_i$$

$$\Rightarrow \lambda_{FT1(3)} = \lambda_3 = 4 \ f/yr$$

From Equation (12b),

$$\lambda_{FT2(i)} = [\lambda_{BE_{A[i]}} + \lambda_{BE_{B[i]}}]$$

$$\Rightarrow \lambda_{FT2(3)} = [\lambda_{BE_{A[3]}} + \lambda_{BE_{B[3]}}]$$

$$\Rightarrow \lambda_{FT2(3)} = [0.025 + 0.025] = 0.05 \ f/yr$$

For element i=3, J_i = {4}; K_i = {1}. (From Table 1)

$\lambda_1 = 5\ f/yr;\ \lambda_1 = 2\ f/yr$

From Equation (15),

$$\lambda_{FT3(i)} = \left(\sum_{\forall j \in J_i} (\lambda_j * P_{missing(PT_{A[j]})}) \right) + \left(\sum_{\forall k \in K_i} (\lambda_k * P_{missing(PT_{B[k]})}) \right)$$

$$\Rightarrow \lambda_{FT3(3)} = \lambda_4 * P_{missing(PT_{A[4]})} + \lambda_1 * P_{missing(PT_{B[1]})}$$

$$Thus,\ \lambda_{FT3(3)} = 5 * 0.0205 + 2 * 0.0205 = 0.1435\ f/yr$$

From Equation (18),

$$\lambda_{FT4(i)} = \left(\begin{array}{l} \left(\sum_{\forall j \in J_i} [\lambda_j * P(PT_{A-j})] + \sum_{\forall k \in K_i} [\lambda_k * P(PT_{B-k})] \right) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} - P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \right) \end{array} \right)$$

For element i=3, J_i = {4}; K_i = {1}. (From Table 1)

$$\lambda_{FT4(3)} = \left(\begin{array}{l} ([\lambda_4 * P(PT_{A-4})] + [\lambda_1 * P(PT_{B-1})]) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})} \right) \end{array} \right)$$

From Equations (7) & (8),

$$P(PT_{A-4}) = [1 - P_{missing(PT_{A[4]})}] = [1 - 0.0205] = 0.9795$$

$$P(PT_{B-1}) = [1 - P_{missing(PT_{B[1]})}] = [1 - 0.0205] = 0.9795$$

$$\Rightarrow \lambda_{FT4(3)} = (5 * 0.9795 + 2 * 0.9795) * [0.007 + 0.007 - 0.007 * 0.007] = 0.095655\ f/yr$$

Failure rates (f/yr) on account of different failure modes for element 3 when it is a part of MC{2, 3}

$\lambda_{FT1(3)} = 4$
$\lambda_{FT2(3)} = 0.05$
$\lambda_{FT3(3)} = 0.1435$
$\lambda_{FT4(3)} = 0.095655$

From Equation (22),

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}$$

$$\Rightarrow \lambda_{Eq.(3)} = \lambda_{FT1(3)} + \lambda_{FT2(3)} + \lambda_{FT3(3)} + \lambda_{FT4(3)}$$

$$\Rightarrow \lambda_{Eq.(3)} = 4 + 0.05 + 0.1435 + 0.095655 = 4.289155\ f/yr$$

$$r_{FT1(3)} = 12\ h;\ r_{FT2(3)} = 2\ h;\ r_{FT3(3)} = 0.5\ h;\ r_{FT4(3)} = 0.5\ h$$

From Equation (28),

$$U_{(i)} = \lambda_{FT1(i)} r_{FT1(i)} + \lambda_{FT2(i)} r_{FT2(i)} + \lambda_{FT3(i)} r_{FT3(i)} + \lambda_{FT4(i)} r_{FT4(i)} \;\; h/yr$$

$$\Rightarrow U_{(3)} = \lambda_{FT1(3)} r_{FT1(3)} + \lambda_{FT2(3)} r_{FT2(3)} + \lambda_{FT3(3)} r_{FT3(3)} + \lambda_{FT4(3)} r_{FT4(3)} \;\; h/yr$$

$$\Rightarrow U_{(3)} = (4*12) + (0.05*2) + (0.1435*0.5) + (0.095655*0.5) = 48.2195775 \; h/yr$$

From Equation (29),

$$r_{(i)} = \frac{U_{(i)}}{\lambda_{Eq.(i)}} \;\; h$$

$$\Rightarrow r_{(3)} = \frac{U_{(3)}}{\lambda_{Eq.(3)}} = \frac{48.2195775}{4.289155} = 11.24220913 \; h$$

Reliability parameters of element 3 when it is a part of MC{2, 3}

$\lambda_{Eq.(3)} = 4.289155 \; f/yr$
$U_{(3)} = 48.2195775 \; h/yr$
$r_{(3)} = 11.24220913 \; h$

Analysis of Cutset {2, 3}:

Reliability parameters of elements 2 & 3 when part of MC{2, 3}

Element i	$\lambda_{Eq.(i)}$ *(f/yr)*	r_i *(h)*
2	3.289155	13.74808347
3	4.289155	11.24220913

From Equation (30),

$$\lambda_{Eq.\{x,y\}} = \frac{\lambda_{Eq.(x)} * \lambda_{Eq.(y)} (r_{(x)} + r_{(y)})}{8760} \;\; f/yr$$

$$\Rightarrow \lambda_{Eq.\{2,3\}} = \frac{\lambda_{Eq.(2)} * \lambda_{Eq.(3)} (r_{(2)} + r_{(3)})}{8760} \;\; f/yr$$

$$\Rightarrow \lambda_{Eq.\{2,3\}} = \frac{(3.289155*4.289155)(13.74808347 + 11.24220913)}{8760} = 0.040246 \; f/yr$$

From Equation (31),

$$r_{\{x,y\}} = \frac{r_{(x)} * r_{(y)}}{r_{(x)} + r_{(y)}} \;\; h$$

$$\Rightarrow r_{\{2,3\}} = \frac{r_{(2)} * r_{(3)}}{r_{(2)} + r_{(3)}} = \frac{(13.74808347*11.24220913)}{(13.74808347 + 11.24220913)} = 6.1847547 \; h$$

From Equation (32),

$$U_{\{x,y\}} = \lambda_{Eq.\{x,y\}} * r_{\{x,y\}} \ h/yr$$

$$\Rightarrow U_{\{2,3\}} = \lambda_{Eq.\{2,3\}} * r_{\{2,3\}} = 0.040246 * 6.1847547 = 0.248912 \ h/yr$$

Result of the analysis of Cutset {2, 3}

$\lambda_{Eq.\{2,3\}}$	0.040246 *f/yr*
$r_{\{2,3\}}$	6.1847547 *h*
$U_{\{2,3\}}$	0.248912 *h/yr*

Analysis of Minimal Cutset (MC) {x, y}: x=2; y=4

(This minimal cutset group contains neighbouring lines)

Element 2 when part of (MC) {2, 4}:

Note: The reliability parameters of element 2 to be used for the analysis of minimal cutset {2, 4} are **NOT** the same as those obtained for element 2 when it was analysed as part of the minimal cutset {2, 3}.

From Equation (36),

$$\lambda'_{Eq.(x)} = \lambda_{FT1(x)} + \lambda_{FT2(x)} + \lambda'_{FT3(x)} + \lambda'_{FT4(x)}$$

$$\Rightarrow \lambda'_{Eq.(2)} = \lambda_{FT1(2)} + \lambda_{FT2(2)} + \lambda'_{FT3(2)} + \lambda'_{FT4(2)}$$

From Equation (38),

$$\lambda'_{FT3(x)} = \lambda_{FT3(x)} - \lambda_y * P_{missing(PT_{A[y]})} \ if\, y \in J_x$$

$$= \lambda_{FT3(x)} - \lambda_y * P_{missing(PT_{B[y]})} \ if\, y \in K_x$$

For element x=2, J₂ = {1}; K₂ = {4}. (From Table 1)

But, $y{=}4 \in K_2$

$$\Rightarrow \lambda'_{FT3(x)} = \lambda_{FT3(x)} - \lambda_y * P_{missing(PT_{B[y]})}$$

$$\Rightarrow \lambda'_{FT3(2)} = \lambda_{FT3(2)} - \lambda_4 * P_{missing(PT_{B[4]})}$$

As computed earlier, $\lambda_{FT3(2)} = 2*0.0205 + 5*0.0205 = 0.1435 \ f/yr$

$$\Rightarrow \lambda'_{FT3(2)} = 0.1435 - 5*0.0205 = 0.041$$

From Equation (40),

$$\begin{aligned}\lambda'_{FT4(x)} &= \lambda_{FT4(x)} - \left(\left(\lambda_y * P(PT_{A-y})\right) * \left(\begin{array}{l} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{array} \right) \right) \; if\, y \in J_x \\ &= \lambda_{FT4(x)} - \left(\left(\lambda_y * P(PT_{B-y})\right) * \left(\begin{array}{l} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{array} \right) \right) \; if\, y \in K_x\end{aligned}$$

For element x=2, $J_2 = \{1\}$; $K_2 = \{4\}$. (From Table 1)

But, $y=4 \in K_2$

$$\Rightarrow \lambda'_{FT4(x)} = \lambda_{FT4(x)} - \left(\left(\lambda_y * P(PT_{B-y})\right) * \left(\begin{array}{l} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{array} \right) \right)$$

$$\Rightarrow \lambda'_{FT4(2)} = \lambda_{FT4(2)} - \left(\left(\lambda_4 * P(PT_{B-4})\right) * \left(\begin{array}{l} P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} \\ -P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \end{array} \right) \right)$$

As computed earlier,

$$\lambda_{FT4(2)} = (2*0.9795 + 5*0.9795)*[0.007 + 0.007 - 0.007*0.007] = 0.095655\, f/yr$$

$$\Rightarrow \lambda'_{FT4(2)} = 0.095655 - \left((5*0.9795)*(0.007 + 0.007 - [0.007*0.007]) \right) = 0.02733\, f/yr$$

Thus,

$$\lambda_{FT1(2)} = \lambda_2 = 3\, f/yr$$

$$\lambda_{FT2(2)} = [0.025 + 0.025] = 0.05\, f/yr$$

$$\lambda'_{FT3(2)} = 0.041\, f/yr$$

$$\lambda'_{FT4(2)} = 0.02733\, f/yr$$

$$\Rightarrow \lambda'_{Eq.(2)} = 3 + 0.05 + 0.041 + 0.02733 = 3.11833\, f/yr$$

Corresponding value of U is obtained by using Equation (28) with $\lambda'_{FT3(i)}$ and $\lambda'_{FT4(i)}$ substituted for the existing $\lambda_{FT3(i)}$ and $\lambda_{FT4(i)}$, respectively therein. Thus,

$$U'_{(i)} = \lambda_{FT1(i)} r_{FT1(i)} + \lambda_{FT2(i)} r_{FT2(i)} + \lambda'_{FT3(i)} r_{FT3(i)} + \lambda'_{FT4(i)} r_{FT4(i)} \;\; h/yr$$

$$\Rightarrow U'_{(2)} = \lambda_{FT1(2)} r_{FT1(2)} + \lambda_{FT2(2)} r_{FT2(2)} + \lambda'_{FT3(2)} r_{FT3(2)} + \lambda'_{FT4(2)} r_{FT4(2)} \;\; h/yr$$

$$r_{FT1(2)} = 15\ h;\; r_{FT2(2)} = 2\ h;\; r_{FT3(2)} = 0.5\ h;\; r_{FT4(2)} = 0.5\ h$$

$$\Rightarrow U'_{(2)} = (3*15) + (0.05*2) + (0.041*0.5) + (0.02733*0.5)\ h/yr$$

$$= 45.134165\ h/yr$$

Corresponding value of r is obtained by using Equation (29) with $U'_{(i)}$ and $\lambda'_{Eq.(i)}$ substituted for the existing $U_{(i)}$ and $\lambda_{Eq.(i)}$, respectively therein. Thus,

$$r'_{(i)} = \frac{U'_{(i)}}{\lambda'_{Eq.(i)}}\ h$$

$$\Rightarrow r'_{(2)} = \frac{U'_{(2)}}{\lambda'_{Eq.(2)}} = \frac{45.134165}{3.11833} = 14.4738257\ h$$

Reliability parameters of element 2 when it is a part of MC{2, 4}

$\lambda'_{Eq.(2)} = 3.11833\ f/yr$
$U'_{(2)} = 45.134165\ h/yr$
$r'_{(2)} = 14.4738257\ h$

Element 4 when part of (MC) {2, 4}:

$$P_{unwanted(PT_{A[4]})} = P_{unwanted(PT_{B[4]})} = 0.007$$

$$P_{unwanted-Ns.(PT_{A[4]})} = P_{unwanted-Ns.(PT_{B[4]})} = 0.007$$

$$P_{missing(PT_{A[4]})} = P_{missing(PT_{B[4]})} = 0.0205$$

$$\lambda_{BE_{A[4]}} = \lambda_{BE_{B[4]}} = 0.025\ f/yr$$

$$\lambda_4 = 5\ f/yr$$

From Equations (7) & (8),

$$P(PT_{A-i}) = [1 - P_{missing(PT_{A[i]})}]$$

$$P(PT_{B-i}) = [1 - P_{missing(PT_{B[i]})}]$$

$$\Rightarrow P(PT_{A-4}) = [1 - P_{missing(PT_{A[4]})}] = [1 - 0.0205] = 0.9795$$

$$P(PT_{B-4}) = [1 - P_{missing(PT_{B[4]})}] = [1 - 0.0205] = 0.9795$$

From Equation (11),

$$\lambda_{FT1(i)} = \lambda_i$$

$$\Rightarrow \lambda_{FT1(4)} = \lambda_4 = 5\ f/yr$$

From Equation (12b),

$$\lambda_{FT2(i)} = [\lambda_{BE_{A[i]}} + \lambda_{BE_{B[i]}}]$$

$$\Rightarrow \lambda_{FT2(4)} = [\lambda_{BE_{A[4]}} + \lambda_{BE_{B[4]}}]$$

$$\lambda_{FT2(4)} = [0.025 + 0.025] = 0.05\ f/yr$$

For element i=4, J_i = {3}; K_i = {2}. (From Table 1)

$$\lambda_3 = 4\ f/yr;\ \lambda_2 = 3\ f/yr$$

From Equation (39),

$$\begin{aligned}\lambda'_{FT3(y)} &= \lambda_{FT3(y)} - \lambda_x * P_{missing(PT_{A[x]})} \quad if\, x \in J_y \\ &= \lambda_{FT3(y)} - \lambda_x * P_{missing(PT_{B[x]})} \quad if\, x \in K_y\end{aligned}$$

For element y=4, J_4 = {3}; K_4 = {2}. (From Table 1)

But, $x=2 \in K_4$

$$\Rightarrow \lambda'_{FT3(y)} = \lambda_{FT3(y)} - \lambda_x * P_{missing(PT_{B[x]})}$$

$$\Rightarrow \lambda'_{FT3(4)} = \lambda_{FT3(4)} - \lambda_2 * P_{missing(PT_{B[2]})}$$

From Equation (15),

$$\lambda_{FT3(i)} = \left(\sum_{\forall j \in J_i} (\lambda_j * P_{missing(PT_{A[j]})}) \right) + \left(\sum_{\forall k \in K_i} (\lambda_k * P_{missing(PT_{B[k]})}) \right)$$

$$\Rightarrow \lambda_{FT3(4)} = \lambda_3 * P_{missing(PT_{A[3]})} + \lambda_2 * P_{missing(PT_{B[2]})}$$

$$P_{missing(PT_{A[3]})} = P_{missing(PT_{B[2]})} = 0.0205$$

$$Thus,\ \lambda_{FT3(4)} = 4 * 0.0205 + 3 * 0.0205 = 0.1435\ f/yr$$

$$\Rightarrow \lambda'_{FT3(4)} = 0.1435 - 3 * 0.0205 = 0.082$$

From Equation (41),

$$\begin{aligned}\lambda'_{FT4(y)} &= \lambda_{FT4(y)} - \left((\lambda_x * P(PT_{A-x})) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \right) \quad if\, x \in J_y \\ &= \lambda_{FT4(y)} - \left((\lambda_x * P(PT_{B-x})) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \right) \quad if\, x \in K_y\end{aligned}$$

For element y=4, J_4 = {3}; K_4 = {2}. (From Table 1)

But, $x=2 \in K_4$

$$\Rightarrow \lambda'_{FT4(y)} = \lambda_{FT4(y)} - \left((\lambda_x * P(PT_{B-x})) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \right)$$

$$\Rightarrow \lambda'_{FT4(4)} = \lambda_{FT4(4)} - \left((\lambda_2 * P(PT_{B-2})) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} \\ -P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \end{pmatrix} \right)$$

From Equation (18),

$$\lambda_{FT4(i)} = \left(\left(\sum_{\forall j \in J_i} [\lambda_j * P(PT_{A-j})] + \sum_{\forall k \in K_i} [\lambda_k * P(PT_{B-k})] \right) * \left(P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} - P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \right) \right)$$

For element i=4, $J_4 = \{3\}$; $K_4 = \{2\}$. (From Table 1)

$$\lambda_{FT4(4)} = \left(\left([\lambda_3 * P(PT_{A-3})] + [\lambda_2 * P(PT_{B-2})] \right) * \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \right)$$

From Equations (7) & (8),

$$P(PT_{A-3}) = [1 - P_{missing(PT_{A[3]})}] = [1 - 0.0205] = 0.9795$$

$$P(PT_{B-2}) = [1 - P_{missing(PT_{B[2]})}] = [1 - 0.0205] = 0.9795$$

$$\Rightarrow \lambda_{FT4(4)} = (4 * 0.9725 + 3 * 0.9725) * [0.007 + 0.007 - 0.007 * 0.007]$$

$$= \ 0.095655 \ f/yr$$

$$\Rightarrow \lambda'_{FT4(4)} = 0.095655 - \left((3 * 0.9725) * [0.007 + 0.007 - 0.007 * 0.007] \right)$$

$$= 0.05466 \ f/yr$$

Thus,

$$\lambda_{FT1(4)} = \lambda_4 = 5 \ f/yr$$

$$\lambda_{FT2(4)} = 0.05 \ f/yr$$

$$\lambda'_{FT3(4)} = 0.082 \ f/yr$$

$$\lambda'_{FT4(4)} = 0.05466 \ f/yr$$

$$\Rightarrow \lambda'_{Eq.(4)} = 5 + 0.05 + 0.082 + 0.05466 = 5.18666 \ f/yr$$

Corresponding value of U is obtained by using Equation (28) with $\lambda'_{FT3(i)}$ and $\lambda'_{FT4(i)}$ substituted for the existing $\lambda_{FT3(i)}$ and $\lambda_{FT4(i)}$, respectively therein. Thus,

$$U'_{(i)} = \lambda_{FT1(i)} r_{FT1(i)} + \lambda_{FT2(i)} r_{FT2(i)} + \lambda'_{FT3(i)} r_{FT3(i)} + \lambda'_{FT4(i)} r_{FT4(i)} \ h/yr$$

$$\Rightarrow U'_{(4)} = \lambda_{FT1(4)} r_{FT1(4)} + \lambda_{FT2(4)} r_{FT2(4)} + \lambda'_{FT3(4)} r_{FT3(4)} + \lambda'_{FT4(4)} r_{FT4(4)} \ h/yr$$

$$r_{FT1(4)} = 10 \ h; \ r_{FT2(2)} = 2 \ h; \ r_{FT3(2)} = 0.5 \ h; \ r_{FT4(2)} = 0.5 \ h$$

$$\Rightarrow U'_{(4)} = (5 * 10) + (0.05 * 2) + (0.082 * 0.5) + (0.05466 * 0.5) \ h/yr$$

$$= 50.16833 \ h/yr$$

Corresponding value of r is obtained by using Equation (29) with $U'_{(i)}$ and $\lambda'_{Eq.(i)}$ substituted for the existing $U_{(i)}$ and $\lambda_{Eq.(i)}$, respectively therein. Thus,

$$r'_{(i)} = \frac{U'_{(i)}}{\lambda'_{Eq.(i)}}\ h$$

$$\Rightarrow r'_{(4)} = \frac{U'_{(4)}}{\lambda'_{Eq.(4)}} = \frac{50.16833}{5.18666} = 9.6725696\ h$$

Reliability parameters of element 4 when it is a part of MC{2, 4}

$\lambda'_{Eq.(4)} = 5.18666\ f/yr$
$U'_{(4)} = 50.16833\ h/yr$
$r'_{(4)} = 9.6725696\ h$

Dependency mode failure rate of cutset {2, 4}:

From Equation (51),

$$\lambda_D = \lambda'_D + \lambda''_D$$

From Equation (45),

$$\lambda'_D = \lambda^*_{CS2FT1(x)} + \lambda^*_{CS2FT1(y)}$$

$$\Rightarrow \lambda'_D = \lambda^*_{CS2FT1(2)} + \lambda^*_{CS2FT1(4)}$$

From Equation (50),

$$\lambda''_D = \lambda^*_{CS1FT1(x)} + \lambda^*_{CS1FT1(y)}$$

$$\Rightarrow \lambda''_D = \lambda^*_{CS1FT1(2)} + \lambda^*_{CS1FT1(4)}$$

Thus,

$$\lambda_D = \lambda^*_{CS2FT1(x)} + \lambda^*_{CS2FT1(y)} + \lambda^*_{CS1FT1(x)} + \lambda^*_{CS1FT1(y)}$$

$$\Rightarrow \lambda_D = \lambda^*_{CS2FT1(2)} + \lambda^*_{CS2FT1(4)} + \lambda^*_{CS1FT1(2)} + \lambda^*_{CS1FT1(4)}$$

From Equation (43),

$$\lambda^*_{CS2FT1(x)} = \lambda_x * P_{missing(PT_{B[x]})}$$

$$\Rightarrow \lambda^*_{CS2FT1(2)} = \lambda_2 * P_{missing(PT_{B[2]})} = 3 * 0.0205 = 0.0615\ f/yr$$

From Equation (44),

$$\lambda^*_{CS2FT1(y)} = \lambda_y * P_{missing(PT_{B[y]})}$$

$$\Rightarrow \lambda^*_{CS2FT1(4)} = \lambda_4 * P_{missing(PT_{B[4]})} = 5 * 0.0205 = 0.1025\ f/yr$$

From Equation (48),

$$\lambda^*_{CS1FT1(x)} = [\lambda_x * P(PT_{B-x})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix}$$

$$\Rightarrow \lambda^{*}_{CS1FT1(2)} = [\lambda_2 * P(PT_{B-2})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} \\ -P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \end{pmatrix}$$

$$= (3*0.9795)*[0.007+0.007-0.007*0.007] = 0.040995\ f/yr$$

From Equation (49),

$$\lambda^{*}_{CS1FT1(y)} = [\lambda_y * P(PT_{B-y})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{pmatrix}$$

$$\Rightarrow \lambda^{*}_{CS1FT1(4)} = [\lambda_4 * P(PT_{B-4})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} \\ -P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \end{pmatrix}$$

$$= (5*0.9795)*[0.007+0.007-0.007*0.007] = 0.068325$$

$$\Rightarrow \lambda_D = 0.0615+0.1025\ +0.040995+0.068325 = 0.273320036\ f/yr$$

Using Equation (33),

$$\lambda_{Eq.\{2,4\}} = \frac{\lambda'_{Eq.(2)} * \lambda'_{Eq.(4)} (r'_{(2)} + r'_{(4)})}{8760} + \lambda_D\ f/yr$$

$$\Rightarrow \lambda_{Eq.\{2,4\}} = \frac{(3.11833*5.18666)(14.47382+9.67256)}{8760} + 0.273320036$$
$$= 0.317901883\ f/yr$$

Using Equation (34), and restoration time = 0.5 h,

$$U_{\{2,4\}} = \left(\frac{\lambda'_{Eq.(2)} * \lambda'_{Eq.(4)} * r'_{(2)} * r'_{(4)}}{8760} \right) + (\lambda_D * r_D)\ h/yr$$

$$U_{\{2,4\}} = \left(\frac{(3.11833*5.18666*14.47382*9.67256)}{8760} \right) + (0.273320036*0.5)$$
$$= 0.395142\ h/yr$$

Using Equation (35),

$$r_{\{2,4\}} = \frac{U_{\{2,4\}}}{\lambda_{Eq.\{2,4\}}}\ h$$

$$\Rightarrow r_{\{2,4\}} = \frac{0.395142}{0.317901883} = 1.2429696\ h$$

Result of the analysis of Cutset {2, 4}

$\lambda_{Eq.\{2,4\}}$	0.317901883 *f/yr*
$r_{\{2,4\}}$	1.2429696 *h*
$U_{\{2,4\}}$	0.395142 *h/yr*

Combination of Minimal Cutsets:

Using Equation (52),

$$\lambda_{Eq.(LP1)} = \lambda_{Eq.\{2,3\}} + \lambda_{Eq.\{2,4\}}$$

$$\Rightarrow \lambda_{Eq.(LP1)} = 0.040246 + 0.317901883 = 0.358147938 \, f/yr$$

Using Equation (53),

$$U_{(LP1)} = (\lambda_{Eq.\{2,3\}} * r_{\{2,3\}}) + (\lambda_{Eq.\{2,4\}} * r_{\{2,4\}})$$

$$\Rightarrow U_{(LP1)} = (0.040246 * 6.1847547) + (0.317901883 * 1.2429696) = 0.644054379 \; h/yr$$

Using Equation (54),

$$r_{(LP1)} = \frac{U_{(LP1)}}{\lambda_{Eq.(LP1)}}$$

$$\Rightarrow r_{(LP1)} = \frac{0.644054379}{0.358147938} = 1.7982914 \; h$$

Basic reliability indices for load point L1

$\lambda_{Eq.(LP1)} = 0.302429975 \, f/yr$
$U_{(LP1)} = 0.616210203 \; h/yr$
$r_{(LP1)} = 2.037530184 \; h$

7 Conclusions and Future Work

There is a considerable effect of reliability of protection systems on the reliability of supply, and hence appropriate protection system reliability models must be incorporated in power system reliability studies. A detailed mathematical modeling of the dominant failure modes of transmission lines due to various protection system response scenarios has been provided in this memo. The uniqueness of the proposed approach lies in its ability to model the impacts of transmission protection system failures on power system reliability without the need for complex Markov models, while accounting for the dependency effects, using the approximate frequency and duration methods. Sample delivery point indices based on the proposition have been calculated for the OPAL test network. The developed procedure of incorporating protection system failure modes in reliability studies allows for the inclusion of additional failure modes if necessary, and is generic.

The approximate methods yield pessimistic estimates, and the results are in fact upper bounds for the reliability indices. The proposed method of handling dependencies is not well suited for obtaining lower bounds, in which case Markov models must be resorted to. However, the obtained information is sufficient enough for practical uses. In terms of validation, the proposed methodology of handling protection system imperfections in power system reliability calculations for the OPAL test system yields somewhat identical results as those of the preliminary results of [10]. The applicability of approximate methods themselves in general, has been established by comparisons with the accurate analytical state space method. It must be pointed out that the algorithmic approach as posited in this memo is comprehensive, and accounts for a more systematic way of handling dependencies, forming the basis for arriving at generic expressions for more complex real life transmission networks.

The work put forward in this memo will be extended through further research with the following issues addressed:

- Inclusion of higher order cutsets for reliability analysis,
- Procedural extension for multi circuit meshed transmission systems, and
- Analysis of the impact of station configurations on reliability indices.

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APPENDIX 2

Project memo AN 13.12.33

Incorporation of various protection system failure modes in composite power system reliability studies in the OPAL framework –
Part II: Additional considerations of dependencies and inclusion of higher order cutsets

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Project memo

Incorporation of various protection system failure modes in composite power system reliability studies in the OPAL framework – Part II

Additional considerations of dependencies and inclusion of higher order cutsets

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ABSTRACT

Building on the previously established procedure of including basic transmission protection system dependencies (as documented by the memo AN 12.12.66), improvement to the OPAL methodology for the reliability analysis phase has been initiated by considering two additional protection system dependencies brought on by (i) the presence of parallel transmission lines between bus pairs, and (ii) the presence of higher order (3rd level) minimal cutsets. The purpose of this memo is to present the results of investigation carried out in this regard. To this effect, modified and extended versions of the OPAL network have been constructed. Whereas the case study on basic OPAL network yielded very few minimal cutsets, the multitude of minimal cutsets obtained in the modified and extended versions of the OPAL network pave the way for further feedback in making the reliability analysis methodology robust. This memo primarily focuses on the case study involving the calculation of basic delivery point reliability indices, with and without the consideration of protection system failures, on the four-bus Modified OPAL (MOPAL) test network.

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Table of contents

1 Introduction

In the previous project memo AN 12.12.66 [1], the results of investigation carried out to improve the then existing module on protection system reliability considerations in the OPAL methodology for reliability analysis of power systems were presented. Analytical methods for quantifying the impact of protection system imperfections on power system reliability were initially developed as part of the SINTEF technical report TR A6429 [2] on the requirement specification for reliability analysis in meshed power networks. Building on this first reported conceptual foundation, the methodology put forward in the previous memo [1] retained the uniqueness of capturing the impact of protection system failure modes in composite power system reliability studies without the need for complex Markov models, while accounting in detail for the constituent complex dependency effects. The classification of protection system faults to be considered for the reliability analysis was expanded, and their detailed mathematical modelling for further analysis was presented. Throughout, only the approximate methods of system reliability evaluation were used as the foundation. Based on the single-circuit meshed transmission system – OPAL network as a reference case, generic expressions for failure rates were developed for similar meshed systems. These accounted for the four revised and comprehensively *expanded* fault types that a transmission line could experience because of the various associated protection system response scenarios. A simple case study involving the calculation of basic delivery point reliability indices, with and without the consideration of protection system failures, was then illustrated on the four-bus OPAL test network.

Building on the previous memo [1], improvement to the OPAL methodology for the reliability analysis phase has been initiated in this report by considering *two additional protection system dependencies brought on by the presence of parallel transmission lines between bus pairs, and the presence of higher order (3rd level) minimal cutsets.* The purpose of the current memo is to present the results of investigation carried out in this regard. To this effect, modified and extended versions of the OPAL network have been constructed. Whereas the case study on basic OPAL network yielded very few minimal cutsets, the multitude of minimal cutsets obtained in the modified and extended versions of the OPAL network pave the way for further feedback in making the reliability analysis methodology robust. This memo primarily focuses on the case study involving the calculation of basic delivery point reliability indices, with and without the consideration of protection system failures, on the four-bus Modified OPAL (MOPAL) test network.

2 Minimal Cutsets

Theoretically, all the minimal cutsets of a power system must be analyzed for a given operating state in order to carry out accurate reliability analysis. However, keeping in mind that the probability of higher order cutsets is negligible when compared to that of lower order cutsets, for the sake of computational efficiency, reasonable approximations can be resorted to. Thus, the assessment may be limited to credible contingencies based on pre-select contingency cut-off criteria. In general, fixed criteria such as the selection of single or double level contingencies and/or variable criteria such as frequency/probability cut-off limit and/or ranking cut-off limit are used [3]. Selection of an appropriate cut-off level is dictated by various factors such as the size of the system, the failure and repair rates of lines, the severity associated with an outage event, the purpose of the adequacy studies, and the computation time required to evaluate each outage event [4]. Ranking of contingencies by an appropriate performance index is also a viable option, which selectively chooses a subset of outage states from the set of all credible contingency states.

A good rule of thumb, generally accepted, is to consider minimal cutsets up to order n+1 where n is the lowest-order minimal cutset of the system [4]. The lowest possible order being 1 in general, it is mandatory to have a methodology in place that at least analyzes second order cutsets for reliability analysis. Such a methodology was put forward in the previous memo [1] based on approximate methods of system reliability evaluation. *In the present memo, an appropriate methodology to analyze third order minimal cutsets has been put forward since some of the sample case studies investigated previously involved no first order minimal cutsets, i.e., the lowest order cutsets were second order minimal cutsets.* This effectively enables the handling of contingency analysis of up to third order.

Further, it is generally acknowledged that the importance of a minimal cutset is inversely proportional to its order [4]. Analysis of minimal cutsets can also provide some indications on the criticality of various components. Qualitatively speaking, those appearing in the lower order minimal cutsets and those most frequently appearing in several minimal cutsets are potential candidates critical for the reliable operation of the system.

3 Recap of Fault Types

A consolidated description of transmission line failure modes (fault types) due to the various protection system response scenarios are reproduced below from [1]:

Fault Type 1 (FT1): A fault occurs on the transmission line i, upon which there could be two consequent scenarios:

Consequent Scenario 1 (CS1): Because of the readiness of line i's primary protection system, the fault is cleared correctly. The line remains isolated from the system until its repair is complete.

The outage time associated with FT1 of line i, $r_{FT1(i)}$, is the same as the line's repair time.

Consequent Scenario 2 (CS2): Because of the unreadiness of line i's primary protection system, the fault cannot be cleared, and protection system unit(s) of the neighbouring lines must act to isolate the faulted line.

The fault on line i cannot be cleared by the line's primary protection system on account of the one of the following conditions:

- *Unreadiness of protection system at one end of the line.*
- *Unreadiness of protection system at the other end of the line.*
- *Unreadiness of protection systems at both ends of the line.*

Fault Type 2 (FT2): The transmission line i is fault-free, but because of faulty operation of the line's primary protection system, unwanted spontaneous tripping of the circuit breaker(s) occurs. This results in isolation of the healthy line i. This situation can be remedied by auto-reclosure of the breaker associated with the corresponding protection system unit.

The outage time associated with FT2 of line i, $r_{FT2(i)}$, is the switching time.

Fault Type 3 (FT3): A fault occurs on one of the neighbouring transmission lines, but because of the faulty operation of a protection system of the neighbouring line, its corresponding circuit breaker fails to act. This results in missing operation of a circuit breaker, because of which the faulted neighbouring line cannot be isolated by its own circuit breakers. In such a case, a protection system assembly of line i acts as backup to isolate the faulted neighbouring line. This also results in isolation of the healthy line i.

The outage time associated with FT3 of line i, $r_{FT3(i)}$, is the same as the switching time.

Fault Type 4 (FT4): A fault occurs on one of the neighbouring transmission lines, upon which the neighbouring line's primary protection system clears the fault correctly. However, because of faulty operation of either of the protection system units of line i or both protection system units of line i, unwanted non-selective tripping of line i's circuit breaker(s) occurs. This results in healthy line i's isolation.

The outage time associated with FT4 of line i, $r_{FT4(i)}$, is the same as the switching time.

Fig. 1 is a depiction of interdependencies among the various fault types between the two elements A and B of a second order minimal cutset.

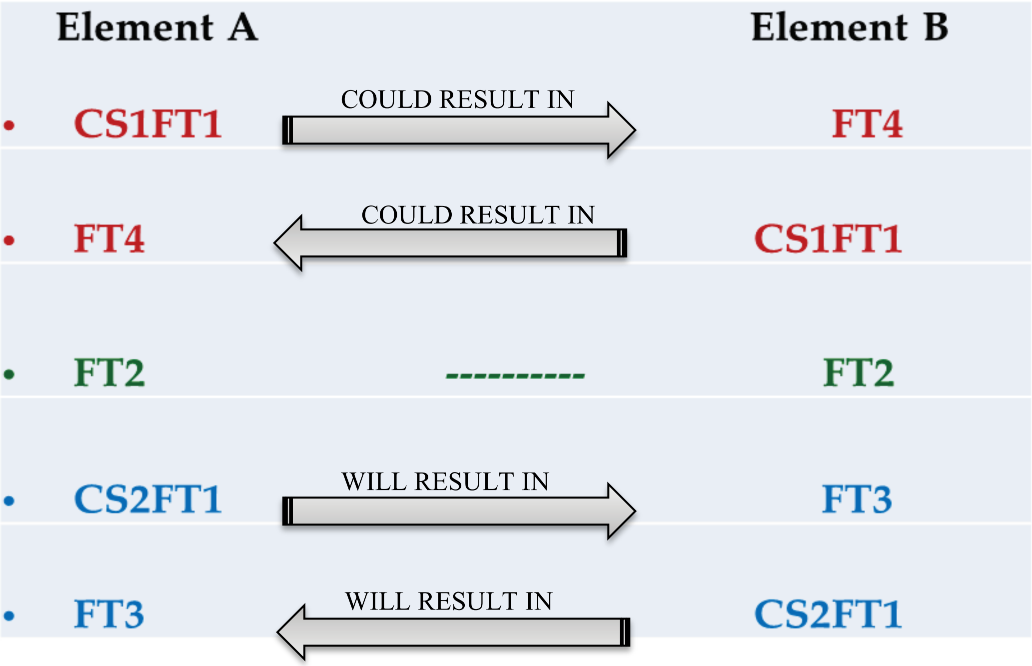

Fig. 1. Depiction of interdependencies between elements of a 2nd order minimal cutset

4 Handling of Additional Dependencies

The handling of protection system dependencies arising in a single circuit meshed transmission network, where only minimal cutsets up to only second order were chosen for reliability analysis, was central to the previous memo [1]. The presence of parallel transmission lines between bus pairs (in a multi circuit meshed transmission network) creates additional protection system dependencies. Also, a different treatment than the one used for second order minimal cutsets is needed for handling dependencies in the presence of higher order (3rd level) minimal cutsets.

Once all the minimal cutsets are obtained from the contingency analysis phase, for every element (transmission line) of each of these minimal cutsets, the equivalent failure rate (summation of individual failure rates of the four established fault types) is obtained. This value is a starting point for the subsequent three tiered analysis that follows (as outlined in [1]), which culminates in the evaluation of basic reliability parameters of interest - interruption frequency (equivalent failure rate) $\lambda_{Eq.}$, annual interruption duration (expected annual outage time) U, and average interruption duration (equivalent outage time) r. Subsequently, composite reliability indices such as the annual power interrupted (P_{Interr}), annual energy not supplied (ENS) and annual interruption costs (IC) can be computed as outlined in [5]. The required procedure for up to second order minimal cutsets, for both cases of presence of non-neighbouring and neighbouring elements in the minimal cutsets, was developed in [1] for single circuit meshed transmission circuits. The way this procedure needs to be suitably modified and adapted for the case of multi circuit meshed transmission systems containing parallel transmission lines between bus pairs, is outlined below. *This is demonstrated step by step in the sample calculations that follow later.*

For each line belonging to a minimal cutset, *a combinatorial analysis of all possible backup coordination related interaction scenarios among its neighbouring lines* is carried out. (Note: Neighbouring lines were previously defined as transmission lines connected to the common bus. By the same convention, parallel lines between bus pairs fall in this category. For a finer distinction, there can be a further division of neighbouring lines as parallel neighbouring lines and non-parallel neighbouring lines.) For each of these interaction scenarios, a failure rate contribution expression is formulated from the first principles with respect to fault types FT3 and FT4. This is relatively straight forward for minimal cutsets with constituent non-neighbouring lines. However, in the case of minimal cutsets with constituent neighbouring parallel lines or neighbouring non-parallel lines or a mixture, a subset of these interaction scenarios, which pertain to dependency aspects among **all** the minimal cutset constituents are set aside. Such failure rate contributions are not included in the failure rate expressions of FT3 and FT4, but utilized only in the expressions for dependence-mode failure rates of the minimal cutsets (i.e. $\lambda_D = \lambda_D^{'} + \lambda_D^{''}$ from Equations 45 and 50 of the previous memo [1]).

A simple bus arrangement is initially chosen for the preliminary analysis. Detailed station configurations will be addressed in the next phase of research. Some of the operational aspects of the simple bus arrangement are given below:

- Every time there is a fault on a parallel line, if it is not cleared, its counterpart will 'successfully' get disconnected.
- Every time a parallel line performs a backup action, its counterpart also does the same.
  - ➢ Implication: Calculation of FT3 changes.
- If there is unwanted non selective operation of a parallel line, it is assumed its counterpart will NOT experience the same (because of the assumption that faulty operations happen one at a time!)
  - ➢ Implication: Calculation of FT4 changes.

5 Third Order Minimal Cutsets – Equations

Recap: Analysis of First and Second Order Cutsets: Formulae [1]

a) Element level: Employing the logic of approximate methods applied for series systems,

$$U_{(i)} = \lambda_{FT1(i)} r_{FT1(i)} + \lambda_{FT2(i)} r_{FT2(i)} + \lambda_{FT3(i)} r_{FT3(i)} + \lambda_{FT4(i)} r_{FT4(i)} \ h/yr \tag{1}$$

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)} \ f/yr \tag{2}$$

$$r_{(i)} = \frac{U_{(i)}}{\lambda_{Eq.(i)}} \ h \tag{3}$$

b) Cutset level: If the cutset is of first order, $\lambda_{Eq.}$, U and r are the same as obtained at the element level. The composition of second order cutset may be such that the two elements could be either non-neighbouring or neigbouring transmission lines.

Case (i): Cutset {x, y} where x and y are non-neighbouring lines:

Employing the logic of approximate methods applied for parallel systems,

$$\lambda_{Eq.\{x,y\}} = \frac{\lambda_{Eq.(x)} * \lambda_{Eq.(y)} (r_{(x)} + r_{(y)})}{8760} \ f/yr \tag{4}$$

$$r_{\{x,y\}} = \frac{r_{(x)} * r_{(y)}}{r_{(x)} + r_{(y)}} \ h \tag{5}$$

$$U_{\{x,y\}} = \lambda_{Eq.\{x,y\}} * r_{\{x,y\}} \ h/yr \tag{6}$$

Case (ii): Cutset {x, y} where x and y are neighbouring lines:

If x and y are two components of a parallel system that has a common mode/dependency mode failure, the resulting reliability block diagram can be represented as simplified to a two component independent parallel system ***in series*** with a *component* accounting for the common mode/dependency mode failure. Such a 'series' system can fail either when the parallel block of x and y ***fails independently*** or when there is an occurrence of the common mode/dependency mode failure.

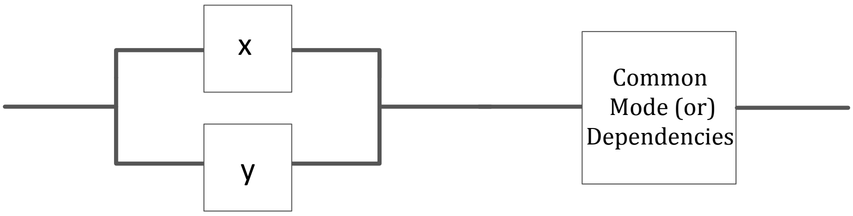

Fig. 2. Equivalent 'series' system representation of a 2 component dependent parallel system

$$\lambda_{Eq.\{x,y\}} = \frac{\lambda'_{Eq.(x)} * \lambda'_{Eq.(y)} (r'_{(x)} + r'_{(y)})}{8760} + \lambda_D \ f/yr \tag{7}$$

$$U_{\{x,y\}} = \left(\frac{\lambda'_{Eq.(x)} * \lambda'_{Eq.(y)} * r'_{(x)} * r'_{(y)}}{8760} \right) + (\lambda_D * r_D) \ h/yr \tag{8}$$

$$r_{\{x,y\}} = \frac{U_{\{x,y\}}}{\lambda_{Eq.\{x,y\}}} \ h \tag{9}$$

where

$$\lambda'_{Eq.(x)} = \lambda_{FT1(x)} + \lambda_{FT2(x)} + \lambda'_{FT3(x)} + \lambda'_{FT4(x)} \tag{10}$$

$$\lambda'_{Eq.(y)} = \lambda_{FT1(y)} + \lambda_{FT2(y)} + \lambda'_{FT3(y)} + \lambda'_{FT4(y)} \tag{11}$$

λ_D is the dependency-mode failure rate of cutset {x, y}, and r_D is the restoration time taken for the switching action (switching time). The procedure to obtain the dependency-mode failure rate was developed in the previous memo [1], founded on the observations from Fig. 1 depicting the interdependency possibilities in a second order cutset. $\lambda'_{FT3(x)}$ is a portion of $\lambda_{FT3(x)}$ that does not contain parameters related to the neighbouring line y present in the cutset being analyzed. $\lambda'_{FT4(x)}$ is a portion of $\lambda_{FT4(x)}$ that does not contain parameters related to the neighbouring line y present in the cutset being analyzed. These subtractions are done to avoid double counting when evaluating λ_D . $\lambda'_{FT3(y)}$ and $\lambda'_{FT4(y)}$ are defined on similar lines.

Case (iii): Cutset {x, y, z} where x, y and z are non-neighbouring lines:

On similar lines, analysis of Cutset {x, y, z} where x, y and z are non-neighbouring lines is done as follows, employing the logic of approximate methods applied for parallel systems, and appropriately accounting for the consistency of units:

$$\lambda_{Eq.\{x,y,z\}} = \frac{\left(\lambda_{Eq.(x)} * \lambda_{Eq.(y)} * \lambda_{Eq.(z)}\right)\left(r_{(x)}r_{(y)} + r_{(y)}r_{(z)} + r_{(z)}r_{(x)}\right)}{8760 * 8760} \ f/yr \tag{12}$$

$$r_{\{x,y,z\}} = \frac{r_{(x)} * r_{(y)} * r_{(z)}}{r_{(x)}r_{(y)} + r_{(y)}r_{(z)} + r_{(z)}r_{(x)}} \; h \qquad (13)$$

$$U_{\{x,y,z\}} = \frac{\lambda_{Eq.\{x,y,z\}} * r_{\{x,y,z\}}}{8760 * 8760} \; h/yr$$

$$\Rightarrow U_{\{x,y,z\}} = \frac{\left(r_{(x)} * r_{(y)} * r_{(z)}\right)\left(\lambda_{Eq.(x)} * \lambda_{Eq.(y)} * \lambda_{Eq.(z)}\right)}{8760 * 8760} \; h/yr \qquad (14)$$

Case (iv): Cutset {x, y, z} where some/all elements are neighbouring lines:

Following a similar logic of equivalent 'series' system representation of a three component dependent parallel system, the resulting expressions are as shown below. Unlike the elaborate considerations of interdependency possibilities for a second order cutset that resulted in its dependency-mode failure rate, *the dependency mode failure rate for a third order cutset is obtained from the analysis of backup coordination related interaction scenarios among the corresponding three transmission lines*. This is illustrated in the sample calculations in Chapter 7. Further, in order to avoid double counting, the equivalent failure rates of elements x, y and z are computed by eliminating the respective terms pertaining to the dependency effects.

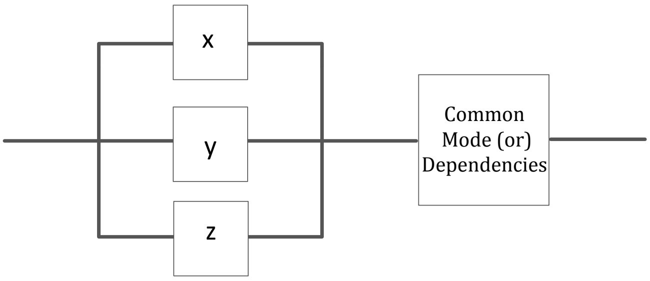

Fig. 3. Equivalent 'series' system representation of a 3 component dependent parallel system

$$\lambda_{Eq.\{x,y,z\}} = \frac{\left(\lambda'_{Eq.(x)} * \lambda'_{Eq.(y)} * \lambda'_{Eq.(z)}\right)\left(r'_{(x)}r'_{(y)} + r'_{(y)}r'_{(z)} + r'_{(z)}r'_{(x)}\right)}{8760 * 8760} + \lambda_D \; f/yr \qquad (15)$$

$$r_{\{x,y,z\}} = \frac{r'_{(x)} * r'_{(y)} * r'_{(z)}}{r'_{(x)}r'_{(y)} + r'_{(y)}r'_{(z)} + r'_{(z)}r'_{(x)}} \; h \qquad (16)$$

$$U_{\{x,y,z\}} = \frac{\lambda_{Eq.\{x,y,z\}} * r_{\{x,y,z\}}}{8760 * 8760} + (\lambda_D * r_D) \; h/yr$$

$$\Rightarrow U_{\{x,y,z\}} = \frac{\left(r'_{(x)} * r'_{(y)} * r'_{(z)}\right)\left(\lambda'_{Eq.(x)} * \lambda'_{Eq.(y)} * \lambda'_{Eq.(z)}\right)}{8760 * 8760} + (\lambda_D * r_D) \; h/yr \qquad (17)$$

6 Extensions to OPAL network – Development of New Test Systems

Whereas the case study on basic OPAL network yielded very few minimal cutsets, the multitude of minimal cutsets obtained in the modified and extended versions of the OPAL network can pave the way for further feedback in making the reliability analysis methodology robust. New networks (refer to Appendix A) are constructed to facilitate a realistic investigation on the handling of higher order cutsets and the effect of protection system dependencies arising on account of parallel lines between bus pairs. The focal point of this report is the studies conducted on the Modified OPAL (MOPAL) network. Once an appropriate validation methodology for the procedures put forward in this memo is established, which studies are underway and are to be included in the next memo, the other two networks, can be effectively utilised to test the increased scale and scope of investigations with relative ease.

6.1 Modified OPAL (MOPAL) network

MOPAL is a 4-bus network with parallel lines: A line 5 is added between OPAL8 (Bus 1) and OPAL10 (Bus 3), and a line 6 is added between OPAL9 (Bus 2) and OPAL11 (Bus 4). Line capacities are changed so that line 5 and line 2 together have the same capacity as line 2 had in the OPAL network, and correspondingly for line 3 and line 6. All lines in the OPAL network have a capacity of 135 MW. So, the new line 5 in the MOPAL network will have a capacity of 67.5 MW, and line 2's capacity changes to 67.5 MW. The same goes for lines 3 and 6. Lines 2 and 5 in the MOPAL network will each have half the admittance of line 2 of the OPAL network and each has the same failure rate as that of line 2 of the OPAL network; similarly for lines 3 and 6. *Failure rates of the additional lines are chosen to be the same as those of their parallel counterparts.* A schematic of MOPAL network is as shown in Fig. 4.

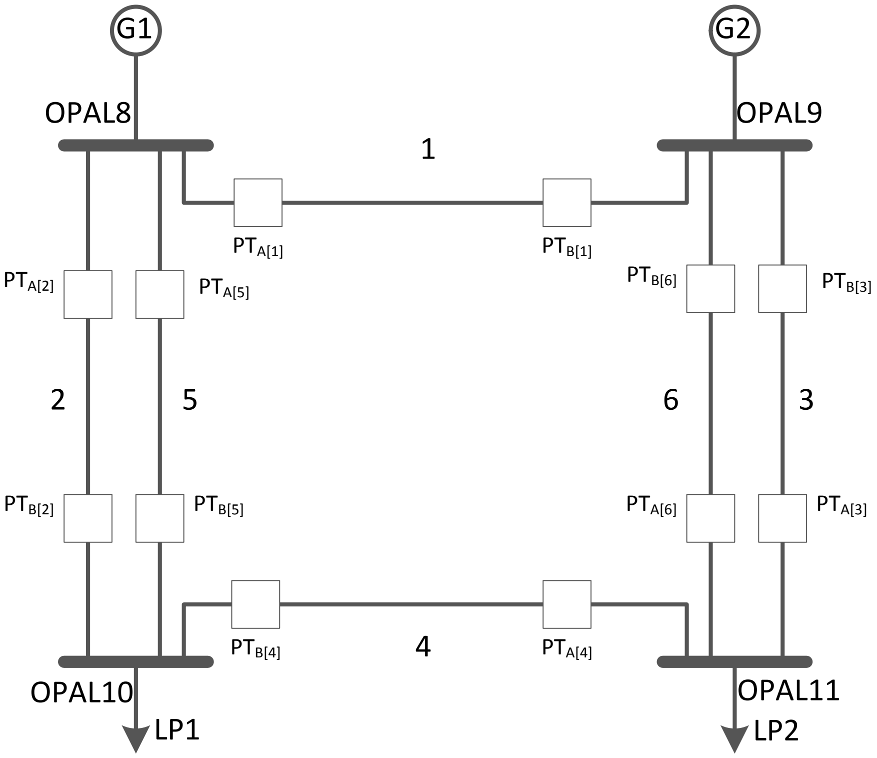

Fig. 4. Schematic of MOPAL network

7 MOPAL Case Study

MOPAL is a four-bus network with two generators, two delivery points and six transmission lines, as shown in Fig. 4. The transmission network operates at 132 kV. The capacity of transmission lines is as follows: Lines 1 & 4 - 135 MW; Lines 2, 3, 5 & 6 – 67.5 MW (i.e. 135/2 MW). The two generators are assumed to be 100% reliable. Delivery point 1, LP1, has industry customers; delivery point 2, LP2 has energy-intensive industry customers. The network data is given in Table 1.

Table 1. MOPAL network data

Line No.	Failure Rate (f/yr)	Repair Time (h)
1	2	20
2	3	15
3	4	12
4	5	10
5	3	15
6	4	12

All the protection system units have the same repair time of 2 h. All the protection system units have the same repair time of 2 h. The missing and unwanted non-selective probabilities of all the protection system units are assumed to be 0.0205 and 0.007, respectively. Failure rate of unwanted spontaneous tripping of the circuit breakers of all protection system units is 0.025 f/yr. A switching time of 0.5 hours is assumed.

Multiple operating states (loading conditions) are prevalent for different durations in a year. Two uniform loading conditions are assumed to prevail throughout certain duration of a year at a delivery point.

- In a 'heavy' load condition (designated as Operating State 1 (OS1)), delivery point LP1 is assumed to have a constant load demand of 100 MW, and delivery point LP2 a constant demand of 75 MW.
- In a 'light' load condition (designated as Operating State 1 (OS2)), delivery point LP1 is assumed to have a constant load demand of 60 MW, and delivery point LP2 a constant demand of 30 MW.

By assigning probability weightages, the effect of multiple loading conditions can be easily captured. For a twelve month period (December through November) OS1 is assumed to last for 9 months (March to November) a year. Hence, the probability of occurrence of heavy load condition is 9/12=0.75. OS2 is assumed to last for 3 months (December, January and February). Hence, the probability of occurrence of heavy load condition is 3/12=0.25. *Different operating states result in different minimal cutsets during the system contingency analysis.*

Table 2. MOPAL minimal cutsets for different operating states

OS1LP1	OS1LP2	OS2LP1	OS2LP2
4, 5	5, 6	2, 4, 5	3, 5, 6
2, 4	4, 6		3, 4, 6
3, 5, 6	3, 6		2, 5, 6
2, 5, 6	3, 5		2, 3, 6
2, 3, 6	3, 4		2, 3, 5
2, 3, 5	2, 6		
	2, 5		
	2, 3		

Detailed sample calculations for the analysis of minimal cutsets for OS1LP2 shown in the following sub-section.

Note: In the subsequent sections (illustrative calculations and tables), the units of λ, r and U are in failures/year, hours and hours/year, respectively.

7.1 Illustrative calculations for the analysis of minimal cutsets for OS1LP2

The minimal cutsets for OS1LP2 are shown in Fig. 5.

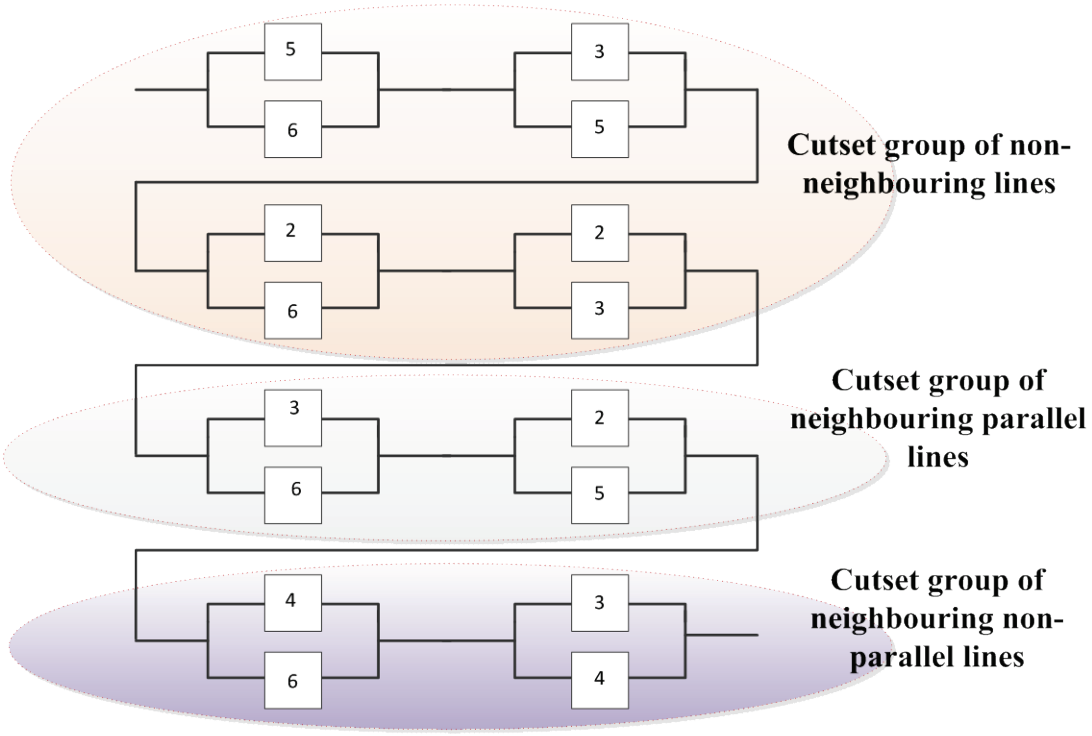

Fig. 5. MOPAL minimal cutsets for OS1LP2

Analysis of Minimal Cutset (MC) {5, 6}

(This minimal cutset contains non-neighbouring lines)

The sample calculations detailed here (for element 5) are representative for all calculations for all other elements which are parts of cutsets that contain only non-neighbouring lines.

Element 5 when part of (MC) {5, 6}:

$$P_{unwanted(PT_{A[5]})} = P_{unwanted(PT_{B[5]})} = 0.007$$

$$P_{missing(PT_{A[5]})} = P_{missing(PT_{B[5]})} = 0.0205$$

$$\lambda_{BE_{A[5]}} = \lambda_{BE_{B[5]}} = 0.025$$

$$\lambda_5 = 3$$

$$P(PT_{A-i}) = [1 - P_{missing(PT_{A[i]})}]$$

$$P(PT_{B-i}) = [1 - P_{missing(PT_{B[i]})}]$$

$$\Rightarrow P(PT_{A-5}) = [1 - P_{missing(PT_{A[5]})}] = [1 - 0.0205] = 0.9795$$

$$P(PT_{B-5}) = [1 - P_{missing(PT_{B[5]})}] = [1 - 0.0205] = 0.9795$$

Fault Type 1

$$\lambda_{FT1(i)} = \lambda_i$$

$$\Rightarrow \lambda_{FT1(5)} = \lambda_5 = 3$$

Fault Type 2

$$\lambda_{FT2(i)} = [\lambda_{BE_{A[i]}} + \lambda_{BE_{B[i]}}]$$

$$\Rightarrow \lambda_{FT2(5)} = [\lambda_{BE_{A[5]}} + \lambda_{BE_{B[5]}}]$$

$$\lambda_{FT2(5)} = [0.025 + 0.025] = 0.05$$

Fault Type 3

For line 5, the neighbouring lines are lines 1, 4 and 2.

Situations resulting in FT3 on line 5:

(i) Fault on line 1 and failure of $PT_{A[1]}$

(ii) Fault on line 4 and failure of $PT_{B[4]}$

(iii) Fault on line 2 and failure of $PT_{A[2]}$ or $PT_{B[2]}$ or both

Analysis of situations resulting in FT3 on line 5:

(i) Fault on line 1 and failure of $PT_{A[1]}$

$PT_{A[5]}$ performs the backup action and line 5 is out of service

Failure rate contribution of this situation to $\lambda_{FT3(5)}$ is $\lambda_1 * P_{missing(PT_{A[1]})}$

Note: Every time a parallel line's protection system unit performs a CORRECT backup action, its counterpart's protection system unit also performs the same action. In the case of missed operation of $PT_{A[1]}$, when line 5's protection unit $PT_{A[5]}$ performs the backup action, line 2's protection unit $PT_{A[2]}$ also acts to isolate Bus 1 (OPAL8).

(ii) Fault on line 4 and failure of $PT_{B[4]}$

$PT_{B[5]}$ performs the backup action and line 5 is out of service

Failure rate contribution of this situation to $\lambda_{FT3(5)}$ is $\lambda_4 * P_{missing(PT_{B[4]})}$

(iii) Fault on line 2 and failure of $PT_{A[2]}$ or $PT_{B[2]}$ or both

$PT_{A[5]}$ or $PT_{B[5]}$ or both perform backup action in respective cases, and line 5 is out of service

Failure rate contribution of this situation to $\lambda_{FT3(5)}$ is:

$$\lambda_2(P_{missing(PT_{A[2]})} + P_{missing(PT_{B[2]})} - P_{missing(PT_{A[2]})} * P_{missing(PT_{B[2]})})$$

Contribution of all situations resulting in FT3 on line 5 to the total failure rate of FT3:

$$\lambda_{FT3(5)} = \lambda_1 * P_{missing(PT_{A[1]})} + \lambda_4 * P_{missing(PT_{B[4]})} + \lambda_2(P_{missing(PT_{A[2]})} + P_{missing(PT_{B[2]})} - P_{missing(PT_{A[2]})} * P_{missing(PT_{B[2]})})$$

=0.26523925

Fault Type 4

For line 5, the neighbouring lines are lines 1, 4 and 2.

Situations resulting in FT4 on line 5:

(i) Fault on line 1, correct operation of PT$_{A[1]}$, but unwanted non-selective operation of PT$_{A[5]}$ or PT$_{B[5]}$ or both.

(ii) Fault on line 4, correct operation of PT$_{B[4]}$, but unwanted non-selective operation of PT$_{A[5]}$ or PT$_{B[5]}$ or both.

(iii) Fault on line 2, correct operation of both PT$_{A[2]}$ and PT$_{B[2]}$ but unwanted non-selective operation of PT$_{A[5]}$ or PT$_{B[5]}$ or both.

Analysis of situations resulting in FT4 on line 5:

(i) Fault on line 1, correct operation of PT$_{A[1]}$, but unwanted non-selective operation of PT$_{A[5]}$ or PT$_{B[5]}$ or both.

Failure rate contribution of this situation to $\lambda_{FT4(5)}$ is:

$$\left(\begin{array}{l}\lambda_1 * P(PT_{A-1}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{array}\right)$$

where

$$P(PT_{A-1}) = [1 - P_{missing(PT_{A[1]})}]$$

(ii) Fault on line 4, correct operation of PT$_{B[4]}$, but unwanted non-selective operation of PT$_{A[5]}$ or PT$_{B[5]}$ or both.

Failure rate contribution of this situation to $\lambda_{FT4(5)}$ is:

$$\left(\begin{array}{l}\lambda_4 * P(PT_{B-4}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{array}\right)$$

where

$$P(PT_{B-4}) = [1 - P_{missing(PT_{B[1]})}]$$

(iii) Fault on line 2, correct operation of both PTA[2] and PTB[2], but unwanted non-selective operation of PTA[5] or PTB[5] or both.

Failure rate contribution of this situation to $\lambda_{FT4(5)}$ is:

$$\left(\lambda_2 * P(PT_{A-2}) * P(PT_{B-2}) * \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})} \right) \right)$$

where

$$P(PT_{A-2}) = [1 - P_{missing(PT_{A[2]})}]$$

$$P(PT_{B-2}) = [1 - P_{missing(PT_{B[2]})}]$$

Contribution of all situations resulting in FT4 on line 5 to the net failure rate of FT4:

$$\begin{aligned}\lambda_{FT4(5)} = &\left(\lambda_1 * P(PT_{A-1}) * \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})} \right) \right) + \\ &\left(\lambda_4 * P(PT_{B-4}) * \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})} \right) \right) + \\ &\left(\lambda_2 * P(PT_{A-2}) * P(PT_{B-2}) * \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})} \right) \right)\end{aligned}$$

=0.135809647

The equivalent failure rate of a line on account of its failure due to various protection system response scenarios is given as the summation of the failure rates of the identified failure modes.

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}$$

$$\lambda_{Eq.(5)} = \lambda_{FT1(5)} + \lambda_{FT2(5)} + \lambda_{FT3(5)} + \lambda_{FT4(5)} = \mathbf{3.451048897}$$

Element 6 when part of (MC) {5, 6}:

The expressions for failure rates of various fault types for line 6 are given as follows based on the logic used in the previous sample computations. For line 6, the neighbouring lines are lines 1, 4 and 3.

$$\lambda_{FT1(6)} = \lambda_6 = 4$$

$$\lambda_{FT2(6)} = [\lambda_{BE_{A[6]}} + \lambda_{BE_{B[6]}}] = 0.05$$

$$\lambda_{FT3(6)} = \lambda_1 * P_{missing(PT_{B[1]})} + \lambda_4 * P_{missing(PT_{A[4]})} + \lambda_3 (P_{missing(PT_{A[3]})} + P_{missing(PT_{B[3]})} - P_{missing(PT_{A[3]})} * P_{missing(PT_{B[3]})})$$

=0.305819

$$\begin{aligned}\lambda_{FT4(6)} = &\left(\begin{aligned}&\lambda_1 * P(PT_{B-1}) * \\ &\quad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})}\right)\end{aligned}\right) + \\ &\left(\begin{aligned}&\lambda_4 * P(PT_{A-4}) * \\ &\quad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})}\right)\end{aligned}\right) + \\ &\left(\begin{aligned}&\lambda_3 * P(PT_{A-3}) * P(PT_{B-3}) * \\ &\quad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})}\right)\end{aligned}\right)\end{aligned}$$

=0.149194519

where

$$P(PT_{B-1}) = [1 - P_{missing(PT_{B[1]})}]$$

$$P(PT_{A-4}) = [1 - P_{missing(PT_{A[4]})}]$$

$$P(PT_{A-3}) = [1 - P_{missing(PT_{A[3]})}]$$

$$P(PT_{B-3}) = [1 - P_{missing(PT_{B[3]})}]$$

Element 3 when part of (MC) {3, 5}:

For line 3, the neighbouring lines are lines 1, 4 and 6.

$$\lambda_{FT1(3)} = \lambda_3 = 4$$

$$\lambda_{FT2(3)} = [\lambda_{BE_{A[3]}} + \lambda_{BE_{B[3]}}] = 0.05$$

$$\lambda_{FT3(3)} = \lambda_1 * P_{missing(PT_{B[1]})} + \lambda_4 * P_{missing(PT_{A[4]})} + \lambda_6 (P_{missing(PT_{A[6]})} + P_{missing(PT_{B[6]})} - P_{missing(PT_{A[6]})} * P_{missing(PT_{B[6]})})$$

=0.305819

$$\lambda_{FT4(3)} = \left(\begin{aligned}&\lambda_1 * P(PT_{B-1}) * \\ &\quad \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})}\right)\end{aligned}\right) +$$

$$\begin{pmatrix} \lambda_4 * P(PT_{A-4}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})}\right) \end{pmatrix} +$$

$$\begin{pmatrix} \lambda_6 * P(PT_{A-6}) * P(PT_{B-6}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})}\right) \end{pmatrix}$$

=0.149194519

where

$$P(PT_{B-1}) = [1 - P_{missing(PT_{B[1]})}]$$

$$P(PT_{A-4}) = [1 - P_{missing(PT_{A[4]})}]$$

$$P(PT_{A-6}) = [1 - P_{missing(PT_{A[6]})}]$$

$$P(PT_{B-6}) = [1 - P_{missing(PT_{B[6]})}]$$

Element 5 when part of (MC) {3, 5}: Same expressions as those of Element 5 when part of (MC) {5, 6}.

Element 2 when part of (MC) {2, 6}:

For line 2, the neighbouring lines are lines 1, 4 and 5.

$$\lambda_{FT1(2)} = \lambda_2 = 3$$

$$\lambda_{FT2(2)} = [\lambda_{BE_{A[2]}} + \lambda_{BE_{B[2]}}] = 0.05$$

$$\lambda_{FT3(2)} = \lambda_1 * P_{missing(PT_{A[1]})} + \lambda_4 * P_{missing(PT_{B[4]})} + \lambda_5 (P_{missing(PT_{A[5]})} + P_{missing(PT_{B[5]})} - P_{missing(PT_{A[5]})} * P_{missing(PT_{B[5]})})$$

=0.26523925

$$\lambda_{FT4(2)} = \begin{pmatrix} \lambda_1 * P(PT_{A-1}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right) \end{pmatrix} +$$

$$\begin{pmatrix} \lambda_4 * P(PT_{B-4}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right) \end{pmatrix} +$$

$$\begin{pmatrix} \lambda_5 * P(PT_{A-5}) * P(PT_{B-5}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right) \end{pmatrix}$$

=0.135809647

Element 6 when part of (MC) {2, 6}: Same expressions as those of Element 6 when part of (MC) {5, 6}.

Element 2 when part of (MC) {2, 3}: Same expressions as those of Element 2 when part of (MC) {2, 6}.

Element 3 when part of (MC) {2, 3}: Same expressions as those of Element 3 when part of (MC) {3, 5}.

Analysis of Minimal Cutset (MC) {2, 5}

(This minimal cutset contains parallel lines)

Element 5 when part of (MC) {2, 5}:

Element 5 has the same expressions for FT1 and FT2 as in the case when it was analysed as being part of (MC) {5, 6} (Ref. page 17). However, situation 3 of FT3 (Ref. page 18) is not to be taken into account yet as it pertains to the parallel line-dependency aspect of (MC) {2, 5}. It will be considered in the expression for dependency mode failure rate of element 5. Thus,

$$\lambda_{FT3(5)} = \lambda_1 * P_{missing(PT_{A[1]})} + \lambda_4 * P_{missing(PT_{B[4]})}$$

=0.1435

Similarly when considering FT4, situation 3 of FT4 (Ref. page 19) is not taken into account yet as it pertains to the parallel line dependency aspect of (MC) {2, 5}. It will be considered in the expression for dependency mode failure rate of element 5. Thus,

$$\lambda_{FT4(5)} = \begin{pmatrix} \lambda_1 * P(PT_{A-1}) * \\ \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})} \right) \end{pmatrix} + \begin{pmatrix} \lambda_4 * P(PT_{B-4}) * \\ \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})} \right) \end{pmatrix}$$

=0.095655032

Element 2 when part of (MC) {2, 5}:

Element 2 has the same expressions for FT1 and FT2 as in the case when it was analysed as being part of (MC) {2, 6} (Ref. page 22). However, situation 3 of FT3, involving parameters of line 5 (Ref. page 22) is not taken into account yet as it pertains to the parallel line-dependency aspect of (MC) {2, 5}. It will be considered in the expression for dependency mode failure rate of element 2. Thus,

$$\lambda_{FT3(2)} = \lambda_1 * P_{missing(PT_{A[1]})} + \lambda_4 * P_{missing(PT_{B[4]})}$$

=0.1435

Similarly when considering FT4, situation 3 of FT4, involving parameters of line 5 (Ref. page 22) is not taken into account yet as it pertains to the parallel line dependency aspect of (MC) {2, 5}. It will be considered in the expression for dependency mode failure rate of element 2. Thus,

$$\lambda_{FT4(2)} = \left(\begin{array}{l} \lambda_1 * P(PT_{A-1}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \right) \end{array} \right) + \left(\begin{array}{l} \lambda_4 * P(PT_{B-4}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \right) \end{array} \right)$$

=0.095655032

Dependency mode failure rate for (MC) {2, 5}:

CS2 of FT1 on line 2 will result in FT3 on line 5, and vice-versa (i.e., CS2 of FT1 on line 5 results in FT3 on line 2). These two events are mutually exclusive.

Fault on line 2 and failure of $PT_{A[2]}$ or $PT_{B[2]}$ or both

$PT_{A[5]}$ or $PT_{B[5]}$ or both perform backup action in respective cases, and line 5 is out of service

Dependency mode failure rate contribution of this situation is:

$$\lambda_2 (P_{missing(PT_{A[2]})} + P_{missing(PT_{B[2]})} - P_{missing(PT_{A[2]})} * P_{missing(PT_{B[2]})})$$

Fault on line 5 and failure of $PT_{A[5]}$ or $PT_{B[5]}$ or both

$PT_{A[2]}$ or $PT_{B[2]}$ or both perform backup action in respective cases, and line 2 is out of service

Dependency mode failure rate contribution of this situation is:

$$\lambda_5(P_{missing(PT_{A[5]})} + P_{missing(PT_{B[5]})} - P_{missing(PT_{A[5]})} * P_{missing(PT_{B[5]})})$$

Thus, $\lambda_D^{'}$, the dependency-mode failure rate of cutset {x, y} because of CS2 of FT1 on a line that will result in FT3 on the neighbouring line present in the cutset, is given as

$$\lambda_D^{'} = \lambda_2(P_{missing(PT_{A[2]})} + P_{missing(PT_{B[2]})} - P_{missing(PT_{A[2]})} * P_{missing(PT_{B[2]})}) + \lambda_5(P_{missing(PT_{A[5]})} + P_{missing(PT_{B[5]})} - P_{missing(PT_{A[5]})} * P_{missing(PT_{B[5]})})$$

=0.2434785

CS1 of FT1 on line x ‘may’ result in FT4 on line y, and vice-versa. (i.e., CS1 of FT1 on line y ‘may’ result in FT4 on line x). These two events are mutually exclusive. This is a ‘probable’ effect on the dependency-mode failure rate of the cutset as opposed to the ‘certain’ effect of CS2 of FT1 on a line resulting in FT3 on the neighbouring line in the cutset.

Fault on line 2, correct operation of both PT$_{A[2]}$ and PT$_{B[2]}$, but unwanted non-selective operation of PT$_{A[5]}$ or PT$_{B[5]}$ or both.

Failure rate contribution of this situation is:

$$\left(\begin{array}{l}\lambda_2 * P(PT_{A-2}) * P(PT_{B-2}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{array}\right)$$

Fault on line 5, correct operation of both PT$_{A[5]}$ and PT$_{B[5]}$, but unwanted non-selective operation of PT$_{A[2]}$ or PT$_{B[2]}$ or both.

Failure rate contribution of this situation is:

$$\left(\begin{array}{l}\lambda_5 * P(PT_{A-5}) * P(PT_{B-5}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right)\end{array}\right)$$

Thus, $\lambda_D^{''}$, the dependency-mode failure rate of cutset {x, y} because of CS1 of FT1 on a line that may result in FT4 on the neighbouring line present in the cutset, is given as

$$\lambda_D^{''} = \left(\begin{array}{l}\lambda_2 * P(PT_{A-2}) * P(PT_{B-2}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{array}\right) + \left(\begin{array}{l}\lambda_5 * P(PT_{A-5}) * P(PT_{B-5}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right)\end{array}\right)$$

=0.080309231

The net dependency-mode failure rate of cutset {2, 5} is given as:

$\lambda_D = \lambda_D^{'} + \lambda_D^{''}$ **= 0.2434785 + 0.080309231 = 0.323787731**

Analysis of Minimal Cutset (MC) {3, 6}

(This minimal cutset contains parallel lines)

On the lines of explanation given for the analysis of Minimal Cutset (MC) {2, 5}, the the following failure rates for the elements, and the dependency mode failure rate are obtained:

Element 3 when part of (MC) {3, 6}:

$$\lambda_{FT1(3)} = \lambda_3 = 4$$

$$\lambda_{FT2(3)} = [\lambda_{BE_{A[3]}} + \lambda_{BE_{B[3]}}] = 0.05$$

$$\lambda_{FT3(3)} = \lambda_1 * P_{missing(PT_{B[1]})} + \lambda_4 * P_{missing(PT_{A[4]})}$$

=0.1435

$$\lambda_{FT4(3)} = \left(\lambda_1 * P(PT_{B-1}) * \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})} \right) \right) + \left(\lambda_4 * P(PT_{A-4}) * \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})} \right) \right)$$

=0.095655032

Element 6 when part of (MC) {3, 6}:

$$\lambda_{FT1(6)} = \lambda_6 = 4$$

$$\lambda_{FT2(6)} = [\lambda_{BE_{A[6]}} + \lambda_{BE_{B[6]}}] = 0.05$$

$$\lambda_{FT3(6)} = \lambda_1 * P_{missing(PT_{B[1]})} + \lambda_4 * P_{missing(PT_{A[4]})}$$ =0.1435

$$\lambda_{FT4(6)} = \left(\lambda_1 * P(PT_{B-1}) * \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})} \right) \right) + \left(\lambda_4 * P(PT_{A-4}) * \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})} \right) \right)$$

=0.095655032

Dependency mode failure rate for (MC) {3, 6}:

$$\lambda_D^{'} = \lambda_6 (P_{missing(PT_{A[6]})} + P_{missing(PT_{B[6]})} - P_{missing(PT_{A[6]})} * P_{missing(PT_{B[6]})}) + \lambda_3 (P_{missing(PT_{A[3]})} + P_{missing(PT_{B[3]})} - P_{missing(PT_{A[3]})} * P_{missing(PT_{B[3]})})$$

=0.324638

$$\lambda_D^{''} = \begin{pmatrix} \lambda_6 * P(PT_{A-6}) * P(PT_{B-6}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})} \right) \end{pmatrix} + \begin{pmatrix} \lambda_3 * P(PT_{A-3}) * P(PT_{B-3}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})} \right) \end{pmatrix}$$

=0.107078975

$\lambda_D = \lambda_D^{'} + \lambda_D^{''}$ **= 0.324638 + 0.107078975 = 0.431716975**

Analysis of Minimal Cutset (MC) {4, 6}

(This minimal cutset contains neighbouring lines)

Element 4 when part of (MC) {4, 6}:

For the sake of ease of understanding, expressions for element 4 are first given under the premise that it belongs to a minimal cutset containing non-neighbouring lines. The required expressions for element 4 when belonging to MC {4, 6} are subsequently given.

Element 4:

$$\lambda_{FT1(4)} = \lambda_4 = 5$$

$$\lambda_{FT2(4)} = [\lambda_{BE_{A[4]}} + \lambda_{BE_{B[4]}}] = 0.05$$

Fault Type 3

For line 4, the neighbouring lines are lines 2, 5, 6 and 3.

Situations resulting in FT3 on line 4:

(i) Fault on line 2 and failure of $PT_{B[2]}$

(ii) Fault on line 5 and failure of $PT_{B[5]}$

(iii) Fault on line 6 and failure of $PT_{A[6]}$

(iv) Fault on line 3 and failure of $PT_{A[3]}$

$\lambda_{FT3(4)} = \lambda_2 * P_{missing(PT_{B[2]})} + \lambda_5 * P_{missing(PT_{B[5]})} + \lambda_6 * P_{missing(PT_{A[6]})} + \lambda_3 * P_{missing(PT_{A[3]})}$ **=0.287**

Fault Type 4

Situations resulting in FT4 on line 4:

(i) Fault on line 2, correct operation of PT$_{B[2]}$, but unwanted non-selective operation of PT$_{B[4]}$ or PT$_{A[4]}$ or both.

(ii) Fault on line 5, correct operation of PT$_{B[4]}$, but unwanted non-selective operation of PT$_{B[4]}$ or PT$_{A[4]}$ or both.

(iii) Fault on line 6, correct operation of PT$_{A[6]}$, but unwanted non-selective operation of PT$_{B[4]}$ or PT$_{A[4]}$ or both.

(iv) Fault on line 3, correct operation of PT$_{A[3]}$, but unwanted non-selective operation of PT$_{B[4]}$ or PT$_{A[4]}$ or both.

$$\lambda_{FT4(4)} = \begin{pmatrix} \lambda_2 * P(PT_{B-2}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_5 * P(PT_{B-5}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_6 * P(PT_{A-6}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_3 * P(PT_{A-3}) * \\ \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right) \end{pmatrix}$$

=0.191310063

When element 4 is part of (MC) {4, 6} FT3 and FT4 as shown above get modified as shown below (exclusion of parameters pertaining to line 6)

$$\lambda_{FT3(4)} = \lambda_2 * P_{missing(PT_{B[2]})} + \lambda_5 * P_{missing(PT_{B[5]})} + \lambda_3 * P_{missing(PT_{A[3]})} \mathbf{=0.205}$$

$$\lambda_{FT4(4)} = \begin{pmatrix} \lambda_2 * P(PT_{B-2}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_5 * P(PT_{B-5}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_3 * P(PT_{A-3}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix}$$

=0.136650045

Element 6 when part of (MC) {4, 6}:

If the parameters pertaining to element 4 are removed from the corresponding expressions for FT3 and FT4 when element 6 is part of any non-neighbouring minimal cutset, say {5, 6} (Ref. page 21), we get the required failure rates of element 6 for FT3 and FT4 when belonging to (MC) {4, 6}.

$$\lambda_{FT1(6)} = \lambda_6 = 4$$

$$\lambda_{FT2(6)} = [\lambda_{BE_{A[6]}} + \lambda_{BE_{B[6]}}] = 0.05$$

$$\lambda_{FT3(6)} = \lambda_1 * P_{missing(PT_{B[1]})} + \lambda_3 (P_{missing(PT_{A[3]})} + P_{missing(PT_{B[3]})} - P_{missing(PT_{A[3]})} * P_{missing(PT_{B[3]})})$$

=0.203319

$$\lambda_{FT4(6)} = \left(\begin{array}{l} \lambda_1 * P(PT_{B-1}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})} \right) \end{array} \right) +$$

$$\left(\begin{array}{l} \lambda_3 * P(PT_{A-3}) * P(PT_{B-3}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})} \right) \end{array} \right)$$

=0.080869497

Dependency mode failure rate for (MC) {4, 6}:

The removed parts are collated here.

$$\lambda_D^{'} = \lambda_4 * P_{missing(PT_{A[4]})} + \lambda_6 * P_{missing(PT_{A[6]})}$$ **=0.1845**

$$\lambda_D^{''} = \left(\begin{array}{l} \lambda_6 * P(PT_{A-6}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{array} \right) +$$

$$\left(\begin{array}{l} \lambda_4 * P(PT_{A-4}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})} \right) \end{array} \right)$$

=0.125559

$$\lambda_D = \lambda_D^{'} + \lambda_D^{''}$$ **= 0.1845 + 0.125559 = 0.310059**

Analysis of Minimal Cutset (MC) {3, 4}

(This minimal cutset contains neighbouring lines)

Following the same logic as used above, the following expressions are obtained:

Element 3 when part of (MC) {3, 4}:

$$\lambda_{FT1(3)} = \lambda_3 = 4$$

$$\lambda_{FT2(3)} = [\lambda_{BE_{A[3]}} + \lambda_{BE_{B[3]}}] = 0.05$$

$$\lambda_{FT3(3)} = \lambda_1 * P_{missing(PT_{B[1]})} + \lambda_6 (P_{missing(PT_{A[6]})} + P_{missing(PT_{B[6]})} - P_{missing(PT_{A[6]})} * P_{missing(PT_{B[6]})})$$

=0.203319

$$\lambda_{FT4(3)} = \left(\begin{matrix} \lambda_1 * P(PT_{B-1}) * \\ \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})} \right) \end{matrix} \right) + \left(\begin{matrix} \lambda_6 * P(PT_{A-6}) * P(PT_{B-6}) * \\ \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})} \right) \end{matrix} \right)$$

=0.080869497

Element 4 when part of (MC) {3, 4}:

$$\lambda_{FT1(4)} = \lambda_4 = 5$$

$$\lambda_{FT2(4)} = [\lambda_{BE_{A[4]}} + \lambda_{BE_{B[4]}}] = 0.05$$

$$\lambda_{FT3(4)} = \lambda_2 * P_{missing(PT_{B[2]})} + \lambda_5 * P_{missing(PT_{B[5]})} + \lambda_6 * P_{missing(PT_{A[6]})}$$ **=0.205**

$$\lambda_{FT4(4)} = \left(\begin{matrix} \lambda_2 * P(PT_{B-2}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{matrix} \right) + \left(\begin{matrix} \lambda_5 * P(PT_{B-5}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{matrix} \right) + \left(\begin{matrix} \lambda_6 * P(PT_{A-6}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{matrix} \right)$$

=0.136650045

Dependency mode failure rate for (MC) {3, 4}:

$$\lambda_D^{'} = \lambda_4 * P_{missing(PT_{A[4]})} + \lambda_3 * P_{missing(PT_{A[3]})} = 0.1845$$

$$\lambda_D^{''} = \left(\lambda_4 * P(PT_{A-4}) * \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})} \right) \right) + \left(\lambda_3 * P(PT_{A-3}) * \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \right)$$

=0.122985041

$$\lambda_D = \lambda_D^{'} + \lambda_D^{''} = 0.1845 + 0.122985041 = 0.307485041$$

Overview-tabulations for the computations for OS1LP2:

Summary of the computations for OS1LP2 from the above demonstrated intermediate results, based on the approximate methods of system reliability evaluation are given in the following tables.

Table 3. Equivalent parameters of MC {5, 6}, non-neighbouring lines

Element 5 in {5, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (5)	3	15	45		
FT2 (5)	0.05	2	0.1		
FT3 (5)	0.26523925	0.5	0.132619625		
FT4 (5)	0.135809647	0.5	0.067904824		
Lambda Eq. (5)=	**3.451048897**	**U (5)=**	**45.30052445**	**r (5)=**	**13.12659594**
Element 6 in {5, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (6)	4	12	48		
FT2 (6)	0.05	2	0.1		
FT3 (6)	0.305819	0.5	0.1529095		
FT4 (6)	0.149194519	0.5	0.07459726		
Lambda Eq. (6)	**4.505013519**	**U (6)=**	**48.32750676**	**r (6)=**	**10.72749428**

Equivalent parameters of MC {5, 6}	
λ eq. =	**0.042335624**
r eq. =	**5.903200733**
U eq. =	**0.249915685**

Table 4. Equivalent parameters of MC {3, 5}, non-neighbouring lines

Element 3 in {3, 5}					
	Lambda	**r**	**Lambda*r**		
FT1 (3)	4	12	48		
FT2 (3)	0.05	2	0.1		
FT3 (3)	0.305819	0.5	0.1529095		
FT4 (3)	0.149194519	0.5	0.07459726		
Lambda Eq. (3)	**4.505013519**	**U (3)=**	**48.32750676**	**r (3)=**	**10.72749428**
Element 5 in {3, 5}					
	Lambda	**r**	**Lambda*r**		
FT1 (5)	3	15	45		
FT2 (5)	0.05	2	0.1		
FT3 (5)	0.26523925	0.5	0.132619625		
FT4 (5)	0.135809647	0.5	0.067904824		
Lambda Eq. (5)	**3.451048897**	**U (5)=**	**45.30052445**	**r (5)=**	**13.12659594**

Equivalent parameters of MC {3, 5}	
λ eq. =	**0.042335624**
r eq. =	**5.903200733**
U eq. =	**0.249915685**

Table 5. Equivalent parameters of MC {2, 6}, non-neighbouring lines

Element 2 in {2, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (2)	3	15	45		
FT2 (2)	0.05	2	0.1		
FT3 (2)	0.26523925	0.5	0.132619625		
FT4 (2)	0.135809647	0.5	0.067904824		
Lambda Eq. (2)	**3.451048897**	**U (2)=**	**45.30052445**	**r (2)=**	**13.12659594**
Element 6 in {2, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (6)	4	12	48		
FT2 (6)	0.05	2	0.1		
FT3 (6)	0.305819	0.5	0.1529095		
FT4 (6)	0.149194519	0.5	0.07459726		

Equivalent parameters of MC {2, 6}	
λ eq. =	**0.042335624**
r eq. =	**5.903200733**
U eq. =	**0.249915685**

Lambda Eq. (6)	**4.505013519**	**U (6)=**	**48.32750676**	**r (6)=**	**10.72749428**

Table 6. Equivalent parameters of MC {2, 3}, non-neighbouring lines

Element 2 in {2, 3}					
	Lambda	**r**	**Lambda*r**		
FT1 (2)	3	15	45		
FT2 (2)	0.05	2	0.1		
FT3 (2)	0.26523925	0.5	0.132619625		
FT4 (2)	0.135809647	0.5	0.067904824		
Lambda Eq. (2)	**3.451048897**	**U (2)=**	**45.30052445**	**r (2)=**	**13.12659594**
Element 3 in {2, 3}					
	Lambda	**r**	**Lambda*r**		
FT1 (3)	4	12	48		
FT2 (3)	0.05	2	0.1		
FT3 (3)	0.305819	0.5	0.1529095		
FT4 (3)	0.149194519	0.5	0.07459726		
Lambda Eq. (3)	**4.505013519**	**U (3)=**	**48.32750676**	**r (3)=**	**10.72749428**

Equivalent parameters of MC {2, 3}	
λ eq. =	**0.042335624**
r eq. =	**5.903200733**
U eq. =	**0.249915685**

Table 7. Equivalent parameters of MC {2, 5}, parallel lines

Element 5 in {2, 5}					
	Lambda	**r**	**Lambda*r**		
FT1 (5)	3	15	45		
FT2 (5)	0.05	2	0.1		
FT3 (5)	0.1435	0.5	0.07175		
FT4 (5)	0.095655032	0.5	0.047827516		
Lambda Eq. (5)	**3.289155032**	**U (5)=**	**45.21957752**	**r (5)=**	**13.74808335**
Element 2 in {2, 5}					
	Lambda	**r**	**Lambda*r**		
FT1 (2)	3	15	45		
FT2 (2)	0.05	2	0.1		
FT3 (2)	0.1435	0.5	0.07175		
FT4 (2)	0.095655032	0.5	0.047827516		
Lambda Eq. (2)	**3.289155032**	**U (2)=**	**45.21957752**	**r (2)=**	**13.74808335**
Lambda D' for {2, 5}	0.2434785				
Lambda D'' for {2, 5}	0.080309231				
Lamda D for {2, 5} = Lambda D' for {2, 5} + Lambda D'' for {2, 5}	0.323787731		Restoration Time=	0.5	

Equivalent parameters of MC {2, 5}	
λ eq. =	**0.357745312**
U eq. =	**0.395319687**
r eq. =	**1.105031076**

Table 8. Equivalent parameters of MC {3, 6}, parallel lines

Element 3 in {3, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (3)	4	12	48		
FT2 (3)	0.05	2	0.1		
FT3 (3)	0.1435	0.5	0.07175		
FT4 (3)	0.095655032	0.5	0.047827516		
Lambda Eq. (3)	**4.289155032**	**U (3)=**	**48.21957752**	**r (3)=**	**11.24220905**
Element 6 in {3, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (6)	4	12	48		
FT2 (6)	0.05	2	0.1		
FT3 (6)	0.1435	0.5	0.07175		
FT4 (6)	0.095655032	0.5	0.047827516		
Lambda Eq. (6)	**4.289155032**	**U (6)=**	**48.21957752**	**r (6)=**	**11.24220905**
Lambda D' for {3, 6}	0.324638				
Lambda D'' for {3, 6}	0.107078975				
Lamda D for {3, 6} = Lambda D' for {3, 6} + Lambda D'' for {3, 6}	0.431716975		Restoration Time=	0.5	

Equivalent parameters of MC {3, 6}	
λ eq. =	**0.478936437**
U eq. =	**0.481284019**
r eq. =	**1.004901656**

Table 9. Equivalent parameters of MC {4, 6}, neighbouring lines

Element 4 in {4, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (4)	5	10	50		
FT2 (4)	0.05	2	0.1		
FT3 (4)	0.205	0.5	0.1025		
FT4 (4)	0.136650045	0.5	0.068325023		
Lambda Eq. (4)	**5.391650045**	**U (4)=**	**50.27082502**	**r (4)=**	**9.323829366**
Element 6 in {4, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (6)	4	12	48		
FT2 (6)	0.05	2	0.1		
FT3 (6)	0.203319	0.5	0.1016595		
FT4 (6)	0.080869497	0.5	0.040434748		
Lambda Eq. (6)	**4.334188497**	**U (6)=**	**48.24209425**	**r (6)=**	**11.13059441**
Lambda D' for {4, 6}	0.1845				
Lambda D'' for {4, 6}	0.125559				
Lamda D for {4, 6} = Lambda D' for {4, 6} + Lambda D'' for {4, 6}	0.310059		Restoration Time=	0.5	

Equivalent parameters of MC {4, 6}	
λ eq. =	**0.364623808**
U eq. =	**0.431875377**
r eq. =	**1.184440968**

Table 10. Equivalent parameters of MC {3, 4}, neighbouring lines

Element 3 in {3, 4}					
	Lambda	**r**	**Lambda*r**		
FT1 (3)	4	12	48		
FT2 (3)	0.05	2	0.1		
FT3 (3)	0.203319	0.5	0.1016595		
FT4 (3)	0.080869497	0.5	0.040434748		
Lambda Eq. (3)	**4.334188497**	**U (3)=**	**48.24209425**	**r (3)=**	**11.13059441**
Element 4 in {3, 4}					
	Lambda	**r**	**Lambda*r**		
FT1 (4)	5	10	50		
FT2 (4)	0.05	2	0.1		
FT3 (4)	0.205	0.5	0.1025		
FT4 (4)	0.136650045	0.5	0.068325023		
Lambda Eq. (4)	**5.391650045**	**U (4)=**	**50.27082502**	**r (4)=**	**9.323829366**

Lambda D' for {3, 4}	0.1845				
Lambda D'' for {3, 4}	0.122985041				
Lamda D for {3, 4} = Lambda D' for {3, 4} + Lambda D'' for {3, 4}	0.307485041		Restoration Time=	0.5	

Equivalent parameters of MC {3, 4}	
λ eq. =	**0.362049849**
U eq. =	**0.430588397**
r eq. =	**1.189306937**

Using the approximate methods of reliability evaluation for series systems, based on inputs from Tables 3 through 10, the following is the set of basic reliability parameters of for OS1LP2.

Table 11. Reliability parameters for OS1LP2

Reliability parameters for OS1LP2	
λ eq. =	**1.732697901**
U eq. =	**2.738730219**
r eq. =	**1.580616112**

7.2 Illustrative calculations for the analysis of minimal cutsets for OS2LP1

The minimal cutsets for OS2LP1 are shown in Fig. 6.

MC {2, 4, 5}: *This is a minimal cutset group of three neighbouring lines, two of which are parallel (2 and 5).*

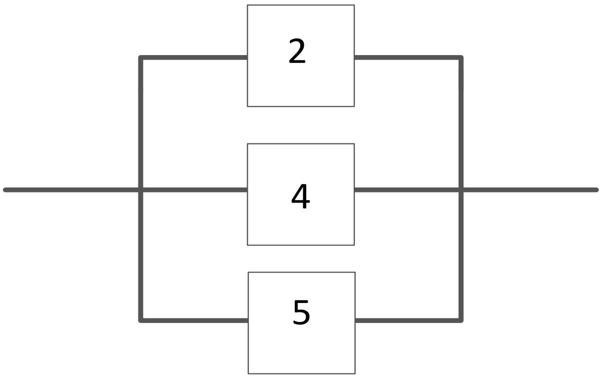

Fig. 6. MOPAL minimal cutsets for OS2LP1

Element 5:

Fault Type 1

$$\lambda_{FT1(i)} = \lambda_i$$

$$\Rightarrow \lambda_{FT1(5)} = \lambda_5 = 3$$

Fault Type 2

$$\lambda_{FT2(i)} = [\lambda_{BE_{A[i]}} + \lambda_{BE_{B[i]}}]$$

$$\Rightarrow \lambda_{FT2(5)} = [\lambda_{BE_{A[5]}} + \lambda_{BE_{B[5]}}]$$

$$\lambda_{FT2(5)} = [0.025 + 0.025] = 0.05$$

Fault Type 3

For line 5, the neighbouring lines are lines 1, 4 and 2.

Situations resulting in FT3 on line 5:

(i) Fault on line 1 and failure of $PT_{A[1]}$

(ii) Fault on line 4 and failure of $PT_{B[4]}$ →**Dependent mode failure of MC {2, 4, 5}**

(iii) Fault on line 2 and failure of $PT_{A[2]}$ or $PT_{B[2]}$ or both

Analysis of situations resulting in FT3 on line 5:

(i) Fault on line 1 and failure of $PT_{A[1]}$

$PT_{A[5]}$ performs the backup action and line 5 is out of service

Failure rate contribution of this situation to $\lambda_{FT3(5)}$ is $\lambda_1 * P_{missing(PT_{A[1]})}$

(ii) Fault on line 4 and failure of $PT_{B[4]}$

$PT_{B[5]}$ performs the backup action and line 5 is out of service

Dependent mode Failure rate contribution of this situation to $\lambda_{FT3(5)}$ is $\lambda_4 * P_{missing(PT_{B[4]})} =$

0.1025

(iii) Fault on line 2 and failure of $PT_{A[2]}$ or $PT_{B[2]}$ or both

$PT_{A[5]}$ or $PT_{B[5]}$ or both perform backup action in respective cases, and line 5 is out of service

Failure rate contribution of this situation to $\lambda_{FT3(5)}$ is:

$$\lambda_2 (P_{missing(PT_{A[2]})} + P_{missing(PT_{B[2]})} - P_{missing(PT_{A[2]})} * P_{missing(PT_{B[2]})})$$

Contribution of all situations (excluding dependent mode failures) resulting in FT3 on line 5 to the total failure rate of FT3:

$$\lambda_{FT3(5)} = \lambda_1 * P_{missing(PT_{A[1]})} + \lambda_2 (P_{missing(PT_{A[2]})} + P_{missing(PT_{B[2]})} - P_{missing(PT_{A[2]})} * P_{missing(PT_{B[2]})}) = 0.16273925$$

Fault Type 4

For line 5, the neighbouring lines are lines 1, 4 and 2.

Situations resulting in FT4 on line 5:

(i) Fault on line 1, correct operation of $PT_{A[1]}$, but unwanted non-selective operation of $PT_{A[5]}$ or $PT_{B[5]}$ or both.

(ii) Fault on line 4, correct operation of $PT_{B[4]}$, but unwanted non-selective operation of $PT_{A[5]}$ or $PT_{B[5]}$ or both.

(iii) Fault on line 2, correct operation of both $PT_{A[2]}$ and $PT_{B[2]}$ but unwanted non-selective operation of $PT_{A[5]}$ or $PT_{B[5]}$ or both.

Contribution of all situations resulting in FT4 on line 5 to the net failure rate of FT3:

$$\begin{aligned}\lambda_{FT4(5)} = &\left(\begin{array}{l}\lambda_1 * P(PT_{A-1}) * \\ \quad\left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{array}\right) + \\ &\left(\begin{array}{l}\lambda_4 * P(PT_{B-4}) * \\ \quad\left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{array}\right) + \\ &\left(\begin{array}{l}\lambda_2 * P(PT_{A-2}) * P(PT_{B-2}) * \\ \quad\left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{array}\right)\end{aligned}$$

=0.135809647

$$\lambda_{Eq.(5)} = \lambda_{FT1(5)} + \lambda_{FT2(5)} + \lambda_{FT3(5)} + \lambda_{FT4(5)} = \mathbf{3 + 0.05 + 0.16273925 + 0.135809647 = 3.348548897}$$

Element 4:

$$\lambda_{FT1(4)} = \lambda_4 = 5$$

$$\lambda_{FT2(4)} = [\lambda_{BE_{A[4]}} + \lambda_{BE_{B[4]}}] = 0.05$$

Fault Type 3

For line 4, the neighbouring lines are lines 2, 5, 6 and 3.

Situations resulting in FT3 on line 4:

(i) Fault on line 2 and failure of $PT_{B[2]}$ →Dependent mode failure of MC {2, 4, 5}

Dependent mode Failure rate contribution of this situation is $\lambda_2 * P_{missing(PT_{B[2]})}$=0.0615

(ii) Fault on line 5 and failure of $PT_{B[5]}$ →Dependent mode failure of MC {2, 4, 5}

Dependent mode Failure rate contribution of this situation is $\lambda_5 * P_{missing(PT_{B[5]})}$ =0.0615

(iii) Fault on line 6 and failure of $PT_{A[6]}$

(iv) Fault on line 3 and failure of $PT_{A[3]}$

Contribution of all situations (excluding dependent mode failures) resulting in FT3 on line 4 to the total failure rate of FT3:

$$\lambda_{FT3(4)} = \lambda_6 * P_{missing(PT_{A[6]})} + \lambda_3 * P_{missing(PT_{A[3]})}$$

=0.164

Fault Type 4

Situations resulting in FT4 on line 4:

(i) Fault on line 2, correct operation of $PT_{B[2]}$, but unwanted non-selective operation of $PT_{B[4]}$ or $PT_{A[4]}$ or both.

(ii) Fault on line 5, correct operation of $PT_{B[4]}$, but unwanted non-selective operation of $PT_{B[4]}$ or $PT_{A[4]}$ or both.

(iii) Fault on line 6, correct operation of $PT_{A[6]}$, but unwanted non-selective operation of $PT_{B[4]}$ or $PT_{A[4]}$ or both.

(iv) Fault on line 3, correct operation of $PT_{A[3]}$, but unwanted non-selective operation of $PT_{B[4]}$ or $PT_{A[4]}$ or both.

$$\begin{aligned}\lambda_{FT4(4)} = &\left(\begin{array}{l}\lambda_2 * P(PT_{B-2}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right)\end{array}\right) + \\ &\left(\begin{array}{l}\lambda_5 * P(PT_{B-5}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right)\end{array}\right) + \\ &\left(\begin{array}{l}\lambda_6 * P(PT_{A-6}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right)\end{array}\right) + \\ &\left(\begin{array}{l}\lambda_3 * P(PT_{A-3}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right)\end{array}\right)\end{aligned}$$

=0.191310063

$\lambda_{Eq.(4)} = \lambda_{FT1(4)} + \lambda_{FT2(4)} + \lambda_{FT3(4)} + \lambda_{FT4(4)}$ **= 5.405310063**

Element 2:

For line 2, the neighbouring lines are lines 1, 4 and 5.

$\lambda_{FT1(2)} = \lambda_2 = 3$

$\lambda_{FT2(2)} = [\lambda_{BE_{A[2]}} + \lambda_{BE_{B[2]}}] = 0.05$

Fault Type 3

Situations resulting in FT3 on line 2:

(i) Fault on line 1 and failure of $PT_{A[1]}$

(ii) Fault on line 4 and failure of $PT_{B[4]}$ →Dependent mode failure of MC {2, 4, 5}

$\lambda_4 * P_{missing(PT_{B[4]})}$

(iii) Fault on line 5 and failure of $PT_{A[5]}$ or $PT_{B[5]}$ or both

$\lambda_5 (P_{missing(PT_{A[5]})} + P_{missing(PT_{B[5]})} - P_{missing(PT_{A[5]})} * P_{missing(PT_{B[5]})})$

Contribution of all situations (excluding dependent mode failures) resulting in FT3 on line 2 to the total failure rate of FT3:

$\lambda_{FT3(2)} = \lambda_1 * P_{missing(PT_{A[1]})} + \lambda_5 (P_{missing(PT_{A[5]})} + P_{missing(PT_{B[5]})} - P_{missing(PT_{A[5]})} * P_{missing(PT_{B[5]})})$ **=0.16273925**

Fault Type 4

Situations resulting in FT4 on line 2:

(i) Fault on line 1, correct operation of $PT_{A[1]}$, but unwanted non-selective operation of $PT_{A[2]}$ or $PT_{B[2]}$ or both.

(ii) Fault on line 4, correct operation of $PT_{B[4]}$, but unwanted non-selective operation of $PT_{A[2]}$ or $PT_{B[2]}$ or both.

(iii) Fault on line 5, correct operation of both $PT_{A[5]}$ and $PT_{B[5]}$ but unwanted non-selective operation of $PT_{A[2]}$ or $PT_{B[2]}$ or both.

$$\lambda_{FT4(2)} = \left(\begin{array}{l} \lambda_1 * P(PT_{A-1}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \right) \end{array} \right) +$$

$$\left(\begin{array}{l} \lambda_4 * P(PT_{B-4}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \right) \end{array} \right) +$$

$$\left(\begin{array}{l} \lambda_5 * P(PT_{A-5}) * P(PT_{B-5}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \right) \end{array} \right)$$

=0.135809647

$$\lambda_{Eq.(2)} = \lambda_{FT1(2)} + \lambda_{FT2(2)} + \lambda_{FT3(2)} + \lambda_{FT4(2)} = 3.348548897$$

'Different' situations resulting in dependent mode failures of MC {2, 4, 5}:

Fault on line 4 and failure of $PT_{B[4]}$

Fault on line 2 and failure of $PT_{B[2]}$

Fault on line 5 and failure of $PT_{B[5]}$

Net dependent mode failure rate contribution λ_D:

$$\lambda_4 * P_{missing(PT_{B[4]})} + \lambda_2 * P_{missing(PT_{B[2]})} + \lambda_5 * P_{missing(PT_{B[5]})} = 0.205$$

Table 12. Equivalent parameters of MC {2, 4, 5}

Element 5 in {2, 4, 5}					
	Lambda	**r**	**Lambda*r**		
FT1 (5)	**3**	**15**	**45**		
FT2 (5)	**0.05**	**2**	**0.1**		
FT3 (5)	**0.16273925**	**0.5**	**0.081369625**		
FT4 (5)	**0.135809647**	**0.5**	**0.067904824**		
Lambda Eq. (5)	**3.28013448**	**U (5)=**	**45.21506724**	**r (5)=**	**13.51309951**
Element 2 in {2, 4, 5}					
	Lambda	**r**	**Lambda*r**		
FT1 (2)	**3**	**15**	**45**		
FT2 (2)	**0.05**	**2**	**0.1**		
FT3 (2)	**0.16273925**	**0.5**	**0.081369625**		
FT4 (2)	**0.135809647**	**0.5**	**0.067904824**		
Lambda Eq. (2)	**3.348548897**	**U=**	**45.24927445**	**r (2)=**	**13.51309951**
Element 4 in {2, 4, 5}					
	Lambda	**r**	**Lambda*r**		
FT1 (4)	**5**	**10**	**50**		
FT2 (4)	**0.05**	**2**	**0.1**		
FT3 (4)	**0.164**	**0.5**	**0.082**		
FT4 (4)	**0.191310063**	**0.5**	**0.095655032**		
Lambda Eq. (4)	**5.405310063**	**U=**	**50.27765503**	**r (4)=**	**9.301530244**
Lambda D for {2, 4, 5}	0.205		Restoration Time=	0.5	

Using Eqns (15) to (17) , the reliability parameters for OS2LP1 are obtained, as given in Table 13.

Table 13. Reliability parameters for OS2LP1

Reliability parameters for OS2LP1	
λ eq. =	**0.205342771**
U eq. =	**0.103841498**
r eq. =	**0.505698338**

7.2 Illustrative calculations for the analysis of minimal cutsets for OS2LP2

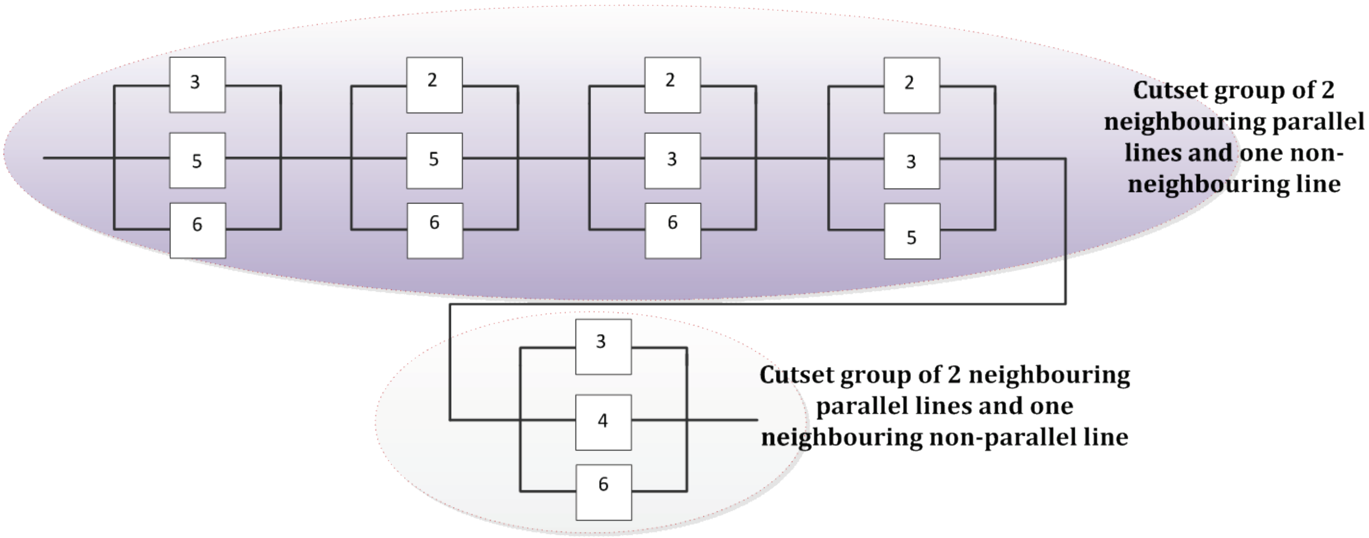

Fig. 7. MOPAL minimal cutsets for OS2LP2

Consider the analysis of MC {3, 5, 6}

This is a minimal cutset group of two neighbouring parallel lines, and one non-neighbouring line. The procedure to analyse a minimal cutset of such composition is different than the one previously demonstrated in the case of MC {2, 4, 5}.

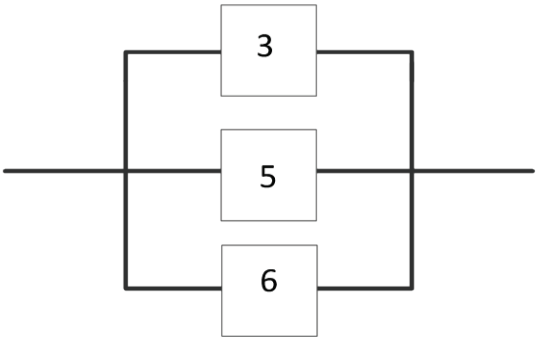

Fig. 8. MOPAL minimal cutset {3, 5, 6} for OS2LP2

In MC {3, 5, 6} for the case of OS2LP2, the subset {3, 6} could be noted as a minimal cutset for the case of OS1LP2, whose analysis was provided on page 26. Elements 3 and 6 are neighbouring parallel lines, and hence there exists a dependency.

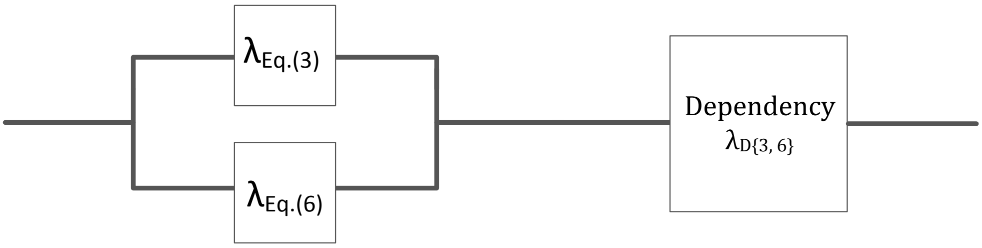

Fig. 9. Analysis of MOPAL minimal cutset {3, 6} for OS1LP2

The equivalent of Fig. 8 is shown below in Fig. 10. Since element 5 is a non-neighbouring line to the remaining two elements of MC {3, 5, 6} for the case of OS2LP2, the equivalent failure rate to be used for element 5 in the analysis is the same as the equivalent failure rate computed for element 5 in MC {5, 6} or MC {3, 5} (i.e., non-neighbouring lines) for the case of OS1LP2.

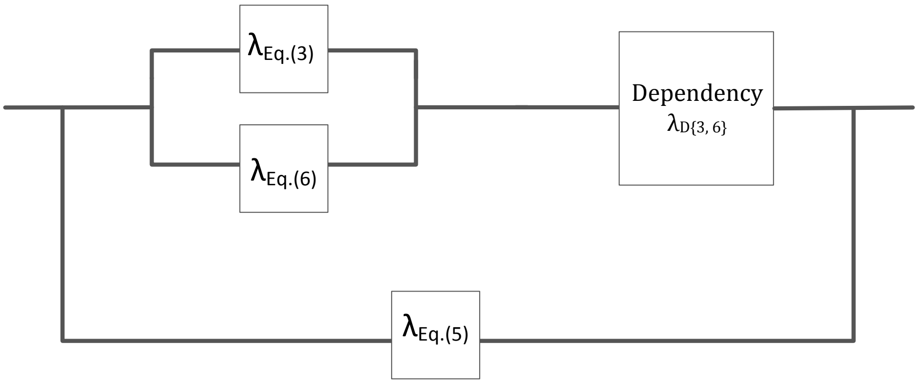

Fig. 10. Equivalent of Fig. 8

The summary of analyses of MC {3, 6} from pages 26 and 27 is shown below:

Table 14. Equivalent parameters of MC {3, 6}

Equivalent parameters of MC {3, 6}	
λ eq. =	**0.478936437**
U eq. =	**0.481284019**
r eq. =	**1.004901656**

The equivalent parameters for element 5 when belonging to MC {5, 6}, based on calculations from pages 17 to 20 are summarized below:

Table 15. Equivalent parameters of element 5 in MC {5, 6}

Element 5 in {5, 6}					
	Lambda	**r**	**Lambda*r**		
FT1 (5)	3	15	45		
FT2 (5)	0.05	2	0.1		
FT3 (5)	0.26523925	0.5	0.132619625		
FT4 (5)	0.135809647	0.5	0.067904824		
Lambda Eq. (5)=	**3.451048897**	**U (5)=**	**45.30052445**	**r (5)=**	**13.12659594**

Using the approximate methods of reliability evaluation for parallel systems, based on inputs from Tables 14 and 15, the following is the set of equivalent parameters of MOPAL minimal cutset {3, 5, 6} for OS2LP2.

Table 16. Equivalent parameters of MC {3, 5, 6}

Equivalent parameters of MC {3, 5, 6}	
λ eq. =	**0.002666325**
U eq. =	**0.002488861**
r eq. =	**0.933442327**

Analysis of MC {2, 5, 6}, MC {2, 3, 6} and MC {2, 3, 5} is done on the same lines as that of MC {3, 5, 6} as shown above.

Analysis of MC {3, 4, 6}:

This is a minimal cutset group of three neighbouring lines, two of which are parallel. Analysis of such a cutset is done on the same lines as that of MC {2, 4, 5} as shown in pages 36 to 41.

Element 3:

$$\lambda_{FT1(3)} = \lambda_3 = 4$$

$$\lambda_{FT2(3)} = [\lambda_{BE_{A[3]}} + \lambda_{BE_{B[3]}}] = 0.05$$

Fault Type 3

For line 3, the neighbouring lines are lines 1, 4 and 6.

Situations resulting in FT3 on line 3:

(i) Fault on line 1 and failure of PT$_{B[1]}$

(ii) Fault on line 4 and failure of PT$_{A[4]}$ →**Dependent mode failure of MC {3, 4, 6}**

Dependent mode Failure rate contribution of this situation is $\lambda_4 * P_{missing(PT_{A[4]})}$

(iii) Fault on line 6 and failure of PT$_{A[6]}$ or PT$_{B[6]}$ or both

Contribution of all situations (excluding dependent mode failures) resulting in FT3 on line 3 to the total failure rate of FT3:

$$\lambda_{FT3(3)} = \lambda_1 * P_{missing(PT_{B[1]})} + \lambda_6 (P_{missing(PT_{A[6]})} + P_{missing(PT_{B[6]})} - P_{missing(PT_{A[6]})} * P_{missing(PT_{B[6]})}) \mathbf{=0.203319}$$

Fault Type 4

Situations resulting in FT4 on line 3:

(i) Fault on line 1, correct operation of PT$_{B[1]}$, but unwanted non-selective operation of PT$_{A[3]}$ or PT$_{B[3]}$ or both.

(ii) Fault on line 4, correct operation of PT$_{A[4]}$, but unwanted non-selective operation of PT$_{A[3]}$ or PT$_{B[3]}$ or both.

(iii) Fault on line 6, correct operation of both PT$_{A[6]}$ and PT$_{B[6]}$ but unwanted non-selective operation of PT$_{A[3]}$ or PT$_{B[3]}$ or both.

Contribution of all situations resulting in FT4 on line 3 to the net failure rate of FT3:

$$\lambda_{FT4(3)} = \begin{pmatrix} \lambda_1 * P(PT_{B-1}) * \\ \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_4 * P(PT_{A-4}) * \\ \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_6 * P(PT_{A-6}) * P(PT_{B-6}) * \\ \left(P_{unwanted-Ns.(PT_{A[3]})} + P_{unwanted-Ns.(PT_{B[3]})} - P_{unwanted-Ns.(PT_{A[3]})} * P_{unwanted-Ns.(PT_{B[3]})}\right) \end{pmatrix}$$

=0.149194519

$$\lambda_{Eq.(3)} = \lambda_{FT1(3)} + \lambda_{FT2(3)} + \lambda_{FT3(3)} + \lambda_{FT4(3)} \mathbf{= 3.402513519}$$

Element 4:

$$\lambda_{FT1(4)} = \lambda_4 = 5$$

$$\lambda_{FT2(4)} = [\lambda_{BE_{A[4]}} + \lambda_{BE_{B[4]}}] = 0.05$$

Fault Type 3

For line 4, the neighbouring lines are lines 2, 5, 6 and 3.

Situations resulting in FT3 on line 4:

(i) Fault on line 2 and failure of $PT_{B[2]}$

(ii) Fault on line 5 and failure of $PT_{B[5]}$

(iii) Fault on line 6 and failure of $PT_{A[6]}$ →Dependent mode failure of MC {3, 4, 6}

Dependent mode Failure rate contribution of this situation is $\lambda_6 * P_{missing(PT_{A[6]})}$

(iv) Fault on line 3 and failure of $PT_{A[3]}$ →Dependent mode failure of MC {3, 4, 6}

Dependent mode Failure rate contribution of this situation is $\lambda_3 * P_{missing(PT_{A[3]})}$

Contribution of all situations (excluding dependent mode failures) resulting in FT3 on line 4 to the total failure rate of FT3:

$\lambda_{FT3(4)} = \lambda_2 * P_{missing(PT_{B[2]})} + \lambda_5 * P_{missing(PT_{B[5]})}$ **=0.123**

Fault Type 4

Situations resulting in FT4 on line 4:

(i) Fault on line 2, correct operation of $PT_{B[2]}$, but unwanted non-selective operation of $PT_{B[4]}$ or $PT_{A[4]}$ or both.

(ii) Fault on line 5, correct operation of $PT_{B[4]}$, but unwanted non-selective operation of $PT_{B[4]}$ or $PT_{A[4]}$ or both.

(iii) Fault on line 6, correct operation of $PT_{A[6]}$, but unwanted non-selective operation of $PT_{B[4]}$ or $PT_{A[4]}$ or both.

(iv) Fault on line 3, correct operation of $PT_{A[3]}$, but unwanted non-selective operation of $PT_{B[4]}$ or $PT_{A[4]}$ or both.

$$\begin{aligned}
\lambda_{FT4(4)} = & \left(\begin{array}{l} \lambda_2 * P(PT_{B-2}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{array} \right) + \\
& \left(\begin{array}{l} \lambda_5 * P(PT_{B-5}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{array} \right) + \\
& \left(\begin{array}{l} \lambda_6 * P(PT_{A-6}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{array} \right) + \\
& \left(\begin{array}{l} \lambda_3 * P(PT_{A-3}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})} \right) \end{array} \right)
\end{aligned}$$

=0.191310063

$$\lambda_{Eq.(4)} = \lambda_{FT1(4)} + \lambda_{FT2(4)} + \lambda_{FT3(4)} + \lambda_{FT4(4)} = \mathbf{5.364310063}$$

Element 6:

For line 6, the neighbouring lines are lines 1, 3 and 4.

$$\lambda_{FT1(6)} = \lambda_6 = 4$$

$$\lambda_{FT2(6)} = [\lambda_{BE_{A[6]}} + \lambda_{BE_{B[6]}}] = 0.05$$

Fault Type 3

Situations resulting in FT3 on line 6:

(i) Fault on line 1 and failure of PT$_{B[1]}$

(ii) Fault on line 4 and failure of PT$_{A[4]}$ →Dependent mode failure of MC {3, 4, 6}

Dependent mode Failure rate contribution of this situation is $\lambda_4 * P_{missing(PT_{A[4]})}$

(iii) Fault on line 3 and failure of PT$_{A[3]}$ or PT$_{B[3]}$ or both

Contribution of all situations (excluding dependent mode failures) resulting in FT3 on line 6 to the total failure rate of FT3:

$$\lambda_{FT3(6)} = \lambda_1 * P_{missing(PT_{B[1]})} + \lambda_3 (P_{missing(PT_{A[3]})} + P_{missing(PT_{B[3]})} - P_{missing(PT_{A[3]})} * P_{missing(PT_{B[3]})}) = \mathbf{0.203319}$$

Fault Type 4

Situations resulting in FT4 on line 6:

(i) Fault on line 1, correct operation of PT$_{B[1]}$, but unwanted non-selective operation of PT$_{A[6]}$ or PT$_{B[6]}$ or both.

(ii) Fault on line 4, correct operation of PT$_{A[4]}$, but unwanted non-selective operation of PT$_{A[6]}$ or PT$_{B[6]}$ or both.

(iii) Fault on line 3, correct operation of both PT$_{A[3]}$ and PT$_{B[3]}$ but unwanted non-selective operation of PT$_{A[6]}$ or PT$_{B[6]}$ or both.

$$\begin{aligned}\lambda_{FT4(6)} = &\left(\begin{array}{l}\lambda_1 * P(PT_{B-1}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})}\right)\end{array}\right) + \\ &\left(\begin{array}{l}\lambda_4 * P(PT_{A-4}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})}\right)\end{array}\right) + \\ &\left(\begin{array}{l}\lambda_3 * P(PT_{A-3}) * P(PT_{B-3}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[6]})} + P_{unwanted-Ns.(PT_{B[6]})} - P_{unwanted-Ns.(PT_{A[6]})} * P_{unwanted-Ns.(PT_{B[6]})}\right)\end{array}\right)\end{aligned}$$

=0.149194519

'Different' situations resulting in dependent mode failures of MC {3, 4, 6}:

Fault on line 4 and failure of $PT_{A[4]}$

Fault on line 6 and failure of $PT_{A[6]}$

Fault on line 3 and failure of $PT_{A[3]}$

Net dependent mode failure rate contribution λ_D:

$$\lambda_4 * P_{missing(PT_{A[4]})} + \lambda_6 * P_{missing(PT_{A[6]})} + \lambda_3 * P_{missing(PT_{A[3]})} = 0.2665$$

Using the formulae from Page 11, the reliability parameters of MC {3, 4, 6} are obtained, as given in Table 17.

Table 17. Equivalent parameters of MC {3, 4, 6}

Equivalent parameters of MC {3, 4, 6}	
λ eq. =	**0.266639325**
U eq. =	**0.133541661**
r eq. =	**0.50083258**

Analysis of MC {2, 5, 6}

In MC {2, 5, 6} for the case of OS2LP2, the subset {2, 5} could be noted as a minimal cutset for the case of OS1LP2, whose analysis was provided in pages 23 through 25. Elements 2 and 5 are neighbouring parallel lines, and hence there exists a dependency. Since element 6 is a non-neighbouring line to the remaining two elements of MC {2, 5, 6} for the case of OS2LP2, the equivalent failure rate to be used for element 6 in the analysis is the same as the equivalent failure rate computed for element 6 in MC {5, 6} or MC {2, 6} (i.e., non-neighbouring lines) for the case of OS1LP2.

Following the procedure outlined in pages 42 and 43, the equivalent of MOPAL minimal cutset {2, 5, 6} for OS2LP2 can thus be obtained as shown below, and the subsequent calculations are summarized in Table 18.

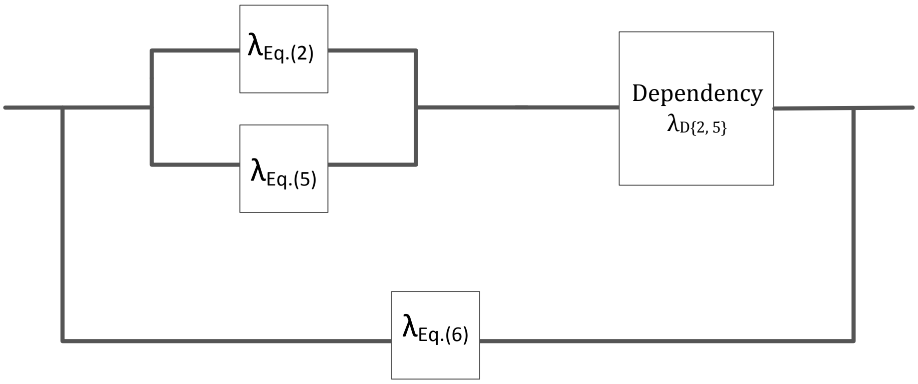

Fig. 11. Equivalent of MOPAL minimal cutset {2, 5, 6} for OS2LP2

Table 18. Equivalent parameters of MC {2, 5, 6}

Equivalent parameters of MC {2, 5, 6}	
λ eq. =	**0.002176925**
U eq. =	**0.002180915**
r eq. =	**1.001833015**

Analysis of MC {2, 3, 6}

In MC {2, 3, 6} for the case of OS2LP2, the subset {3, 6} could be noted as a minimal cutset for the case of OS1LP2. Elements 3 and 6 are neighbouring parallel lines, and hence there exists a dependency. Since element 2 is a non-neighbouring line to the remaining two elements of MC {2, 3, 6} for the case of OS2LP2, the equivalent failure rate to be used for element 2 in the analysis is the same as the equivalent failure rate computed for element 2 in MC {2, 3} or MC {2, 6} (i.e., non-neighbouring lines) for the case of OS1LP2.

Following the procedure outlined in pages 42 and 43, the equivalent of MOPAL minimal cutset {2, 3, 6} for OS2LP2 can thus be obtained as shown below, and the subsequent calculations are summarized in Table 19.

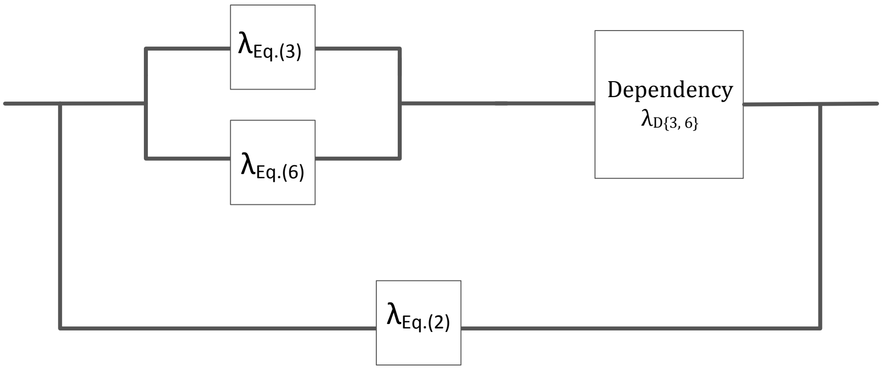

Fig. 12. Equivalent of MOPAL minimal cutset {2, 3, 6} for OS2LP2

Table 19. Equivalent parameters of MC {2, 3, 6}

Equivalent parameters of MC {2, 3, 6}	
λ eq. =	**0.002666325**
U eq. =	**0.002488861**
r eq. =	**0.933442327**

Analysis of MC {2, 3, 5}

In MC {2, 3, 5} for the case of OS2LP2, the subset {2, 5} could be noted as a minimal cutset for the case of OS1LP2. Elements 2 and 5 are neighbouring parallel lines, and hence there exists a dependency. Since element 3 is a non-neighbouring line to the remaining two elements of MC {2, 3, 5} for the case of OS2LP2, the equivalent failure rate to be used for element 3 in the analysis is the same as the equivalent failure rate computed for element 3 in MC {2, 3} or MC {3, 5} (i.e., non-neighbouring lines) for the case of OS1LP2.

Following the procedure outlined in pages 42 and 43, the equivalent of MOPAL minimal cutset {2, 3, 5} for OS2LP2 can thus be obtained as shown below, and the subsequent calculations are summarized in Table 20.

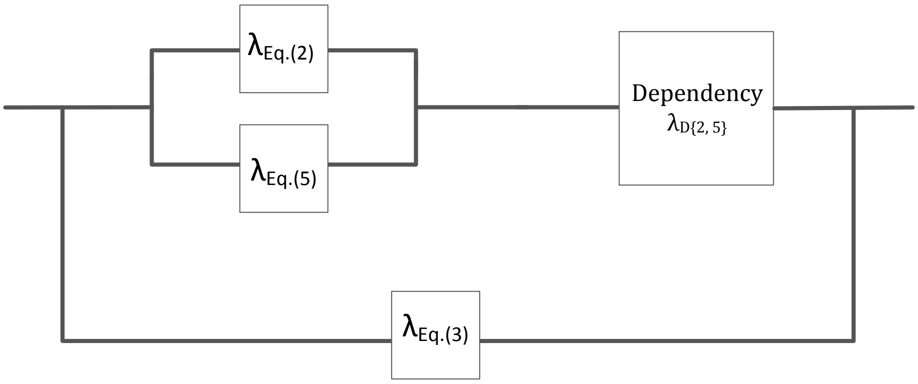

Fig. 13. Equivalent of MOPAL minimal cutset {2, 3, 5} for OS2LP2

Table 20. Equivalent parameters of MC {2, 3, 5}

Equivalent parameters of MC {2, 3, 5}	
λ eq. =	0.002176925
U eq. =	0.002180915
r eq. =	1.001833015

Using the approximate methods of reliability evaluation for series systems, based on inputs from Tables 16 through 20, the basic reliability parameters for OS2LP2 are shown in Table 21.

Table 21. Reliability parameters for OS2LP2

Reliability parameters for OS2LP2	
λ eq. =	0.276325824
U eq. =	0.142881212
r eq. =	0.517075132

7.3 Illustrative Calculations for the analysis of minimal cutsets for OS1LP1

The minimal cutsets for OS1LP1 are shown in Fig. 14.

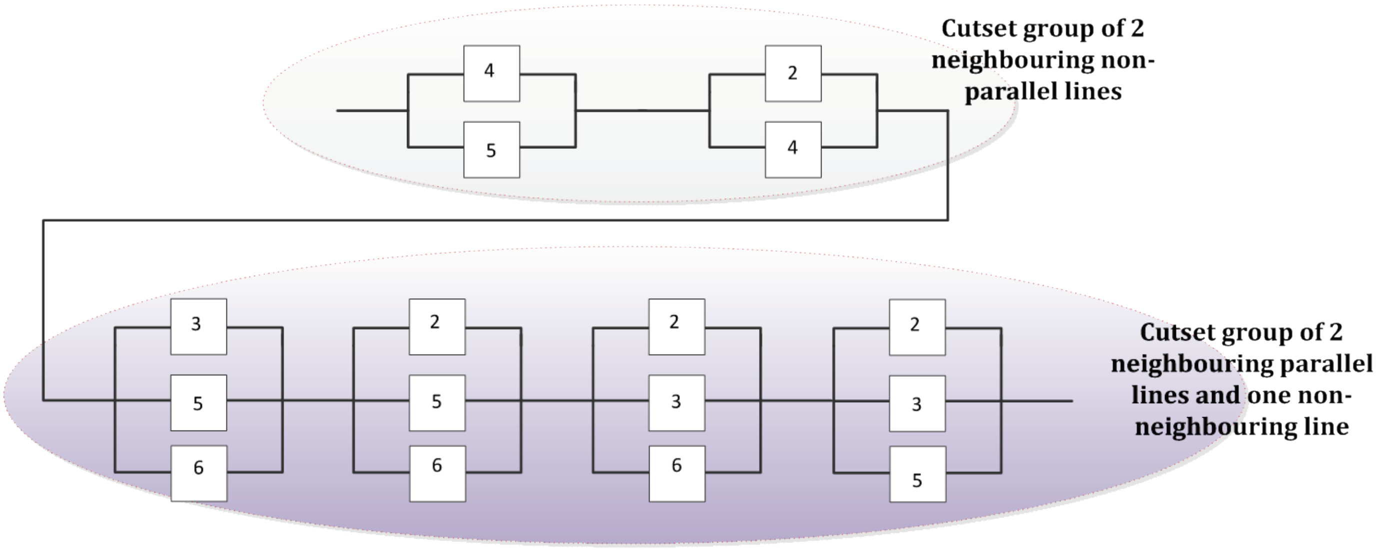

Fig. 14. MOPAL minimal cutsets for OS1LP1

On the lines of procedure explained for the analysis of minimal cutset group of neighbouring non-parallel lines MC {4, 6} from pages 27 to 29, the equivalent parameters obtained for the cutsets MC {4, 5} and MC {2, 4} are summarized in Tables 22 and 23, respectively.

Analysis of Minimal Cutset (MC) {4, 5}

(This minimal cutset contains neighbouring lines)

Element 4 when part of (MC) {4, 5}:

Element 4:

$\lambda_{FT1(4)} = \lambda_4 = 5$

$\lambda_{FT2(4)} = [\lambda_{BE_{A[4]}} + \lambda_{BE_{B[4]}}]$**=0.05**

Fault Type 3

For line 4, the neighbouring lines are lines 2, 5, 6 and 3.

Situations resulting in FT3 on line 4:

(i) Fault on line 2 and failure of PT$_{B[2]}$ →Dependent mode failure of MC {4, 5}

(ii) Fault on line 5 and failure of PT$_{B[5]}$ →Dependent mode failure of MC {4, 5}

(iii) Fault on line 6 and failure of PT$_{A[6]}$

(iv) Fault on line 3 and failure of PT$_{A[3]}$

$\lambda_{FT3(4)} = \lambda_6 * P_{missing(PT_{A[6]})} + \lambda_3 * P_{missing(PT_{A[3]})}$**=0.164**

Fault Type 4

Situations resulting in FT4 on line 4:

(i) Fault on line 2, correct operation of PT$_{B[2]}$, but unwanted non-selective operation of PT$_{B[4]}$ or PT$_{A[4]}$ or both.

(ii) Fault on line 5, correct operation of PT$_{B[4]}$, but unwanted non-selective operation of PT$_{B[4]}$ or PT$_{A[4]}$ or both. →Dependent mode failure of MC {4, 5}

(iii) Fault on line 6, correct operation of PT$_{A[6]}$, but unwanted non-selective operation of PT$_{B[4]}$ or PT$_{A[4]}$ or both.

(iv) Fault on line 3, correct operation of PT$_{A[3]}$, but unwanted non-selective operation of PT$_{B[4]}$ or PT$_{A[4]}$ or both.

$$\lambda_{FT4(4)} = \left(\begin{array}{l} \lambda_2 * P(PT_{B-2}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{array} \right) +$$

$$\left(\begin{array}{l} \lambda_6 * P(PT_{A-6}) * \\ \quad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})} \right) \end{array} \right) +$$

$$\begin{pmatrix}\lambda_3 * P(PT_{A-3}) * \\ \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right)\end{pmatrix}$$

=0.15031505

Element 5 when part of (MC) {4, 5}:

$$\lambda_{FT1(5)} = \lambda_5 = 3$$

$$\lambda_{FT2(5)} = [\lambda_{BE_{A[5]}} + \lambda_{BE_{B[5]}}] = 0.05$$

$$\lambda_{FT3(5)} = \lambda_1 * P_{missing(PT_{A[1]})} = 0.041$$

$$\lambda_{FT4(5)} = \begin{pmatrix}\lambda_1 * P(PT_{A-1}) * \\ \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{pmatrix} +$$

$$\begin{pmatrix}\lambda_2 * P(PT_{A-2}) * P(PT_{B-2}) * \\ \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{pmatrix}$$

= 0.067484625

Dependency mode failure rate for (MC) {4, 5}:

$$\lambda_D^{'} = \lambda_4 * P_{missing(PT_{A[4]})} + \lambda_5 * P_{missing(PT_{B[5]})} + \lambda_2 (P_{missing(PT_{A[2]})} + P_{missing(PT_{B[2]})} - P_{missing(PT_{A[2]})} * P_{missing(PT_{B[2]})})$$

= 0.34723925

$$\lambda_D^{''} = \begin{pmatrix}\lambda_5 * P(PT_{B-5}) * \\ \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right)\end{pmatrix} +$$

$$\begin{pmatrix}\lambda_4 * P(PT_{B-4}) * \\ \left(P_{unwanted-Ns.(PT_{A[5]})} + P_{unwanted-Ns.(PT_{B[5]})} - P_{unwanted-Ns.(PT_{A[5]})} * P_{unwanted-Ns.(PT_{B[5]})}\right)\end{pmatrix}$$

= 0.109320036

$\lambda_D = \lambda_D^{'} + \lambda_D^{''}$ **= 0.456559286**

Analysis of (MC) {2, 4} *(This minimal cutset contains neighbouring lines)*

Element 2 when part of (MC) {2, 4}:

$$\lambda_{FT1(2)} = \lambda_2 = 3$$

$$\lambda_{FT2(2)} = [\lambda_{BE_{A[2]}} + \lambda_{BE_{B[2]}}] = 0.05$$

$\lambda_{FT3(2)} = \lambda_1 * P_{missing(PT_{A[1]})}$ **=0.041**

$$\lambda_{FT4(2)} = \begin{pmatrix} \lambda_1 * P(PT_{A-1}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_5 * P(PT_{A-5}) * P(PT_{B-5}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right) \end{pmatrix}$$

= 0.067484625

Element 4 when part of (MC) {2, 4}:

$$\lambda_{FT1(4)} = \lambda_4 = 5$$

$\lambda_{FT2(4)} = [\lambda_{BE_{A[4]}} + \lambda_{BE_{B[4]}}] = 0.05\,; \lambda_{FT3(4)} = \lambda_3 * P_{missing(PT_{A[3]})} + \lambda_6 * P_{missing(PT_{A[6]})}$ **=0.164**

$$\lambda_{FT4(4)} = \begin{pmatrix} \lambda_3 * P(PT_{A-3}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_5 * P(PT_{B-5}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_6 * P(PT_{A-6}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix}$$

= 0.15031505

Dependency mode failure rate for (MC) {2, 4}:

$$\lambda_D^{'} = \lambda_4 * P_{missing(PT_{B[4]})} + \lambda_2 * P_{missing(PT_{B[2]})} + \lambda_5 * P_{missing(PT_{B[5]})} + \lambda_5 (P_{missing(PT_{A[5]})} + P_{missing(PT_{B[5]})} - P_{missing(PT_{A[5]})} * P_{missing(PT_{B[5]})})$$

= 0.34723925

$$\lambda_D^{''} = \begin{pmatrix} \lambda_4 * P(PT_{B-4}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[2]})} + P_{unwanted-Ns.(PT_{B[2]})} - P_{unwanted-Ns.(PT_{A[2]})} * P_{unwanted-Ns.(PT_{B[2]})}\right) \end{pmatrix} + \begin{pmatrix} \lambda_2 * P(PT_{B-2}) * \\ \qquad \left(P_{unwanted-Ns.(PT_{A[4]})} + P_{unwanted-Ns.(PT_{B[4]})} - P_{unwanted-Ns.(PT_{A[4]})} * P_{unwanted-Ns.(PT_{B[4]})}\right) \end{pmatrix}$$

= 0.109320036

$\lambda_D = \lambda_D^{'} + \lambda_D^{''}$**=0.218364695**

Table 22. Equivalent parameters of MC {4, 5}

Equivalent parameters of MC {4, 5}	
λ eq. =	0.502330752
U eq. =	0.487334879
r eq. =	0.970147413

Table 23. Equivalent parameters of MC {2, 4}

Equivalent parameters of MC {4, 5}	
λ eq. =	0.502330752
U eq. =	0.487334879
r eq. =	0.970147413

Analysis of MC {3, 5, 6}, MC {2, 5, 6}, MC {2, 3, 6} and MC {2, 3, 5} was previously carried out for computing the reliability parameters of OS2LP2. The same results can be used here. Thus, with input from Tables 16, 18, 19, 20, 22 and 23, based on approximate methods for system reliability evaluation, the reliability parameters could be computed for OS1LP1 as shown in Table 24.

Table 24. Reliability parameters for OS1LP1

Reliability parameters for OS1LP1	
λ eq. =	1.014348003
U eq. =	0.984009309
r eq. =	0.970090449

8 Results

With the assumption of perfect protection and control, the basic reliability parameters are first obtained for the different operating states and load points of the MOPAL network using the approximate methods of system reliability evaluation. The results from Tables 11, 13, 21 and 24 are collated in the following tables for a comparative assessment with respect to the corresponding cases of perfect protection and control. The comparisons are made with respect to a MOPAL network with perfect P&C.

Table 25. Comparative analysis of different reliability evaluation methods for OS1LP2

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**	**% Change in 'λ' w.r.t Perfect P&C**	**% Change in 'r' w.r.t Perfect P&C**	**% Change in 'U' w.r.t Perfect P&C**
Perfect P&C	0.323059	6.278798	2.028424	-	-	-
With P&C modelled	**1.732697**	**1.580616**	**2.738730**	436.34	-74.82	35.02

Table 26. Comparative analysis of different reliability evaluation methods for OS2LP1

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**	**% Change in 'λ' w.r.t Perfect P&C**	**% Change in 'r' w.r.t Perfect P&C**	**% Change in 'U' w.r.t Perfect P&C**
Perfect P&C	0.000307	4.285714	0.001319	-	-	-
With P&C modelled	**0.205342**	**0.505698**	**0.103841**	66598.53	-88.20	7770.17

Table 27. Comparative analysis of different reliability evaluation methods for OS1LP1

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**	**% Change in 'λ' w.r.t Perfect P&C**	**% Change in 'r' w.r.t Perfect P&C**	**% Change in 'U' w.r.t Perfect P&C**
Perfect P&C	0.086795	5.978790	0.518934	-	-	-
With P&C modelled	**1.014348**	**0.970090**	**0.984009**	1068.66	-83.77	89.62

Table 28. Comparative analysis of different reliability evaluation methods for OS2LP2

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**	**% Change in 'λ' w.r.t Perfect P&C**	**% Change in 'r' w.r.t Perfect P&C**	**% Change in 'U' w.r.t Perfect P&C**
Perfect P&C	0.001579	4.264502	0.006736	-	-	-
With P&C modelled	**0.276325**	**0.517075**	**0.142881**	17392.06	-87.87	2020.93

With more neighbouring lines in a cutset, unreliability for the delivery points LP1 and LP2 is seen to dramatically increase on account of imperfections in protection and control. For OS2LP1, there is only one third order minimal cutset, and all the transmission lines of this cutset are neighbouring lines, two of which are parallel. For the case of perfect protection systems, this third order 'redundancy' leads to very low unavailability. However, the dependent mode failures of protection systems are responsible for unavailability that is almost 7800 times worse when compared to the corresponding benchmark case of perfect protection systems. For OS1LP2, the minimal cutsets are all of second order. Even though there are third order minimal cutsets for OS1LP1, none of them have all neighbouring lines. The only protection system dependencies affecting the indices are of second order. For OS2LP2, all the minimal cutsets are of third order, only one of which has all neighbouring lines. Non-realistic station configuration can be cited as a plausible reason for the gigantic percentage changes.

For the example case of LP2, noticeably, there is a 436% increase in the failure frequency on account of protection system failure modes when compared to the case of perfect protection and control; a 35% increase is observed in the annual interruption duration. Further, the comparative values of the consequence indices - the annualized values of P_{Interr} and ENS shown in Tables 29 and 30, highlight the impact of P&C imperfections. Compared to the earlier studies conducted on OPAL test network, there is a 25% increase in the % increase in the failure frequency from the case of perfect protection systems to that of imperfect protection systems. This indicates the vulnerability of parallel transmission lines to more dependent failures in simple station configurations on account of protection system unreliability.

Table 29. Additional reliability indices: comparative analysis for LP1

Method	**P_{Interr} (MW/yr)**	**ENS (MWh/yr)**
Perfect P&C	2.82	16.86
P&C Modelled	32.97	31.98

Table 30. Additional reliability indices: comparative analysis for LP2

Method	**P_{Interr} (MW/yr)**	**ENS (MWh/yr)**
Perfect P&C	9.66	63.33
P&C Modelled	45.69	81.52

9 Conclusion and Future Work

There is a considerable effect of reliability of protection systems on the reliability of supply, and hence appropriate protection system reliability models must be incorporated in power system reliability studies. Building on the previously established procedure of including basic transmission protection system dependencies (as documented by the memo AN 12.12.66), improvement to the OPAL methodology for the reliability analysis phase has been initiated in this memo by considering two additional protection system dependencies brought on by (i) the presence of parallel transmission lines between bus pairs, and (ii) the presence of higher order (3rd level) minimal cutsets. To this effect MOPAL network has been devised and formulations and calculations demonstrated step by step.

The work put forward in this memo will be extended through further research with the following issues addressed:

- Procedural extension for various station configurations.
- Sensitivity analysis of various failure modes.

10 References

[1] V. V. Vadlamudi, "Incorporation of various protection system failure modes in composite power system reliability studies in the OPAL framework," *SINTEF Energy Research Technical Memo AN 12.12.66*, Sep. 2012.

[2] K. Samdal, G. H. Kjølle, O. Gjerde, and J. Heggset, "Requirement specification for reliability analysis in meshed power networks," *SINTEF Energy Research Technical Report TR A6429*, Dec. 2006.

[3] R. Billinton, M. E. Khan and S. K. Agarwal, "Contingency cut-off criteria in transmission system adequacy assessment," *IEE Proc.*, vol. 136, pt. C, no. 4, pp. 215-221, July 1989.

[4] IEEE Std. 493, "*IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (Gold Book)*," 2007.

[5] G. H. Kjølle and O. Gjerde, "The OPAL methodology for reliability analysis of power systems," *SINTEF Energy Research Technical Report TR A7175*, Jul. 2012.

Appendix A: OPAL Network Extensions

A.1 Extended OPAL (EOPAL) network:

EOPAL is a coupling of two OPAL networks. An OPAL network with buses OPAL8 to OPAL11 (Buses 1 to 4, respectively) and another OPAL network with the corresponding labeling of buses as OPAL12 to OPAL15 (Buses 5 to 8, respectively), are coupled by a line 9 between generator buses OPAL9 and OPAL12 on one end, and coupled by a line 10 between load buses OPAL11 and OPAL14 on the other end. Lines 9 and 10 are assumed to have a capacity of 135 MW each. Reactances of lines 9 and 10 are the same as that of each line of the OPAL network. A schematic of EOPAL network is as shown in Fig. A.1.

A.2 Extended Modified OPAL (EMOPAL) network:

EMOPAL is a coupling of two MOPAL networks. A MOPAL network with buses OPAL8 to OPAL11 (Buses 1 to 4, respectively) and another MOPAL network with the corresponding labeling of buses as OPAL12 to OPAL15 (Buses 5 to 8, respectively), are coupled by a line 13 between generator buses OPAL9 and OPAL12 on one end, and coupled by a line 14 between load buses OPAL11 and OPAL14 on the other end. Lines 13 and 14 are assumed to have a capacity of 135 MW each. Reactances of lines 13 and 14 are the same as that of each line of the OPAL network. A schematic of EMOPAL network is as shown in Fig. A.2.

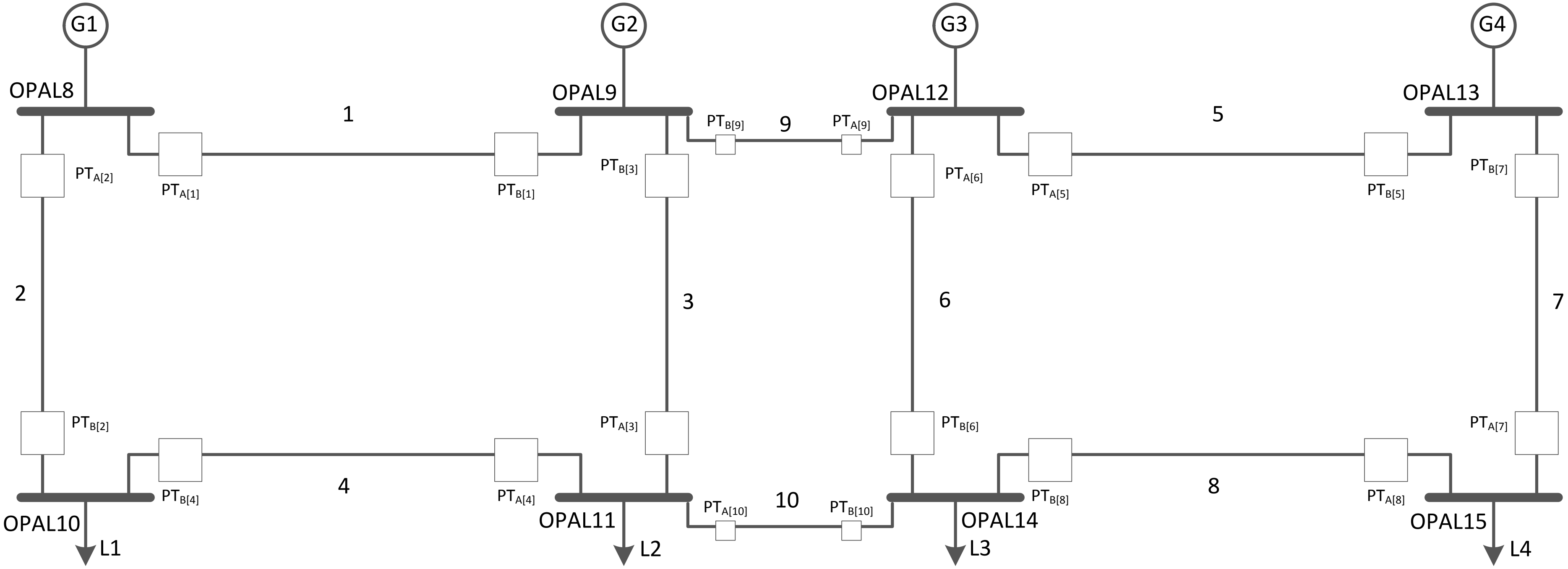

Fig. A.1. Extended OPAL (EOPAL) network

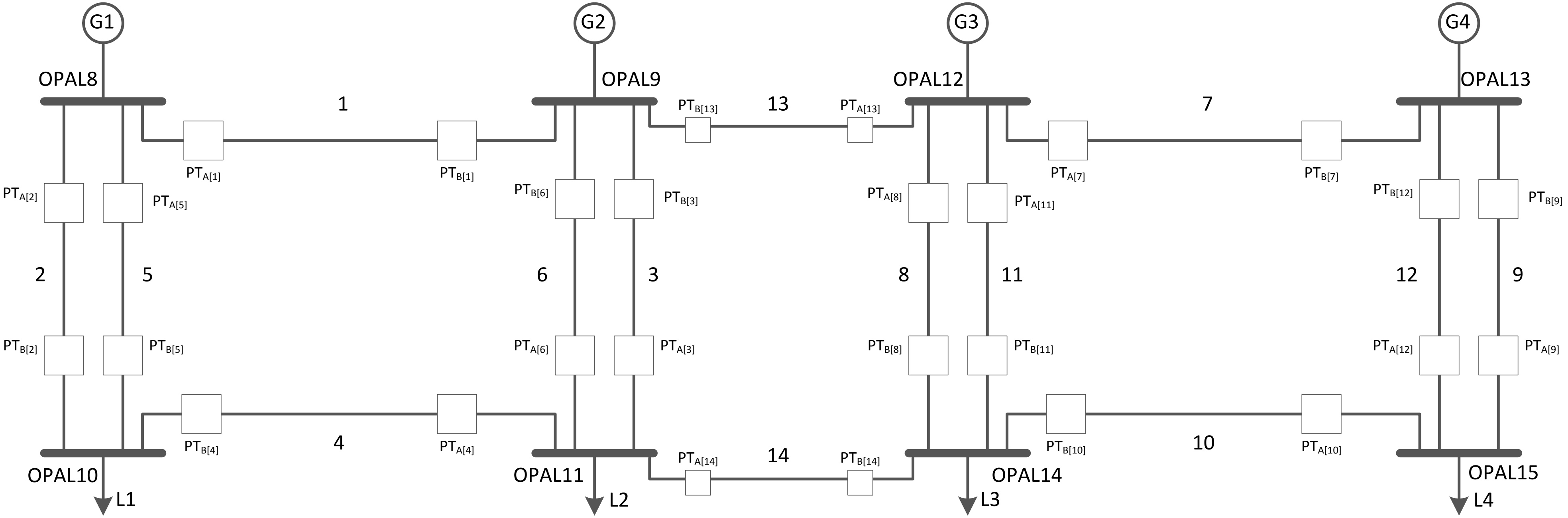

Fig. A.2. Extended Modified OPAL (EMOPAL) network

APPENDIX 3

Project memo AN 14.12.31

Impact of substation configuration on protection system failure propagation and inclusion of the consequent effects in power system reliability studies in the OPAL framework

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Project memo

Impact of substation configuration on protection system failure propagation and inclusion of the consequent effects in power system reliability studies in the OPAL framework

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ABSTRACT

Relatively fewer studies exist in literature on including the comprehensive effects of transmission protection system related failure dependencies in the reliability prediction models. Usage of extensive Markov models has been usually advocated to capture the impact of protection system reliability on power system reliability. A new analytical method which makes use of approximate methods of system reliability evaluation has been recently proposed (documented in the memos AN 12.12.66 and AN 13.12.33), which circumvents the need for Markov models. It is a unique minimal cutset-based approach for single circuit and multi-circuit meshed transmission systems, where several basic and load/energy oriented reliability indices are obtained. The objective of this memo is to extend the procedure to examine the impact of substation configurations on protection system failure dependency propagation and its effect on bulk load point reliability indices. Preliminary investigations show a marked impact of employing a station configuration with simplified bus representation, especially in multi circuit meshed transmission systems, on the resulting reliability indices. The results of the proposed methodology are demonstrated on a suitably modified four bus illustrative test system, for cases with and without the consideration of protection system failures for a realistic station configuration, i.e., breaker-and-a-half substation topology.

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PROJECT MEMO NO.	**CLASSIFICATION**
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Table of contents

1 Introduction

There exist already in literature several notable studies, both analytical and Monte Carlo simulation based, as regards the reliability analysis of substations [1]-[8]. Active and passive failures of the various substation components for connectivity between any pair of source and load buses in the substation network are usually analysed in such works. In this respect, it is important to point out the definition of a substation-originated outage: "It is a forced outage of any number of system generators, lines and/or loads, caused by a failure inside a switching station or a substation [3]". Thus, references [1]-[7] are devoted to the inclusion of station-originated outages (i.e., failure modes, effects and analysis of substation components, which is what the term 'reliability analysis of substation' entails) in composite system reliability evaluation,

The exclusive effects of protection system failures in various substation configurations using the concept of event trees have only been recently studied [9]. Prior to this, a methodology was proposed [10] to evaluate the effects of protection system hidden failures on bulk power system reliability; breaker-oriented substation models were integrated in the network model to consider the influence of protection systems.

An approach to performing risk assessment for the combinative system of transmission network and substation configuration was presented in [11], where it has particularly been emphasized that "evaluating substation configurations under the constraint of a transmission network provides more accurate results than evaluating only substation configurations since the transmission network and failures of its components may have impacts on the reliability of substation configurations." In this memo, this motivating philosophy has been kept in mind while proposing a model and solution for studying the impact of protection system reliability on power system reliability when explicitly taking the substation configuration into account.

The objective of this memo is to examine the impact of substation configuration arrangement (breaker-and-a-half scheme) on transmission protection system failure dependency propagation and study the consequent effects on bulk load point reliability indices, using a unique minimal cutset (MC) approach. It must be noted that this endeavour is not about the typical stand-alone reliability analysis of substation switching configurations, e.g., contingency analysis of substation elements including busbars to capture the effects of all station-originated outages

A new analytical method based on minimal cutsets, which makes use of approximate methods of system reliability evaluation, has been under development at SINTEF Energy Research [12]-[16], which circumvents the need for complex Markov models when analysing the impact of protection system reliability in transmission networks. This memo extends the procedure to examine the impact of substation configuration on protection system failure dependency propagation and its effect on bulk load point reliability indices.

2 Substation Configurations

Electric substations perform various operations, depending upon the specific applications for which they are designed at the generation, transmission and distribution levels. Some of the functions include stepping-up or stepping-down of voltage levels, appropriate routing of lines, and sectionalizing a power system to improve its operational flexibility. Invariably, protection and control schemes are employed in every type of substation. Needless to say, substation reliability is critical for the overall system reliability.

There are typically six different busbar arrangements used for switching at a substation [17]:

1. Single bus – single breaker,
2. Double bus – single breaker with bus-coupler,
3. Double bus – double breaker,
4. Main and transfer bus,
5. Double bus – one and a half breaker, and
6. Ring busbar or four-breaker mesh.

Factors that influence the appropriate selection of the switching arrangement at a substation include cost, reliability, and flexibility for future expansions. From a reliability/cost perspective, an overview of comparison of the various substation configurations is shown as in Table 1 [17]. The number shown in the parenthesis in Table 1 is a per unit amount for comparison of configurations

Table 1. Comparative overview of various substation configurations [17]

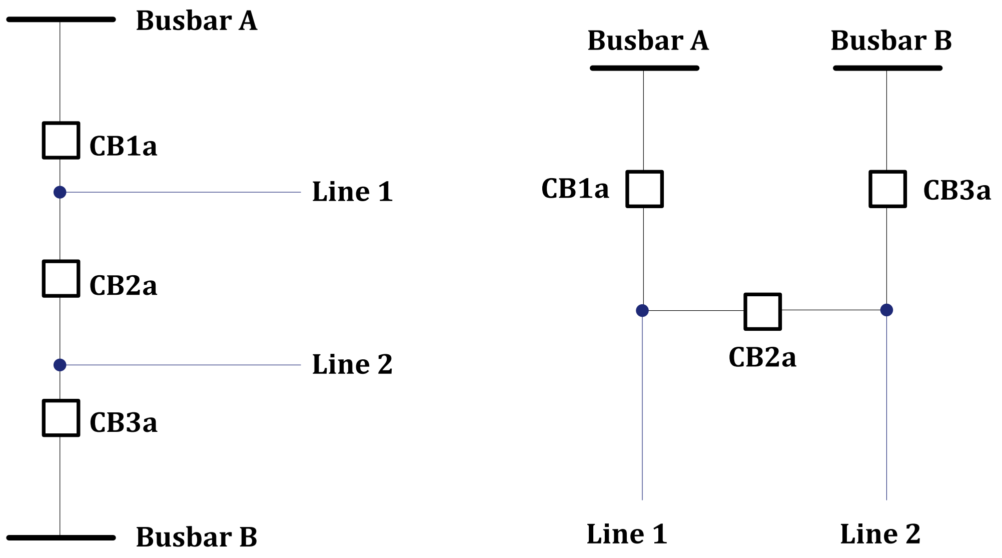
Configuration	Reliability	Cost
Single bus	Least reliable – single failure can cause complete outage	Least cost (1.0) – fewer components
Double bus	Highly reliable – duplicated components; single failure normally isolates single component	High cost (1.8) – duplicated components
Main bus and transfer	Least reliable – same as Single bus, but flexibility in operating and maintenance with transfer bus	Moderate cost (1.76) – fewer components
Double bus, single breaker	Moderately reliable – depends on arrangements of components and bus	Moderate cost (1.78) – more components
Ring bus	High reliability – single failure isolates single component	Moderate cost (1.56) – more components
Breaker-and-a-half	Highly reliabile – single circuit failure isolates single circuit, bus failures do not affect circuits	Moderate cost (1.57) – breaker-and-a-half for each circuit

3 Breaker-and-a-Half Substation Configuration

This configuration is known for its superior reliability standards even from a stand-alone reliability analysis point of view. Hence, this architecture is considered as a starting point for investigating the protection system failure dependency propagation effects. The procedure developed can be easily extended to other configurations from the demonstrated first principles, depending on the case-specific functional design of the respective switching schemes. A thorough understanding of the protection system backup coordination effects in a breaker-and-a-half configuration is essential for performing the necessary scenario analysis introduced later in this memo. In this section, the detailed functional aspects of breaker-and-a-half substation configuration are introduced.

The 'double bus – one and a half breaker' busbar arrangement (also known as breaker-and-a-half-arrangement) is shown in Fig. 1 without the isolators that usually accompany the circuit breakers (CBs), for the sake of simplicity. It has been observed [18] that this design increases the security of supply especially in cases where multiple sources are present, and has minimal bus exposure; it allows for maintenance without supply interruptions and is intended for stations serving as area hubs and/or for serving large loads that are sensitive to loss of load either because of momentary or sustained element outages. In the normal operating state, this arrangement has only 'normally closed' paths.

Two busbars A and B are interconnected by three circuit breakers CB1a, CB2a and CB3a as shown in Fig.1. Another way of depicting the breaker-and-a-half architecture is shown in Fig. 2.



(a) 'I-depiction' of Breaker-and-a-Half Configuration

(b) 'H-depiction' of Breaker-and-a-Half Configuration

Fig. 1. Typical representations of breaker-and-a-half substation configuration

Line 1 is connected between CB1a and CB2a; line 2 is connected between CB2a and CB3a. Line 1 has two feeding paths – Busbar A and CB1a (Fig. 3); Busbar B, CB2a and CB3a (Fig. 4). Line 2 has two feeding paths – Busbar B and CB3a (Fig. 5); Busbar A, CB1a and CB2a (Fig. 6). Busbars A and B are mere physical buses. They are energized by means of the transmission lines or transformers connected between the breakers. The role of busbars is to merely distribute the current between the bays.

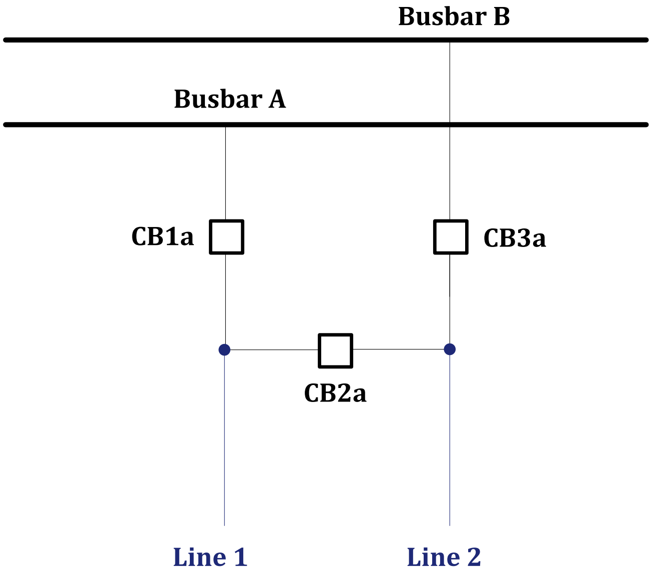


Fig. 2. Alternative representation of breaker-and-a half substation configuration

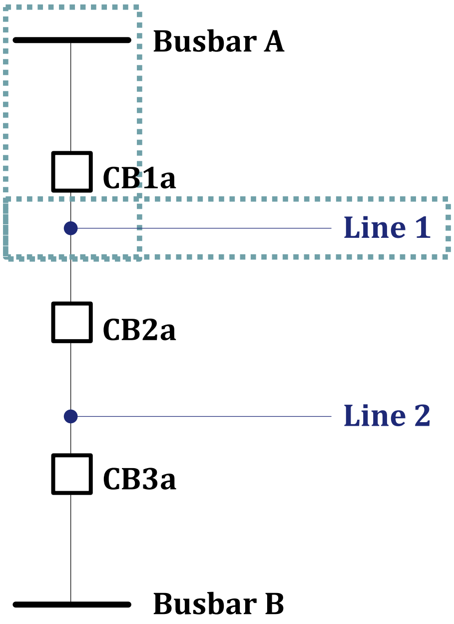


Fig. 3. Feeding path for Line 1: Busbar A and CB1a

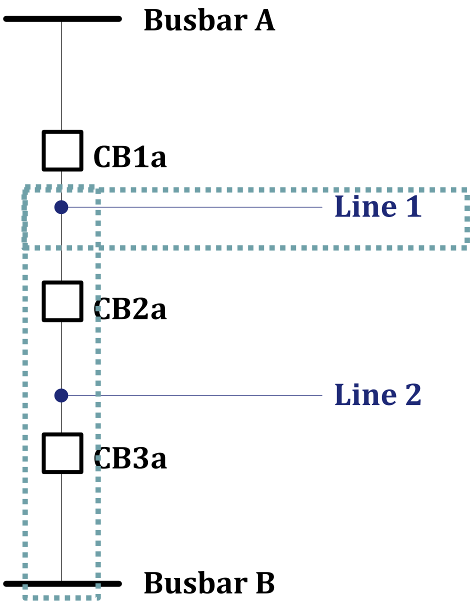


Fig. 4. Alternative feeding path for Line 1: Busbar B, CB2a and CB3a

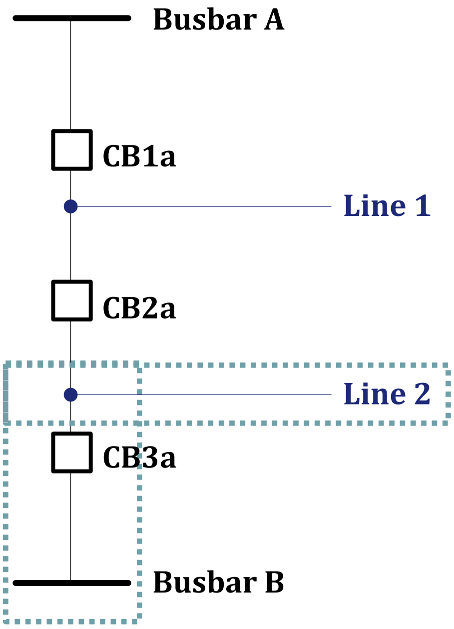


Fig. 5. Feeding path for Line 2: Busbar B and CB3a

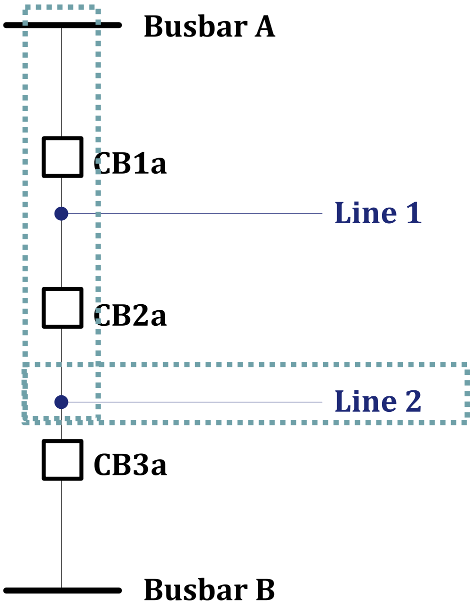


Fig. 6. Alternative feeding path for Line 2: Busbar A, CB1a and CB2a

The two different feeding paths for Line 1 in an H-depiction of the breaker-and-a-half substation configuration are as shown in Fig. 7.

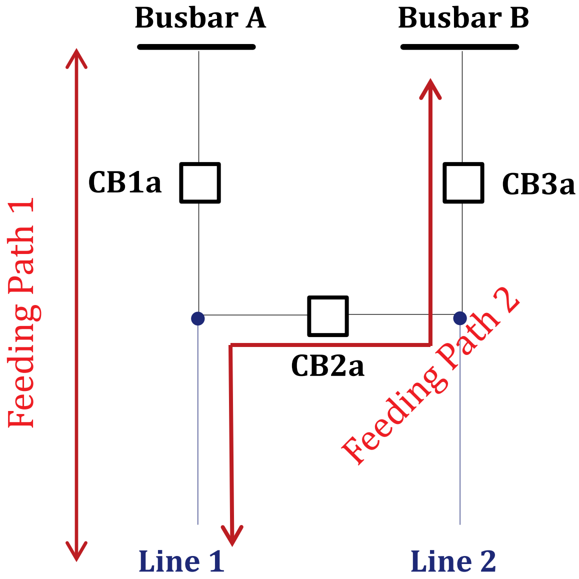


Fig. 7. Feeding paths for Line 1 in a H-depiction

For interrupting only line 1, the circuit breakers that need to be tripped are CB1a and CB2a, e.g., for a fault on line 1 both CB1a and CB2a must trip. This is shown in Fig. 8.

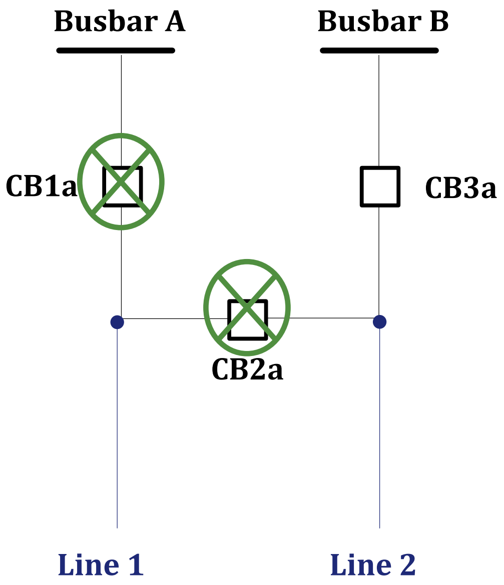


Fig. 8. CB trips required for interrupting Line 1

For interrupting only line 2, the circuit breakers that need to be tripped are CB2a and CB3a, as shown in Fig. 9.

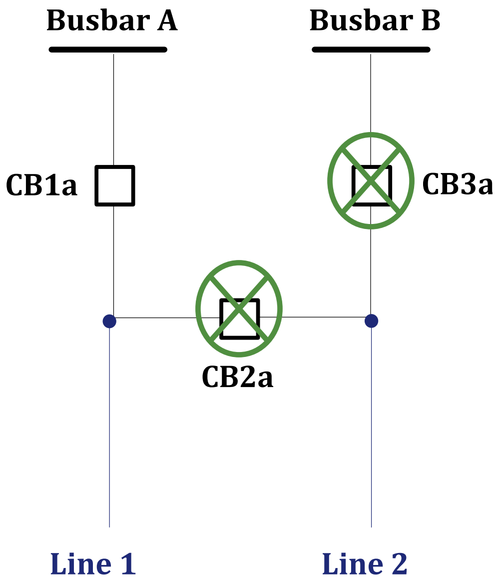


Fig. 9. CB trips required for interrupting Line 2

CB1a is referred to as the main breaker of line 1; CB2a as the tie-breaker; CB3a as the main breaker of line 2. Thus, for any problem on line 'i', the tie-breaker must trip along with the corresponding main breaker of line 'i'. A line and its main breaker and isolators together constitute a 'circuit'. Thus, there are two circuits in Fig. 1(a). If a breaker adjacent to one of the busbars (i.e., a main breaker) fails, then the tripping of tie-breaker does not interrupt power supply to the circuit associated with the healthy breaker (i.e., the breaker adjacent to the other busbar). Only the circuit associated with failed breaker is interrupted.

In a simple busbar configuration, one breaker is sufficient for controlling one feeder. However in this case, 3 breakers are required for controlling two feeders, and hence the name 3/2 or 1½ breaker arrangement. In a breaker-and-a-half arrangement, any circuit breaker can be removed for maintenance without affecting the service of the associated line; eg., if CB1a is to be removed for maintenance, line 1 would still be in service through the feeding path 'Busbar B - CB2a - CB3a'. A fault on either of Busbars A and B can be isolated without interrupting service to lines 1 and 2. This arrangement has a more complicated relaying as the tie-breaker has to act on faults on any of the two circuits it is associated with. If a breaker fails to trip upon a fault, a next 'layer' of breakers is designed to trip to isolate the faulted line.

3.1 Basic Response Scenarios at Substation for Fault on a Line

There are several scenarios that can emerge upon the occurrence of a fault on a line. Ideally speaking, both main breaker of line 1 – CB1a and the tie-breaker – CB2a are required to trip for a fault on line 1. Three protection system response scenarios arise:

(1) Both CB1a and CB2a trip: The faulted line 1 is disconnected from both Busbars A and B. The healthy line 2 remains unaffected. This is shown in Fig. 10.

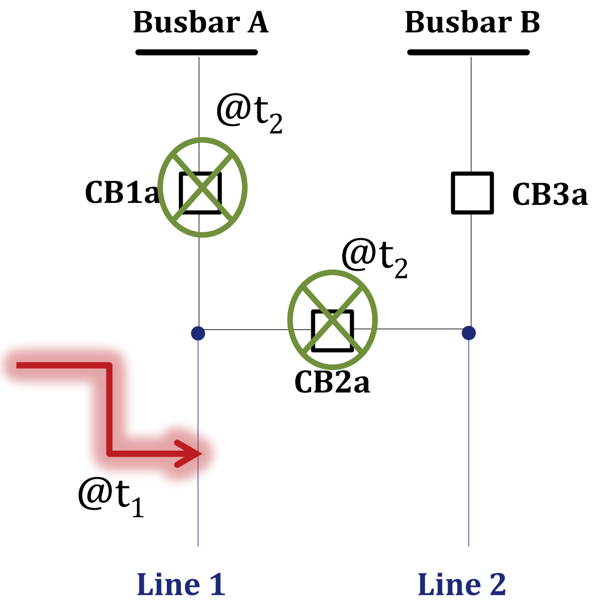


Fig. 10. Response scenario 1 for fault on Line 1

(2) Only the main breaker CB1a trips but the tie-breaker CB2a fails to trip: The consequence will be a loss (disconnections from the busbar) of two lines – both the faulted line 1 as well as the healthy line 2: the main breaker of the healthy line 2 – CB3a, is within the protection zone of backup relaying for circuit 1, and hence it trips to disconnect the connection of faulted line 1 from Busbar B through the closed CB2a. CB1a has already tripped and thus the faulted line 1 and Busbar A are isolated. This is shown in Fig. 11.

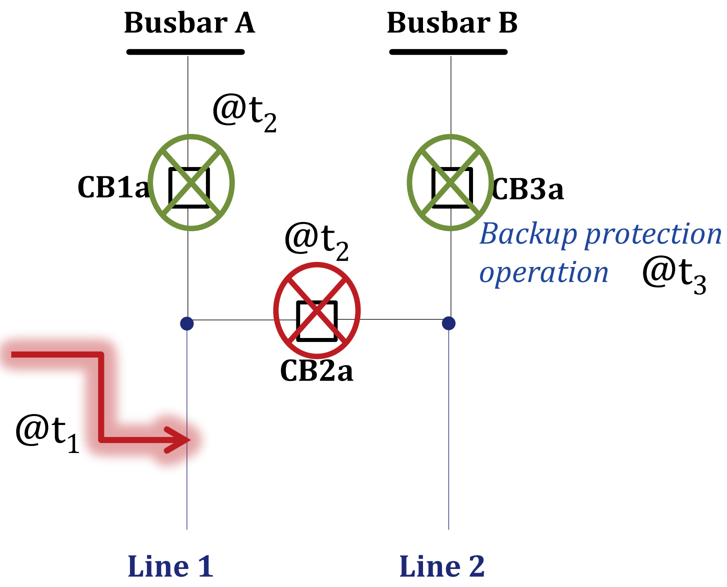


Fig. 11. Response scenario 2 for fault on Line 1

(3) Only the tie-breaker CB2a trips but the main breaker CB1a fails to trip: The faulted line 1 is isolated from having any impact on circuit 2. This is shown in Fig. 12.

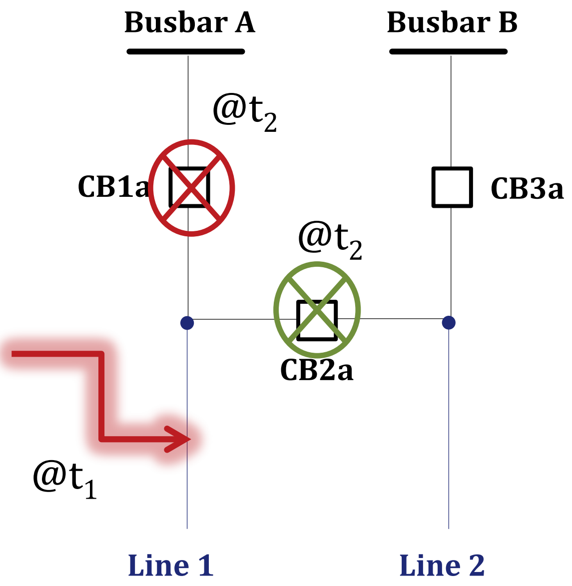


Fig. 12. Response scenario 3 for fault on Line 1

If there are other feeding circuits (e.g., generators/transmission lines) connected to Busbar A, further switching action would follow because of the backup protection settings to disconnect Busbar A from from the faulted line. A breaker-and-a-half substation configuration with two branches/diameters is shown in Fig. 13, which has two branches/diameters as opposed to the one branch shown in Fig. 1.

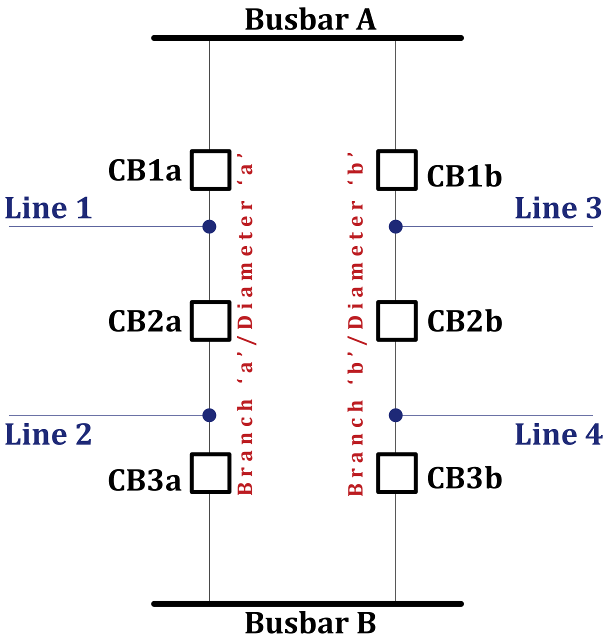


Fig. 13. Breaker-and-a-half substation configuration with two branches/diameters

For a fault on line 1, when the tie-breaker of branch 'a', CB2a, successfully trips but the main breaker of line 1, CB1a, fails to trip, CB1b – the neighbouring layer of breaker in the protection zone of line 1, from the adjacent branch 'b' – trips. This isolates Busbar A from all the remaining healthy circuits. However, the tripping of CB1b does not affect line 3, since for line 3 to be isolated, both CB1b and CB2b must be tripped. This situation is depicted in Fig. 14.

In the case of a breaker-and-a-half configuration with two branches/diameters, different permutations of the four line connections are possible. Strategic placement of these lines governs which lines get disconnected as a result of failure-to-operate state of a protection system unit and the subsequent events due to the backup protection coordination. In general, two lines sharing the circuit breakers in a branch/diameter are usually arranged such that one is connected to a source and the other to a load [19]; this source-load combination minimizes the flow of current on the busbars and the switches.

The information on the breaker-and-a-half substation configuration presented thus far is helpful in understanding the functional aspects of the architecture. This enables performing the analysis of 'backup coordination related interaction scenarios' from the first principles, to be explained subsequently.

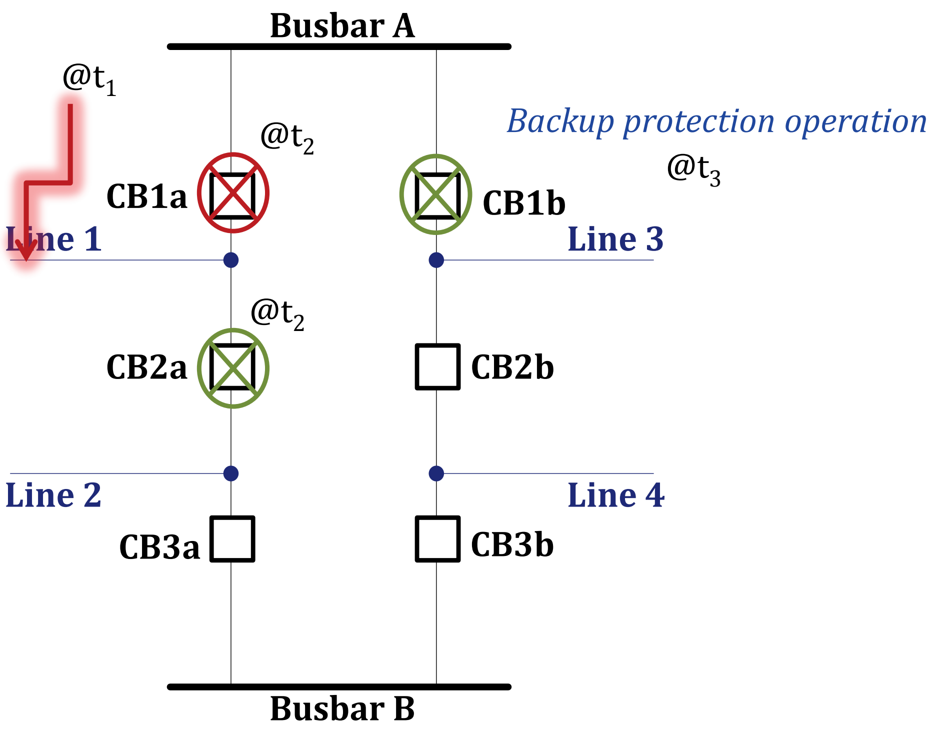


Fig. 14. Response scenario 3 for fault on Line 1 for the architecture with 2 branches/diameters

4 Proposed Methodology

4.1 Equivalent Failure Rate of a Transmission line

The various response scenarios of transmission protection systems are translated to corresponding equivalent failure modes of transmission lines by the definition and quantification of fault types (FTs) as initially proposed in [15]-[16]. A brief generic recapitulation of such fault types is presented below.

Fault Type 1 (FT1): A fault occurs on the transmission line i, upon which there could be two consequent scenarios: Consequent Scenario 1 (CS1) - The fault is successfully cleared by the line's primary protection system; Consequent Scenario 2 (CS2) - The fault could not be cleared because of the unreadiness of the line's primary protection system. The failure rate of FT1 is merely the failure rate of the transmission line.

Fault Type 2 (FT2): The transmission line i is fault-free, but because of faulty operation of the line's primary protection system, unwanted spontaneous tripping of the circuit breaker(s) occurs. This results in isolation of the healthy line i. The failure rate of FT2 is the summation of unwanted spontaneous tripping rates of circuit breakers of line i.

Fault Type 3 (FT3): A fault occurs on one of the neighbouring transmission lines, but the faulty operation of the primary protection system of the neighbouring line results in the missing operation of a circuit breaker, because of which the faulted neighbouring line cannot be isolated by its own circuit breakers. In such a case, the protection system of line i acts as back-up to isolate the faulted neighbouring line. This also results in isolation of the healthy line i.

Fault Type 4 (FT4): A fault occurs on one of the neighbouring transmission lines, upon which the neighbouring line's primary protection system clears the fault correctly. However, because of faulty operation of either of the protection system units of line i or both protection system units of line i, unwanted non-selective tripping of line i's circuit breaker(s) occurs. This results in healthy line i's isolation.

4.2 Types of Minimal Cutsets: Variable Failure Rates

Neighbouring lines are defined as transmission lines connected to a common bus (substation). By the same convention, parallel lines between bus pairs fall in this category. For a finer distinction in the convention, there can be a further classification of neighbouring lines as parallel neighbouring lines and non-parallel neighbouring lines. For an MC with only non-neighbouring transmission lines, the equivalent failure rate of each line in it is obtained by computing failure rates of FT1, FT2, FT3 and FT4 and summing them up.

The equivalent failure rate of a transmission line is 'variable' (not to be confused with time-dependent failure rate), depending upon the composition of the MC which it is a part of. This composition governs the way in which FT3 and FT4 are to be calculated for each of the elements. A line x when part of an MC 1 can have a different equivalent failure rate than when it is a part of MC 2. It must be noted that CS1 of FT1 on line i 'may' result in FT4 on neighbouring line j, and vice-versa. CS2 of FT1 on line i 'will' result in FT3 on neighbouring line j, and vice-versa. If neighbouring lines i and j are constituents of an MC, any of these four scenarios will result in the failure of the whole cutset. Thus, the failure rate contributions from these four scenarios form the dependency failure rate of the MC, and these contributions are duly removed from the corresponding individual equivalent failure rates of the lines.

For each line belonging to an MC, a combinatorial analysis of all possible backup coordination related interaction scenarios among its neighbouring lines is carried out (sample calculations are shown in the illustrative case study section). For each of these interaction scenarios, a failure rate contribution expression is formulated from the first principles with respect to fault types FT3 and FT4 [15]-[16]. This is relatively straight forward for elements of MCs with constituent non-neighbouring lines. However, in the case of MCs with constituent neighbouring parallel lines or neighbouring non-parallel lines or a combination thereof, a subset of these interaction scenarios, which pertains to dependency failure among all the MC constituents are set aside. Such failure rate contributions are not included in the individual failure rate expressions of FT3 and FT4 of the elements in the MCs, but utilized only in the expressions for dependency mode failure rates of the MCs.

4.3 Test Networks

MOPAL [16] is a modified four-bus multi-circuit meshed OPAL test network [15] with two generators, two delivery points and six transmission lines, as shown for recapitulation in Fig. 15. The figure shows a simple bus configuration. The transmission network operates at 132 kV. The capacity of transmission lines is as follows: lines 1 & 4 - 135 MW; lines 2, 3, 5 & 6 – 67.5 MW (i.e. 135/2 MW). The two generators are assumed to be 100% reliable. Delivery point 1, LP1, has industry customers; delivery point 2, LP2 has energy-intensive industry customers. For the simplicity of illustration, one operating state (OS1), a heavy load condition is assumed to prevail throughout the duration of a year at the delivery points. In OS1, delivery point LP1 is assumed to have a constant load demand of 100 MW, and delivery point LP2 a constant demand of 75 MW. By assigning probability weightages, the effect of multiple operating states can be easily captured. All the protection system units have the same repair time of 2 h. The missing and unwanted non-selective probabilities of all the protection system units are assumed to be 0.0205 and 0.007, respectively. Failure rate of unwanted spontaneous tripping of the circuit breakers of all protection system units is 0.025 f/yr. A switching time of 0.5 hours is assumed. In Fig. 15, each of the two ends of a line i, say A-end and B-end, has a protection system unit, PT. The subscript A or B refers to the end at which the unit is located.

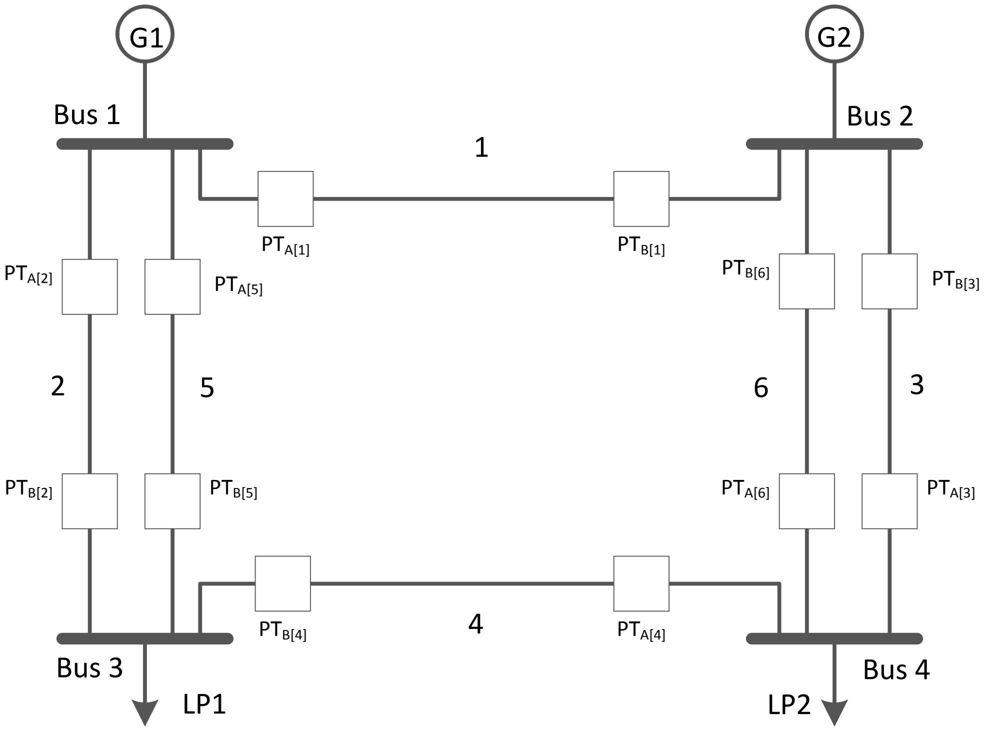


Fig. 15. MOPAL test network with a simple bus configuration

The single line diagram with breaker-and-a-half substation configuration for the MOPAL network is shown in Fig. 16.

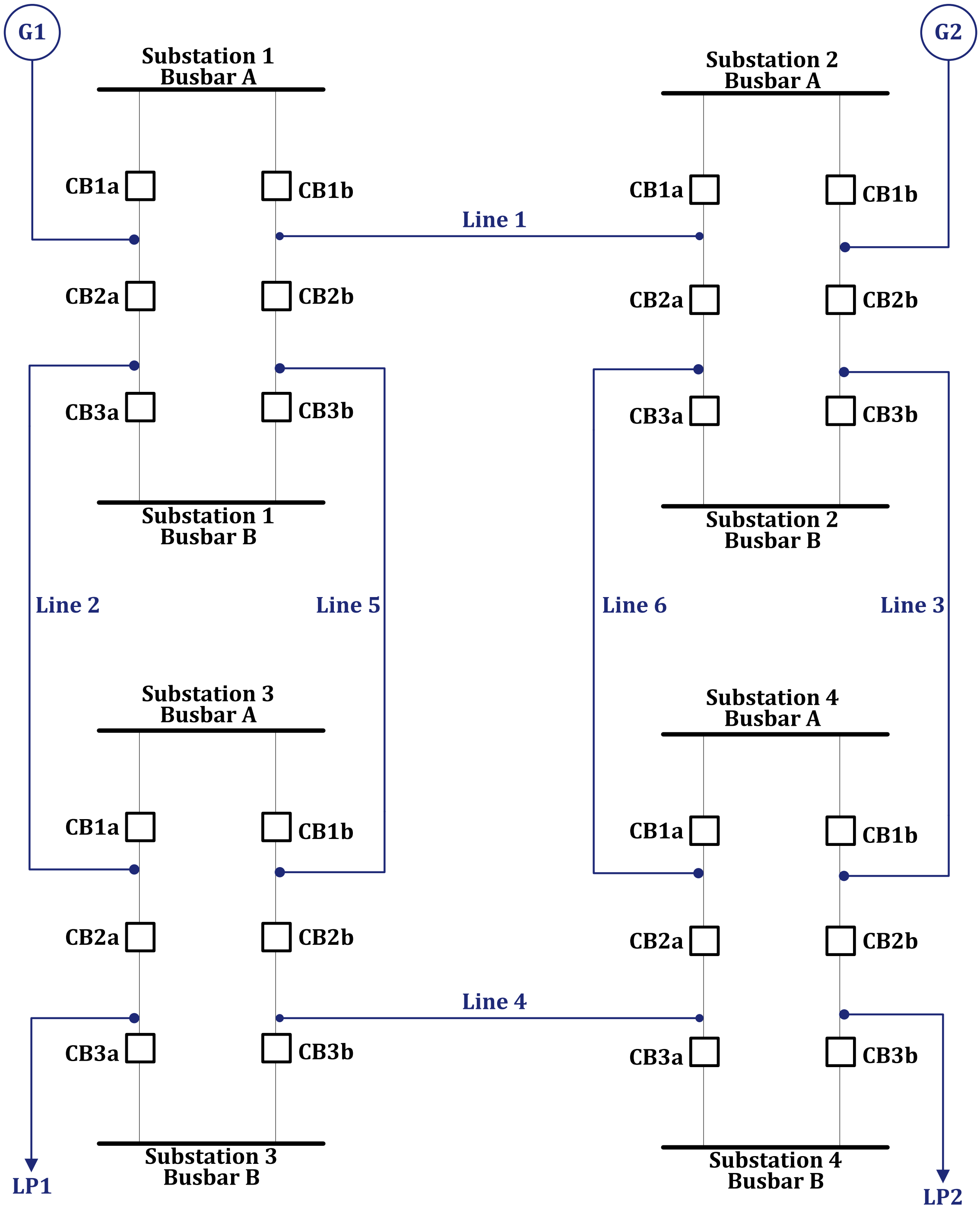


Fig. 16. MOPAL test network with breaker-and-a-half substation configuration

In OPAL and MOPAL networks with simple bus configuration, the assumption of distance protection was made. At substations, differential protection is invariably used. (Refer to Appendix B.)

4.4 Illustrative Procedure

Apropos protection system failure propagation, consider the MOPAL network with simple bus configuration as shown in Fig. 15. If Line 5 is considered to be the focus line, all its neighbouring lines (i.e., lines 1, 2 and 4) will contribute to FT3 and FT4 on it. However each of these neighbouring lines may or may not contribute to FT3 and FT4 when substation configuration is taken into account. This needs to be found out through a combinatorial analysis. A sample explanation of the combinatorial analysis of all possible backup coordination related interaction scenarios among a line's neighbouring lines at the elemental level when substation configuration is taken into account, is initially explained for Line 5 of Fig. 16. For each of these interaction scenarios, a failure rate contribution expression is formulated from the first principles with respect to fault types FT3 and FT4 [15]-[16] (combinatorial analysis is not needed for obtaining the failure rate contribution expressions for FT1 and FT2, as will be seen in the subsequent explanation). There are each of as many FT3 and FT4 potential scenarios as are the number of neighbouring lines for a focus line.

Elemental Analysis – Equivalent failure rate of transmission line 5 on account of the various possible transmission protection scenarios:

FT1:

The failure rate of FT1 of line 5 is merely the failure rate of line 5.

$$\lambda_{FT1(5)} = \lambda_5 \qquad (1)$$

FT2:

There is no fault on line 5, but there is a possibility of unwanted spontaneous tripping of any of the main and tie breakers of line 5 at Substations 1 and 3, one at a time. However, a line is not disconnected from the network at a substation unless both its main and tie breakers trip at the same time. Thus, in the breaker and a half substation configuration, there is no FT2.

$$\lambda_{FT2(5)} = 0 \qquad (2)$$

FT3:

Situations resulting in FT3 on line 5 from the neighbouring lines:

Lines 1 and 4 are non-parallel neighbouring lines of Line 5; Line 2 is a parallel neighbouring line connected between substations 1 and 3.

<u>Scenario 1 – Fault on line 1 and subsequent response of primary protection system of line 1 at Substation 1:</u>

The two response scenarios of primary protection system of line 1 of interest are – (i) failure of main breaker CB1b of line 1 at Substation 1 (SS1), (ii) failure of tie-breaker CB2b of line 1 at SS1.

- ***Scenario 1(i) – What happens when CB1b fails but CB2b works?***
  Failure of the main breaker (i.e., by failure of a breaker is meant the missing operation of protection system associated with the breaker) does not interrupt the continuity of

service from G1. The designed backup for the main breaker of line 1 at SS1 is CB1a, the main breaker of connection from generator G1. Thus, when CB1a opens as a result of missing operation of CB1b, it has no adverse impact on the remaining healthy elements at SS1. Thus, Scenario 1(i) does not contribute to the failure of line 5.

- ***Scenario 1(ii) – What happens when CB2b fails but CB1b works?***
  Failure of line 1's tie-breaker CB2b causes its designed backup CB3b to open, which results in the isolation of line 5 from SS1. Thus, Scenario 1(ii) does contribute to the failure of line 5.

Thus, *the situation resulting in FT3 on line 5 from the neighbouring line 1 can be summarized as 'fault on line 1 (quantified as* λ_1*) and failure of tie-breaker CB2b at SS1 (quantified as the breaker's missing probability* $P_{M[CB2b@SS1]}$*)'.*

(Note: This nomenclature will be used in the subsequent expressions involving missing probability of a given circuit breaker at a given substation: $P_{M[CBXX@SSY]}$ where XX = 1a/1b/2a/2b/3a/3b; Y = 1/2/3/4.)

Thus, the failure rate contribution from FT3 Scenario 1 of line 5 is:

$$\lambda_1 * P_{M[CB2b@SS1]} \tag{3}$$

Scenario 2 – Fault on line 4 and subsequent response of primary protection system of line 4 at Substation 3:

The two response scenarios of primary protection system of line 4 of interest are - (i) failure of main breaker CB3b of line 4 at Substation 3 (SS3), (ii) failure of tie-breaker CB2b of line 4 at SS3.

- ***Scenario 2(i) – What happens when CB3b fails but CB2b works?***
  Failure of main breaker CB3b will cause its designed backup CB3a to open, but this does not interrupt the continuity of service to load point 1, LP1. Thus, Scenario 2(i) does not contribute to the failure of line 5.
- ***Scenario 2(ii) – What happens when CB2b fails but CB3b works?***
  However, failure of the tie-breaker CB2b results in its designed backup CB1b to open, which will isolate line 5 from SS3. Thus, Scenario 2(ii) does contribute to the failure of line 5.

Thus, *the situation resulting in FT3 on line 5 from the neighbouring line 4 can be summarized as 'fault on line 4 and failure of tie-breaker CB2b at SS3'.*

Thus, the failure rate contribution from FT3 Scenario 2 of line 5 is:

$$\lambda_4 * P_{M[CB2b@SS3]} \tag{4}$$

Scenario 3 – Fault on line 2 and subsequent response of primary protection system of line 2 at Substations 1 and 3:

Scenario 3(a) – Fault on line 2 and subsequent response of primary protection system of line 2 at Substation 1:

For a fault on line 2, both CB2a and CB3a at Substation 1 must open to isolate the faulted line from SS1.

- **Scenario 3(a)(i) – *What happens when CB2a fails but CB3a works?***
  If only CB2a fails but CB3a works, then CB2a's designed backup, CB1a, will open, as a result of which generator G1 is disconnected from SS1 in addition to the disconnection of the faulted line 2 from SS1. The isolation of G1 could be thought of as a dependent failure. But line 5 is very much in the network. Thus, Scenario 3(a)(i) indirectly contributes to the failure of line 5.

- **Scenario 3(a)(ii) – *What happens when CB3a fails but CB2a works?***
  If only CB3a fails but CB2a works, then CB3a's designed backup, CB3b, will open, as a result of which only line 2 is disconnected from SS1. This situation has no impact on line 5. This could be thought of as an inbuilt safeguard against the propagation of failure to the neighbouring parallel line. Even though the primary protection system of line 2 at SS1 has failed to safely remove the faulted line 2 from the network, calling for backup action from the primary protection system of the neighbouring line 5 does not affect line 5 on account of the redundancy of paths provided by this station configuration. Thus, Scenario 3(a)(ii) does not contribute to the failure of line 5.

Scenario 3(b) – Fault on line 2 and subsequent response of primary protection system of line 2 at Substation 3:

For a fault on line 2, CB1a and CB2a at Substation 3 must open to isolate the faulted line from SS3.

- **Scenario 3(b)(i) – *What happens when CB2a fails but CB1a works?***
  If only CB2a fails but CB1a works, then CB2a's designed backup, CB3a, will open, as a result of which load point 1, LP1, is disconnected from SS3 in addition to the disconnection of the faulted line 2. The isolation of LP1 could be thought of as a dependent failure. But line 5 is very much in the network. Thus, Scenario 3(b)(i) indirectly contributes to the failure of line 5.

- **Scenario 3(b)(ii) – *What happens when CB1a fails but CB2a works?***
  If only CB1a fails but CB2a works, then CB1a's designed backup, CB1b, will open, disconnecting only the faulted line 2 from the network. But line 5 is very much in the network. Thus, Scenario 3(b)(ii) does not contribute to the failure of line 5.

Thus, *the situations resulting in FT3 on line 5 from the neighbouring line 2 can be summarized as 'fault on line 2 and failure of tie-breaker CB2a at SS1' (i.e.,* Scenario 3(a)(i)*) or 'fault on line 2 and failure of tie-breaker CB2a at SS3'(i.e.,* Scenario 3(b)(i)*).*

Failure rate contribution from FT3 Scenario 3(a)(i) of line 5 is:

$$\lambda_2 * P_{M[CB2a@SS1]} \tag{5}$$

Failure rate contribution from FT3 Scenario 3(b)(i) of line 5 is:

$$\lambda_2 * P_{M[CB2a@SS3]} \tag{6}$$

Thus, the overall failure rate contribution from FT3 Scenario 3 of line 5 is:

$$\lambda_{FT3(5)} = \lambda_2 * P_{M[CB2a@SS1]} + \lambda_2 * P_{M[CB2a@SS3]} \tag{7}$$

FT4:

Situations resulting in FT4 on line 5 from the neighbouring lines:

Unwanted non-selective operation is assumed to be limited to the next layer of breakers designed to trip to isolate a line had a fault taken place on the line.

Scenario 1 – Fault on line 1 and subsequent protection system response at Substation 1:

A fault occurs on line 1 and its primary protection system at Substation 1 acts correctly to isolate the faulted line 1 from SS1. The main breaker of line 1 at SS1, CB1b, and the tie-breaker of line 1 at SS1, CB2b, trip to isolate the faulted line 1 from SS1.

- Either CB1a, the designed backup for CB1b, or CB3b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1a has no impact on the incoming line from generator G1. However, the unwanted non-selective operation of CB3b will isolate line 5 from SS1.

Thus, the situation resulting in FT4 on line 5 from the neighbouring line 1 can be summarized as 'fault on line 1, AND correct operation of CB1b and CB2b at SS1, but unwanted non-selective operation of CB3b at SS1'.

For instance, correct operation of CB1b at SS1 is denoted as $P_{C[CB1b@SS1]}$. Its value is the probability of missing operation of CB1b at SS1 subtracted from 1. The probability of unwanted non-selective operation of CB3b at SS1 is denoted as $P_{U-Ns[CB3b@SS1]}$.

(Note: The following nomenclature will be used subsequently. For expressions involving correct operation of a given circuit breaker at a given substation: $P_{C[CBXX@SSY]}$ where XX = 1a/1b/2a/2b/3a/3b; Y = 1/2/3/4; For expressions involving unwanted non-selective operation of a given circuit breaker at a given substation: $P_{U-Ns[CBXX@SSY]}$ where XX = 1a/1b/2a/2b/3a/3b; Y = 1/2/3/4.)

Thus, failure rate contribution from FT4 Scenario 1 of line 5 is:

$$\lambda_1 * [P_{C[CB1b@SS1]} * P_{C[CB2a@SS1]}] * P_{U-Ns[CB3b@SS1]} \tag{8}$$

Scenario 2 – Fault line 4 and subsequent protection system response at Substation 3:

A fault occurs on line 4 and its primary protection system at Substation 3 acts correctly to isolate the faulted line 4 from SS3. The main breaker of line 4 at SS3, CB3b, and the tie-breaker of line 4 at SS3, CB2b, trip to isolate the faulted line 4 from SS3.

- Either CB3a, the designed backup for CB3b, or CB1b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3a has no impact on the outgoing connection to LP1. However, the unwanted non-selective operation of CB1b will isolate line 5 from SS3.

Thus, *the situation resulting in FT4 on line 5 from the neighbouring line 4 can be summarized as 'fault on line 4, AND correct operation of CB3b and CB2b at SS3, but unwanted non-selective operation of CB1b at SS3'.*

Thus, the failure rate contribution from FT4 Scenario 2 of line 5 is:

$$\lambda_4 * [P_{C[CB3b@SS3]} * P_{C[CB2b@SS3]}] * P_{U-Ns[CB1b@SS3]} \qquad (9)$$

Scenario 3 – Fault on line 2 and subsequent protection system response at Substations 1 and 3:

Scenario 3(a) – At Substation 1, the primary protection system acts correctly to isolate faulted line 2 from SS1. The main breaker of line 2 at SS1, CB3a, and the tie-breaker of line 2 at SS1, CB2a, trip to isolate the faulted line 2 from SS1.

- Either CB3b, the designed backup for CB3a, or CB1a, the designed backup for CB2a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3b has no impact on line 5. However, the unwanted non-selective operation of CB1a will isolate generator G1 from SS1. This could be thought of as a dependent failure.

Thus, the situation resulting in FT4 on line 5 from the neighbouring line 2 at Substation 1 can be summarized as *'fault on line 2, AND correct operation of CB3a and CB2a at SS1, but unwanted non-selective operation of CB1a at SS1'.*

Thus, the failure rate contribution from FT4 Scenario 3(a) of line 5 is:

$$\lambda_2 * [P_{C[CB3a@SS1]} * P_{C[CB2a@SS1]}] * P_{U-Ns[CB1a@SS1]} \qquad (10)$$

Scenario 3(b) – At Substation 3, the primary protection system acts correctly to isolate faulted line 2 from SS3. The main breaker of line 2 at SS3, CB1a, and the tie-breaker of line 2 at SS3, CB2a, trip to isolate the faulted line 2 from SS3.

- Either CB3a, the designed backup for CB2a, or CB1b, the designed backup for CB1a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1b has no impact on line 5. However, the unwanted non-selective operation of CB3a will isolate load point LP1 from SS3. This could be thought of as a dependent failure.

Thus, the situation resulting in FT4 on line 5 from the neighbouring line 2 at Substation 3 can be summarized as *'fault on line 2, AND correct operation of CB1a and CB2a at SS3, but unwanted non-selective operation of CB3a at SS3'*.

Thus, the failure rate contribution from FT4 Scenario 3(b) of line 5 is:

$$\lambda_2 * [P_{C[CB1a@SS3]} * P_{C[CB2a@SS3]}] * P_{U-Ns[CB3a@SS3]} \tag{11}$$

In effect, the situations resulting in FT4 on line 5 from the neighbouring line 2 can be summarized as 'fault on line 2, correct operation of CB3a and CB2a at SS1, but unwanted non-selective operation of CB1a at SS1' or 'fault on line 2, correct operation of CB1a and CB2a at SS3, but unwanted non-selective operation of CB3a at SS3'.

Thus, the overall failure rate contribution from FT4 Scenario 3 of line 5 is:

$$\begin{aligned}&\left(\lambda_2 * [P_{C[CB3a@SS1]} * P_{C[CB2a@SS1]}] * P_{U-Ns[CB1a@SS1]}\right) + \\ &\qquad \left(\lambda_2 * [P_{C[CB1a@SS3]} * P_{C[CB2a@SS3]}] * P_{U-Ns[CB3a@SS3]}\right)\end{aligned} \tag{12}$$

The equivalent failure rate of a line on account of its failure due to various protection system response scenarios is given as the summation of the failure rates of the identified failure types.

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)} \tag{13}$$

For the focus line 5,

$$\lambda_{Eq.(5)} = \lambda_{FT1(5)} + \lambda_{FT2(5)} + \lambda_{FT3(5)} + \lambda_{FT4(5)} \tag{14}$$

The equivalent failure rates of all the remaining transmission lines are obtained on similar lines the descriptive combinatorial analysis for which is provided in Appendix A. The concept of variable failure rates of minimal cutsets as explained in Section 4.2 is then utilized accordingly in the reliability computations.

4.4.1 Summary of Scenario Analysis for FT3 and FT4 analysis

- Conduct a Scenario Analysis of backup protection coordination related interaction scenarios to identify situations resulting in FT3 on a given focus line from the neighbouring lines.
- For a focus line, there are as many potential FT3 Scenarios as are the number of its neighbouring lines. To be more precise, each non-parallel neighbouring line contributes to one scenario. Each parallel neighbouring line contributes to two scenarios (one for each substation between which it is connected) whose cumulative effect is considered as one scenario.
- Each FT3 Scenario may or may not result in 'failure contribution' depending upon the network/substation topology. Scenario analysis reveals this result. A thorough knowledge of the functional aspects of protection system backup coordination effects for the breaker-and-a-half substation architecture is essential to achieve this.
- The same procedure is repeated to identify situations resulting in FT4 on a given focus line.
- For the case of focus line 5, Table 2 provides a sample overview of the failure rate contributions.

Table 2. FT3 Failure rate contribution scenarios for focus line 5

Neighbouring Line	FT3 Scenario	Failure Contribution
Line 1 (non-parallel)	Scenario 1	Expression 1
Line 4 (non-parallel)	Scenario 2	Expression 2
Line 2 (parallel)	*Scenario 3 (a)*	*Expression 3 (a)*
	Scenario 3 (b)	*Expression 3 (b)*
	Net Scenario 3	Expression 3 = Expression 3 (a) + Expression 3 (b)
$\lambda_{FT3(i)} = Expression\ 1\ +\ Expression\ 2\ +\ Expression\ 3$		

5 Results

Minimal cutsets of up to third order for both load points of the MOPAL network, as obtained from a contingency analysis phase, for an operating state OS1, are shown in Table 3. Tables 4 to 7 provide an overview of the comparative analysis of the proposed approach of including the unreliability impact of protection and control (P&C) in the reliability assessment including the breaker-and-a-half substation configuration against the benchmark cases of perfect P&C and P&C modelled simplified bus configuration. The typical reliability indices of interest are - λ , U, and r. Subsequently, the annual power interrupted (PI) and annual energy not supplied (ENS) have been computed. It is clearly seen that simplified busbar configurations yield pessimistic results. A realistic reliability appraisal is possible only when the substation configuration is taken into account for identifying the impact of protection system reliability on power system reliability, as seen from the relative percentage changes.

Table 3. Minimal cutsets for MOPAL network

OS1 LP1	**OS1 LP2**
{4, 5}, {2, 4}, {3, 5, 6}, {2, 5, 6}, {2, 3, 6}, {2, 3, 5}	{5, 6}, {4, 6}, {3, 6}, {3, 5}, {3, 4}, {2, 6}, {2, 5}, {2, 3}

Table 4. Basic reliability indices – comparative analysis for OS1LP2

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**
Perfect P&C	0.323	6.28	2.028
P&C Modelled w/o SS	1.733	1.58	2.739
P&C Modelled with SS	1.073	2.40	2.234

Table 5. Basic reliability indices – comparative analysis for OS1LP1

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**
Perfect P&C	0.087	5.98	0.519
P&C Modelled w/o SS	1.014	0.97	0.984
P&C Modelled with SS	0.395	1.70	0.673

Table 6. Additional reliability indices – comparative analysis for LP1

Method	**PI (MW/yr)**	**ENS (MWh/yr)**
Perfect P&C	2.82	16.86
P&C Modelled w/o SS	32.97	31.98
P&C Modelled with SS	12.83	21.86

Table 7. Additional reliability indices – comparative analysis for LP2

Method	**PI (MW/yr)**	**ENS (MWh/yr)**
Perfect P&C	9.66	63.33
P&C Modelled w/o SS	45.69	81.52
P&C Modelled with SS	27.99	72.49

As expected, the results confirm the generally accepted superior reliability standard [17] of the breaker-and-a-half substation architecture. The assumption of what constitutes a dependent failure in the scenario analyses, e.g., isolation of a load point or a generator from a substation as a consequence of the various possible switching actions in the protection system operation upon the occurrence of a line fault, has a bearing on the values of the reliability parameters.

The proposed methodology is yet to be tested on an actual system. It is however anticipated that the complexity of algorithm should not be an issue for actual systems given as how scenario analysis-related failure rate expressions are simple non-linear equations requiring direct substitutions. The usage of approximate methods for handling the MC-based reliability calculations greatly simplifies the computational burden. The procedure can be easily extended to substations with different busbar configurations, requiring only the FT3 and FT4 failure contribution expressions to be modified, from the first principles, based on the corresponding architecture.

Through the systematic MC-based approach as presented in this paper, the need for Markov models is bypassed, thus eliminating the issue of state space explosion. Future work involves a detailed sensitivity analysis of input data parameters.

6 Conclusions and Future Work

As evidenced by the comparative assessment of the results, comprehensive evaluation of the impact of dependent failures of lines caused by various transmission protection system events cannot be carried out if terminal stations are modelled as simplified single busbars. Due consideration must be given to the internal configuration of substations. Towards this end, a scenario analysis based methodology has been put forward in the paper to model the transmission line failure modes on account of the various protection system response scenarios, which are a function of the substation configuration. The reliability model is based on the minimal cutsets of transmission lines obtained from the information on critical contingencies leading to potential interruptions or reduced supply at various delivery points in the power system. It must be reminded that this memo is not about the typical reliability analysis of station originated events of substations, where forced outages of generators and lines because of random failure events in the substation are analysed. As it is, there is a significant effect of reliability of protection systems on the reliability of supply, demonstrating the need for incorporating appropriate protection system reliability models in predictive power system reliability studies.

Future work involves a possible sensitivity analysis of input data parameters, and refining of some of the assumptions concerning the constitution of dependent failures in scenario analyses. Multiple operating states can be analysed. **The most important further work is the probable implementation of the proposed approach by taking into account typical Nordic substation configurations.**

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Appendix A: Scenario Analysis for the Remaining Lines of MOPAL Network

A.1 Elemental Analysis – Equivalent failure rate of transmission line 6 on account of the various possible transmission protection scenarios:

FT1:

The failure rate of FT1 of line 6 is merely the failure rate of line 6.

FT2:

There is no fault on line 6, but there is a possibility of unwanted spontaneous tripping of any of the main and tie breakers of line 6 at Substations 2 and 4, one at a time. However, a line is not disconnected from the network at a substation unless both its main and tie breakers trip at the same time. Thus, in the breaker and a half substation configuration, there is no FT2.

FT3:

Situations resulting in FT3 on line 6 from the neighbouring lines:

(i) Fault on line 1 and subsequent response of primary protection system of line 1 at Substation 2:

- The two response scenarios of primary protection system of line 1 of interest are - failure of main breaker CB1a or tie-breaker CB2a of line 1 at Substation 2 (SS2). Failure of the main breaker (i.e., by failure of a breaker is meant the missing operation of protection system associated with the breaker) does not interrupt the continuity of service from G2. The designed backup for the main breaker of line 1 at SS2 is CB1b, the main breaker of connection from generator G2. Thus, when CB1b opens as a result of missing operation of CB1a, it has no adverse impact on the remaining healthy elements at SS3. Failure of line 1's tie-breaker CB2a causes its designed backup CB3a to open, which results in the isolation of line 6 from SS2. Thus, *the situation resulting in FT3 on line 6 from the neighbouring line 1 can be summarized as 'fault on line 1 and failure of tie-breaker CB2a at SS2'.*

(ii) Fault on line 4 and subsequent response of primary protection system of line 4 at Substation 4:

- The two response scenarios of primary protection system of line 4 of interest are - failure of main breaker CB3a or tie-breaker CB2a of line 4 at Substation 4 (SS4). Failure of main breaker CB3a will cause its designed backup CB3b to open, but this does not interrupt the continuity of service to load point 2, LP2. However, failure of the tie-breaker CB2a results in its designed backup CB1a to open, which will isolate line 6 from SS4. Thus, *the situation resulting in FT3 on line 6 from the neighbouring line 4 can be summarized as 'fault on line 4 and failure of tie-breaker CB2a at SS4'.*

(iii) Fault on line 3 and subsequent response of primary protection system of line 3 at Substations 2 and 4:

- For a fault on line 3, both CB2b and CB3b at Substation 2 must open to isolate the faulted line from SS2. If only CB2b fails but CB3b works, then CB2b's designed backup, CB1b, will open, as a result of which generator G2 is disconnected from SS2 in addition to the disconnection of the faulted line 3 from SS2. The isolation of G2 could be thought of as a dependent failure. But line 6 is very much in the network. If only CB3b fails but CB2b works, then CB3b's designed backup, CB3a, will open, as a result of which only line 3 is disconnected from SS2. This situation has no impact on line 6. This could be thought of as an inbuilt safeguard against the propagation of failure to the neighbouring parallel line. Even though the primary protection system of line 3 at SS2 has failed to safely remove the faulted line 3 from the network, calling for backup action from the primary protection system of the neighbouring line 6 does not affect line 6 on account of the redundancy of paths provided by this station configuration.
- For a fault on line 3, CB1b and CB2b at Substation 4 must open to isolate the faulted line from SS4. If only CB2b fails but CB1b works, then CB2b's designed backup, CB3b, will open, as a result of which load point 2, LP2, is disconnected from SS4 in addition to the disconnection of the faulted line 3. The isolation of LP2 could be thought of as a dependent failure. But line 6 is very much in the network. If only CB1b fails but CB2b works, then CB1b's designed backup, CB1a, will open, disconnecting only the faulted line 3 from the network. But line 6 is very much in the network.

Thus, *the situations resulting in FT3 on line 6 from the neighbouring line 3 can be summarized as 'fault on line 3 and failure of tie-breaker CB2b at SS2' or 'fault on line 3 and failure of tie-breaker CB2b at SS4'.*

FT4:

Situations resulting in FT4 on line 6 from the neighbouring lines:

Unwanted non-selective operation is assumed to be limited to the next layer of breakers designed to trip to isolate a line had a fault taken place on the line.

(i) Fault on line 1 and subsequent protection system response at Substation 2:

<u>When a fault occurs on line 1 and its primary protection system at Substation 2 acts correctly to isolate faulted line 1 from SS2:</u>

- The main breaker of line 1 at SS2, CB1a, and the tie-breaker of line 1 at SS2, CB2a, trip to isolate the faulted line 1 from SS2. Either CB1b, the designed backup for CB1a, or CB3a, the designed backup for CB2a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1b has no impact on the incoming line from generator G2. However, the unwanted non-selective operation of CB3a will isolate line 6 from SS2. *Thus, the situation resulting in FT4 on line 6 from the* *neighbouring line 1 can be summarized as 'fault on line 1, correct operation of CB1a and CB2a at SS2, but unwanted non-selective operation of CB3a at SS2'.*

(ii) Fault on line 4 and subsequent protection system response at Substation 4:

<u>When a fault occurs on line 4 and its primary protection system at Substation 4 acts correctly to isolate faulted line 4 from SS4:</u>

- The main breaker of line 4 at SS4, CB3a, and the tie-breaker of line 4 at SS4, CB2a, trip to isolate the faulted line 4 from SS4. Either CB3b, the designed backup for CB3a, or CB1a, the designed backup for CB2a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3b has no impact on the outgoing connection to LP2. However, the unwanted non-selective operation of CB1a will isolate line 6 from SS4. Thus, *the situation resulting in FT4 on line 6 from the neighbouring line 4 can be summarized as 'fault on line 4, correct operation of CB3a and CB2a at SS4, but unwanted non-selective operation of CB1a at SS4'.*

(iii) Fault on line 3 and subsequent protection system response at Substations 2 and 4:

<u>At Substation 2, the primary protection system acts correctly to isolate faulted line 3 from SS2:</u>

- The main breaker of line 3 at SS2, CB3b, and the tie-breaker of line 3 at SS2, CB2b, trip to isolate the faulted line 3 from SS2. Either CB3a, the designed backup for CB3b, or CB1b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3a has no impact on line 6. However, the unwanted non-selective operation of CB1b will isolate generator G2 from SS2. This could be thought of as a dependent failure. Thus, the situation resulting in FT4 on line 6 from the neighbouring line 3 at Substation 2 can be summarized as 'fault on line 3, correct operation of CB3b and CB2b at SS2, but unwanted non-selective operation of CB1b at SS2'.

<u>At Substation 4, the primary protection system acts correctly to isolate faulted line 3 from SS4:</u>

- The main breaker of line 3 at SS4, CB1b, and the tie-breaker of line 3 at SS4, CB2b, trip to isolate the faulted line 3 from SS4. Either CB3b, the designed backup for CB2b, or CB1a, the designed backup for CB1b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1a has no impact on line 6. However, the unwanted non-selective operation of CB3b will isolate load point LP2 from SS4. This could be thought of as a dependent failure. Thus, the situation resulting in FT4 on line 6 from the neighbouring line 3 at Substation 4 can be summarized as 'fault on line 3, correct operation of CB1b and CB2b at SS4, but unwanted non-selective operation of CB3b at SS4'.

In effect, the situations resulting in FT4 on line 6 from the neighbouring line 3 can be summarized 'fault on line 3, correct operation of CB3b and CB2b at SS2, but unwanted non-

selective operation of CB1b at SS2' or 'fault on line 3, correct operation of CB1b and CB2b at SS4, but unwanted non-selective operation of CB3b at SS4'.

The equivalent failure rate of a line on account of its failure due to various protection system response scenarios is given as the summation of the failure rates of the identified failure modes.

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}$$

For the focus line 6,

$$\lambda_{Eq.(6)} = \lambda_{FT1(6)} + \lambda_{FT2(6)} + \lambda_{FT3(6)} + \lambda_{FT4(6)}$$

A.2 Elemental Analysis – Equivalent failure rate of transmission line 3 on account of the various possible transmission protection scenarios:

FT1:

The failure rate of FT1 of line 3 is merely the failure rate of line 3.

FT2:

There is no fault on line 3, but there is a possibility of unwanted spontaneous tripping of any of the main and tie breakers of line 2 at Substations 2 and 4, one at a time. However, a line is not disconnected from the network at a substation unless both its main and tie breakers trip at the same time. Thus, in the breaker and a half substation configuration, there is no FT2.

FT3:

Situations resulting in FT3 on line 3 from the neighbouring lines:

(i) Fault on line 1 and subsequent response of primary protection system of line 1 at Substation 2:

- The two response scenarios of primary protection system of line 1 of interest are - failure of main breaker CB1a or tie-breaker CB2a of line 1 at Substation 2 (SS2). Failure of the main breaker (i.e., by failure of a breaker is meant the missing operation of protection system associated with the breaker) does not interrupt the continuity of service from G2. The designed backup for the main breaker of line 1 at SS2 is CB1b, the main breaker of connection from generator G2. Thus, when CB1b opens as a result of missing operation of CB1a, it has no adverse impact on the remaining healthy elements at SS3. Failure of line 1's tie-breaker CB2a causes its designed backup CB3a to open, which results in the isolation of line 6 from SS2. However, line 3 remains intact. Thus, *there is no situation resulting in FT3 on line 3 from the neighbouring line 1.*

(ii) Fault on line 4 and subsequent response of primary protection system of line 4 at Substation 4:

- The two response scenarios of primary protection system of line 4 of interest are - failure of main breaker CB3a or tie-breaker CB2a of line 4 at Substation 4 (SS4). Failure of main breaker CB3a will cause its designed backup CB3b to open, but this does not interrupt the continuity of service to load point 2, LP2. Failure of the tie-breaker CB2a results in its designed backup CB1a to open, which will isolate line 6 from SS4. However, line 3 remains intact. Thus, *there is no situation resulting in FT3 on line 3 from the neighbouring line 4.*

(iii) Fault on line 6 and subsequent response of primary protection system of line 6 at Substations 2 and 4:

- For a fault on line 6, both CB2a and CB3a at Substation 2 must open to isolate the faulted line from SS2. If only CB2a fails but CB3a works, then CB2a's designed backup, CB1a, will open, as a result of which line 1 is disconnected from SS2 in addition to the disconnection of the faulted line 6 from SS2. However, line 3 remains intact. If only CB3a fails but CB2a works, then CB3a's designed backup, CB3b, will open. Again, this situation has no impact on line 3. This could be thought of as an inbuilt safeguard against the propagation of failure to the neighbouring parallel line. Even though the primary protection system of line 6 at SS2 has failed to safely remove the faulted line 6 from the network, calling for backup action from the primary protection system of the neighbouring line 3 does not affect line 3 on account of the redundancy of paths provided by this station configuration. Thus, *there is no situation resulting in FT3 on line 3 from the neighbouring line 6 at SS2.*
- For a fault on line 6, CB1a and CB2a at Substation 4 must open to isolate the faulted line from SS4. If only CB2a fails but CB1a works, then CB2a's designed backup, CB3a, will open, as a result of which line 4 is disconnected from SS4 in addition to the disconnection of the faulted line 6 from SS4. However, line 3 remains intact. If only CB1a fails but CB2a works, then CB1a's designed backup, CB1b, will open, disconnecting only the faulted line 6 from the network. But line 3 is very much in the network. Thus, *there is no situation resulting in FT3 on line 3 from the neighbouring line 6 at SS3.*

In effect, there is no situation resulting in FT3 on line 3 from the neighbouring line 6.

FT4:

Situations resulting in FT4 on line 3 from the neighbouring lines:

Unwanted non-selective operation is assumed to be limited to the next layer of breakers designed to trip to isolate a line had a fault taken place on the line.

(i) Fault on line 1 and subsequent protection system response at Substation 2:

<u>When a fault occurs on line 1 and its primary protection system at Substation 2 acts correctly to isolate faulted line 1 from SS2:</u>

- The main breaker of line 1 at SS2, CB1a, and the tie-breaker of line 1 at SS2, CB2a, trip to isolate the faulted line 1 from SS2. Either CB1b, the designed backup for CB1a, or CB3a, the designed backup for CB2a, is prone to unwanted non-selective operation.

The unwanted non-selective operation of CB1b has no impact on the incoming line from generator G2. However, the unwanted non-selective operation of CB3a will isolate line 6, but not line 3 from SS2. Thus, *there is no situation resulting in FT4 on line 3 from the neighbouring line 1.*

(ii) Fault on line 4 and subsequent protection system response at Substation 4:

<u>When a fault occurs on line 4 and its primary protection system at Substation 4 acts correctly to isolate faulted line 4 from SS4:</u>

- The main breaker of line 4 at SS4, CB3a, and the tie-breaker of line 4 at SS4, CB2a, trip to isolate the faulted line 4 from SS4. Either CB3b, the designed backup for CB3a, or CB1a, the designed backup for CB2a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3b has no impact on the outgoing connection to LP2. However, the unwanted non-selective operation of CB1a will isolate line 6, but not line 3 from SS4. Thus, *there is no situation resulting in FT4 on line 3 from the neighbouring line 4.*

(iii) Fault on line 6 and subsequent protection system response at Substations 2 and 4:

<u>At Substation 2, the primary protection system acts correctly to isolate faulted line 6 from SS2:</u>

- The main breaker of line 6 at SS2, CB3a, and the tie-breaker of line 6 at SS2, CB2a, trip to isolate the faulted line 6 from SS2. Either CB3b, the designed backup for CB3a, or CB1a, the designed backup for CB2a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3b has no impact on line 3. However, the unwanted non-selective operation of CB1a will disconnect line 1 from SS2. Line 3 is still intact. Thus, *there is no situation resulting in FT4 on line 3 from the neighbouring line 6 at SS2.*

<u>At Substation 4, the primary protection system acts correctly to isolate faulted line 6 from SS4:</u>

- The main breaker of line 6 at SS4, CB1a, and the tie-breaker of line 6 at SS4, CB2a, trip to isolate the faulted line 6 from SS4. Either CB3a, the designed backup for CB2a, or CB1b, the designed backup for CB1a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1b has no impact on line 3. The unwanted non-selective operation of CB3a will disconnect line 4 from SS4, and has no impact on line 3 Thus, *there is no situation resulting in FT4 on line 3 from the neighbouring line 6 at SS4.*

In effect, there is no situation resulting in FT4 on line 3 from the neighbouring line 6.

The equivalent failure rate of a line on account of its failure due to various protection system response scenarios is given as the summation of the failure rates of the identified failure modes. $\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}$

For the focus line 3, $\lambda_{Eq.(3)} = \lambda_{FT1(3)} + \lambda_{FT2(3)} + \lambda_{FT3(3)} + \lambda_{FT4(3)}$

A.3 Elemental Analysis – Equivalent Failure Rate of transmission line 2 on account of the various possible transmission protection scenarios:

FT1:

The failure rate of FT1 of line 2 is merely the failure rate of line 2.

FT2:

There is no fault on line 2, but there is a possibility of unwanted spontaneous tripping of any of the main and tie breakers of line 2 at Substations 1 and 3, one at a time. However, a line is not disconnected from the network at a substation unless both its main and tie breakers trip at the same time. Thus, in the breaker and a half substation configuration, there is no FT2.

FT3:

Situations resulting in FT3 on line 2 from the neighbouring lines:

(i) Fault on line 1 and subsequent response of primary protection system of line 1 at Substation 1:

- The two response scenarios of primary protection system of line 1 of interest are - failure of main breaker CB1b or tie-breaker CB2b of line 1 at Substation 1 (SS1). Failure of the main breaker (i.e., by failure of a breaker is meant the missing operation of protection system associated with the breaker) does not interrupt the continuity of service from G1. The designed backup for the main breaker of line 1 at SS1 is CB1a, the main breaker of connection from generator G1. Thus, when CB1a opens as a result of missing operation of CB1b, it has no adverse impact on the remaining healthy elements at SS1. Failure of line 1's tie-breaker CB2b causes its designed backup CB3b to open, which results in the isolation of line 5 from SS1, but line 2 remains intact. *Thus, there is no situation resulting in FT3 on line 2 from the neighbouring line 1.*

(ii) Fault on line 4 and subsequent response of primary protection system of line 4 at Substation 3:

- The two response scenarios of primary protection system of line 4 of interest are - failure of main breaker CB3b or tie-breaker CB2b of line 4 at Substation 3 (SS3). Failure of main breaker CB3b will cause its designed backup CB3a to open, but this does not interrupt the continuity of service to load point 1, LP1. Failure of the tie-breaker CB2b results in its designed backup CB1b to open, which will isolate line 5 from SS3. However, line 2 remains intact. *Thus, there is no situation resulting in FT3 on line 2 from the neighbouring line 4.*

(iii) Fault on line 5 and subsequent response of primary protection system of line 5 at Substations 1 and 3:

- For a fault on line 5, both CB2b and CB3b at Substation 1 must open to isolate the faulted line from SS1. If only CB2b fails but CB3b works, then CB2b's designed backup, CB1b, will open, as a result of which line 1 is disconnected from SS1 in addition to the disconnection of the faulted line 5 from SS1. But line 2 is very much in the network. If only CB3b fails but CB2b works, then CB3b's designed backup, CB3a, will open, as a result of which only line 5 is disconnected from SS1. This situation has no impact on line 2. This could be thought of as an inbuilt safeguard against the propagation of failure to the neighbouring parallel line. Even though the primary protection system of line 5 at SS1 has failed to safely remove the faulted line 5 from the network, calling for backup action from the primary protection system of the neighbouring line 2 does not affect line 2 on account of the redundancy of paths provided by this station configuration. *Thus, there is no situation resulting in FT3 on line 2 from the neighbouring line 5 at SS1.*

- For a fault on line 5, CB1b and CB2b at Substation 3 must open to isolate the faulted line from SS3. If only CB2b fails but CB1b works, then CB2b's designed backup, CB3b, will open, as a result of which line 4 is disconnected from SS3 in addition to the disconnection of the faulted line 2. However, line 2 is very much in the network. If only CB1b fails but CB2b works, then CB1b's designed backup, CB1a, will open, disconnecting only the faulted line 5 from the network. But line 2 is very much in the network. *Thus, there is no situation resulting in FT3 on line 2 from the neighbouring line 5 at SS3.*

In effect, there is no situation resulting in FT3 on line 2 from the neighbouring line 5.

FT4:

Situations resulting in FT4 on line 2 from the neighbouring lines:

Unwanted non-selective operation is assumed to be limited to the next layer of breakers designed to trip to isolate a line had a fault taken place on the line.

(i) Fault on line 1 and subsequent protection system response at Substation 1:

When a fault occurs on line 1 and its primary protection system at Substation 1 acts correctly to isolate faulted line 1 from SS1:

- The main breaker of line 1 at SS1, CB1b, and the tie-breaker of line 1 at SS1, CB2b, trip to isolate the faulted line 1 from SS1. Either CB1a, the designed backup for CB1b, or CB3b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1a has no impact on the incoming line from generator G1. However, the unwanted non-selective operation of CB3b will isolate line 5 from SS1, but not line 2. *Thus, there is no situation resulting in FT4 on line 2 from the neighbouring line 1.*

(ii) Fault on line 4 and subsequent protection system response at Substation 3:

When a fault occurs on line 4 and its primary protection system at Substation 3 acts correctly to isolate faulted line 4 from SS3:

- The main breaker of line 4 at SS3, CB3b, and the tie-breaker of line 4 at SS3, CB2b, trip to isolate the faulted line 4 from SS3. Either CB3a, the designed backup for CB3b, or CB1b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3a has no impact on the outgoing connection to LP1. However, the unwanted non-selective operation of CB1b will isolate line 5 from SS3, but not line 2. Thus, *there is no situation resulting in FT4 on line 2 from the neighbouring line 4.*

(iii) Fault on line 5 and subsequent protection system response at Substations 1 and 3:

At Substation 1, the primary protection system acts correctly to isolate faulted line 5 from SS1:

- The main breaker of line 5 at SS1, CB3b, and the tie-breaker of line 5 at SS1, CB2b, trip to isolate the faulted line 5 from SS1. Either CB3a, the designed backup for CB3b, or CB1b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3a has no impact on line 2. The unwanted non-selective operation of CB1b will isolate line 1 from SS1. *Thus, there is no situation resulting in FT4 on line 2 from the neighbouring line 5 at SS1.*

At Substation 3, the primary protection system acts correctly to isolate faulted line 5 from SS3:

- The main breaker of line 5 at SS3, CB1b, and the tie-breaker of line 5 at SS3, CB2b, trip to isolate the faulted line 5 from SS3. Either CB3b, the designed backup for CB2b, or CB1a, the designed backup for CB1b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1a has no impact on line 2. The unwanted non-selective operation of CB3b will isolate only line 4 from SS3. *Thus, there is no situation resulting in FT4 on line 2 from the neighbouring line 5 at SS3.*

In effect, *there is no situation resulting in FT4 on line 2 from the neighbouring line 5.*

The equivalent failure rate of a line on account of its failure due to various protection system response scenarios is given as the summation of the failure rates of the identified failure modes.

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}$$

For the focus line 2,

$$\lambda_{Eq.(2)} = \lambda_{FT1(2)} + \lambda_{FT2(2)} + \lambda_{FT3(2)} + \lambda_{FT4(2)}$$

A.4 Elemental Analysis – Equivalent Failure Rate of transmission line 1 on account of the various possible transmission protection scenarios:

FT1:

The failure rate of FT1 of line 1 is merely the failure rate of line 1.

FT2:

There is no fault on line 1, but there is a possibility of unwanted spontaneous tripping of any of the main and tie breakers of line 1 at Substations 1 and 2, one at a time. However, a line is not disconnected from the network at a substation unless both its main and tie breakers trip at the same time. Thus, in the breaker and a half substation configuration, there is no FT2.

FT3:

Situations resulting in FT3 on line 1 from the neighbouring lines:

(i) Fault on line 5 and subsequent response of primary protection system of line 5 at Substation 1:

- For a fault on line 5, both CB2b and CB3b at Substation 1 must open to isolate the faulted line from SS1. If only CB2b fails but CB3b works, then CB2b's designed backup, CB1b, will open, as a result of which line 1 is disconnected from SS1 in addition to the disconnection of the faulted line 5 from SS1. This is a dependent failure of line 1 on account of failure of line 5. If only CB3b fails but CB2b works, then CB3b's designed backup, CB3a, will open, as a result of which only line 5 is disconnected from SS1. This situation has no impact on line 1.

Thus, the situation resulting in FT3 on line 1 from the neighbouring line 5 can be summarized as 'fault on line 5 and failure of tie-breaker CB2b at SS1'.

(ii) Fault on line 2 and subsequent response of primary protection system of line 2 at Substation 1:

- For a fault on line 2, both CB2a and CB3a at Substation 1 must open to isolate the faulted line from SS1. If only CB2a fails but CB3a works, then CB2a's designed backup, CB1a, will open, as a result of which generator G1 is disconnected from SS1 in addition to the disconnection of the faulted line 2 from SS1. The isolation of G1 could be thought of as a dependent failure even though line 1 is very much in the network. If only CB3a fails but CB2a works, then CB3a's designed backup, CB3b, will open, as a result of which only line 2 is disconnected from SS1. This situation has no impact on line 1. *Thus, the situation resulting in FT3 on line 1 from the neighbouring line 2 can be summarized as 'fault on line 2 and failure of tie-breaker CB2a at SS1'.*

(iii) Fault on line 6 and subsequent response of primary protection system of line 6 at Substation 2:

- For a fault on line 6, both CB2a and CB3a at Substation 2 must open to isolate the faulted line from SS2. If only CB2a fails but CB3a works, then CB2a's designed backup, CB1a, will open, as a result of which line 1 is disconnected from SS2 in addition to the disconnection of the faulted line 6 from SS2. This is a dependent failure of line 1 on account of failure of line 6. If only CB3a fails but CB2a works, then CB3a's designed backup, CB3b, will open. But, this situation has no impact on line 1. *Thus, the situation resulting in FT3 on line 1 from the neighbouring line 6 can be summarized as 'fault on line 6 and failure of tie-breaker CB2a at SS2'.*

(iv) Fault on line 3 and subsequent response of primary protection system of line 3 at Substation 2:

- For a fault on line 3, both CB2b and CB3b at Substation 2 must open to isolate the faulted line from SS2. If only CB2b fails but CB3b works, then CB2b's designed backup, CB1b, will open, as a result of which generator G2 is disconnected from SS2 in addition to the disconnection of the faulted line 3 from SS2. The isolation of G2 could be thought of as a dependent failure even though line 1 is very much in the network. If only CB3b fails but CB2b works, then CB3b's designed backup, CB3a, will open, as a result of which only line 3 is disconnected from SS2. This situation has no impact on line 1. *Thus, the situation resulting in FT3 on line 1 from the neighbouring line 3 can be summarized as 'fault on line 3 and failure of tie-breaker CB2b at SS2'.*

FT4:

Situations resulting in FT4 on line 1 from the neighbouring lines:

Unwanted non-selective operation is assumed to be limited to the next layer of breakers designed to trip to isolate a line had a fault taken place on the line.

(i) Fault on line 5 and subsequent protection system response at Substation 1:

- The main breaker of line 5 at SS1, CB3b, and the tie-breaker of line 5 at SS1, CB2b, trip to isolate the faulted line 5 from SS1. Either CB3a, the designed backup for CB3b, or CB1b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3a has no impact on line 1. However, the unwanted non-selective operation of CB1b will isolate line 1 from SS1. This is a dependent failure of line 1 on account of failure of the neighbouring line 5. *Thus, the situation resulting in FT4 on line 1 from the neighbouring line 5 can be summarized as 'fault on line 5, correct operation of CB3b and CB2b at SS1, but unwanted non-selective operation of CB1b at SS1'.*

(ii) Fault on line 2 and subsequent protection system response at Substation 1:

- The main breaker of line 2 at SS1, CB3a, and the tie-breaker of line 2 at SS1, CB2a, trip to isolate the faulted line 2 from SS1. Either CB3b, the designed backup for CB3a, or CB1a, the designed backup for CB2a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3b has no impact on line 1. However, the unwanted non-selective operation of CB1a will isolate generator G1 from SS1. This could be thought of as a dependent failure even though line 1 is still in the network. *Thus, the situation resulting in FT4 on line 1 from the neighbouring line 2 can be summarized as 'fault on line 2, correct operation of CB3a and CB2a at SS1, but unwanted non-selective operation of CB1a at SS1'.*

(iii) Fault on line 6 and subsequent protection system response at Substation 2:

- The main breaker of line 6 at SS2, CB3a, and the tie-breaker of line 6 at SS2, CB2a, trip to isolate the faulted line 6 from SS2. Either CB3b, the designed backup for CB3a, or CB1a, the designed backup for CB2a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3b has no impact on line 1. However, the unwanted non-selective operation of CB1a will disconnect line 1 from SS2. This is a dependent failure of line 1 on account of failure of the neighbouring line 6. *Thus, the situation resulting in FT4 on line 1 from the neighbouring line 6 can be summarized as* *'fault on line 6, correct operation of CB3a and CB2a at SS2, but unwanted non-selective operation of CB1a at SS2'.*

(iv) Fault on line 3 and subsequent protection system response at Substation 2:

- The main breaker of line 3 at SS2, CB3b, and the tie-breaker of line 3 at SS2, CB2b, trip to isolate the faulted line 3 from SS2. Either CB3a, the designed backup for CB3b, or CB1b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3a has no impact on line 1. However, the unwanted non-selective operation of CB1b will isolate generator G2 from SS2. This could be thought of as a dependent failure even though line 1 is still in the network. *Thus, the situation resulting in FT4 on line 1 from the neighbouring line 3 at Substation 2 can be summarized as 'fault on line 3, correct operation of CB3b and CB2b at SS2, but unwanted non-selective operation of CB1b at SS2'.*

The equivalent failure rate of a line on account of its failure due to various protection system response scenarios is given as the summation of the failure rates of the identified failure modes.

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}$$

For the focus line 1,

$$\lambda_{Eq.(1)} = \lambda_{FT1(1)} + \lambda_{FT2(1)} + \lambda_{FT3(1)} + \lambda_{FT4(1)}$$

A.5 Elemental Analysis – Equivalent Failure Rate of transmission line 4 on account of the various possible transmission protection scenarios:

FT1:

The failure rate of FT1 of line 4 is merely the failure rate of line 4.

FT2:

There is no fault on line 4, but there is a possibility of unwanted spontaneous tripping of any of the main and tie breakers of line 4 at Substations 3 and 4, one at a time. However, a line is not disconnected from the network at a substation unless both its main and tie breakers trip at the same time. Thus, in the breaker and a half substation configuration, there is no FT2.

FT3:

Situations resulting in FT3 on line 4 from the neighbouring lines:

(i) Fault on line 5 and subsequent response of primary protection system of line 5 at Substation 3:

- For a fault on line 5, CB1b and CB2b at Substation 3 must open to isolate the faulted line from SS3. If only CB2b fails but CB1b works, then CB2b's designed backup, CB3b, will open, as a result of which line 4 is disconnected from SS3 in addition to the disconnection of the faulted line 2. This is a dependent failure of line 4 on account of failure of line 5.

- If only CB1b fails but CB2b works, then CB1b's designed backup, CB1a, will open, disconnecting only the faulted line 5 from the network. But line 4 is very much in the network. *Thus, the situation resulting in FT3 on line 4 from the neighbouring line 5 can be summarized as 'fault on line 5 and failure of tie-breaker CB2b at SS3'.*

(ii) Fault on line 2 and subsequent response of primary protection system of line 2 at Substation 3:

- For a fault on line 2, CB1a and CB2a at Substation 3 must open to isolate the faulted line from SS3. If only CB2a fails but CB1a works, then CB2a's designed backup, CB3a, will open, as a result of which load point 1, LP1, is disconnected from SS3 in addition to the disconnection of the faulted line 2. The isolation of LP1 could be thought of as a dependent failure even though line 4 is very much in the network. If only CB1a fails but CB2a works, then CB1a's designed backup, CB1b, will open, disconnecting only the faulted line 2 from the network. But line 4 is very much in the network. Thus, *the situation resulting in FT3 on line 4 from the neighbouring line 2 can be summarized as 'fault on line 2 and failure of tie-breaker CB2a at SS3'.*

(iii) Fault on line 6 and subsequent response of primary protection system of line 6 at Substation 4:

- For a fault on line 6, CB1a and CB2a at Substation 4 must open to isolate the faulted line from SS4. If only CB2a fails but CB1a works, then CB2a's designed backup, CB3a, will open, as a result of which line 4 is disconnected from SS4 in addition to the disconnection of the faulted line 6 from SS4. This is a dependent failure of line 4 on account of failure of line 6. If only CB1a fails but CB2a works, then CB1a's designed backup, CB1b, will open, disconnecting only the faulted line 6 from the network. But line 4 is very much in the network. Thus, *the situation resulting in FT3 on line 4 from the neighbouring line 6 can be summarized as 'fault on line 6 and failure of tie-breaker CB2a at SS4'.*

(iv) Fault on line 3 and subsequent response of primary protection system of line 3 at Substation 4:

- For a fault on line 3, CB1b and CB2b at Substation 4 must open to isolate the faulted line from SS4. If only CB2b fails but CB1b works, then CB2b's designed backup, CB3b, will open, as a result of which load point 2, LP2, is disconnected from SS4 in addition to the disconnection of the faulted line 3. The isolation of LP2 could be thought of as a dependent failure even though line 4 is very much in the network. If only CB1b fails but CB2b works, then CB1b's designed backup, CB1a, will open, disconnecting only the faulted line 3 from the network. But line 4 is still intact. Thus, *the situations resulting in FT3 on line 4 from the neighbouring line 3 can be summarized as 'fault on line 3 and failure of tie-breaker CB2b at SS4'.*

FT4:

Situations resulting in FT4 on line 4 from the neighbouring lines:

Unwanted non-selective operation is assumed to be limited to the next layer of breakers designed to trip to isolate a line had a fault taken place on the line.

(i) Fault on line 5 and subsequent primary protection system response of line 5 at Substation 3:

- The main breaker of line 5 at SS3, CB1b, and the tie-breaker of line 5 at SS3, CB2b, trip to isolate the faulted line 5 from SS3. Either CB3b, the designed backup for CB2b, or CB1a, the designed backup for CB1b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1a has no impact on line 4. However, the unwanted non-selective operation of CB3b will isolate line 4 from SS3. This is a dependent failure of line 4 on account of failure of line 5. *Thus, the situation resulting in FT4 on line 4 from the neighbouring line 5 at SS3 can be summarized as 'fault on line 5, correct operation of CB1b and CB2b at SS3, but unwanted non-selective operation of CB3b at SS3'.*

(ii) Fault on line 2 and subsequent response of primary protection system of line 2 at Substation 3:

- The main breaker of line 2 at SS3, CB1a, and the tie-breaker of line 2 at SS3, CB2a, trip to isolate the faulted line 2 from SS3. Either CB3a, the designed backup for CB2a, or CB1b, the designed backup for CB1a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1b has no impact on line 4. However, the unwanted non-selective operation of CB3a will isolate load point LP1 from SS3. This could be thought of as a dependent failure even though line 4 is still in the network. Thus, the situation resulting in FT4 on line 4 from the neighbouring line 2 at Substation 3 can be summarized as *'fault on line 2, correct operation of CB1a and CB2a at SS3, but unwanted non-selective operation of CB3a at SS3'.*

(iii) Fault on line 3 and subsequent response of primary protection system of line 3 at Substation 4:

- The main breaker of line 3 at SS4, CB1b, and the tie-breaker of line 3 at SS4, CB2b, trip to isolate the faulted line 3 from SS4. Either CB3b, the designed backup for CB2b, or CB1a, the designed backup for CB1b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1a has no impact on line 4. However, the unwanted non-selective operation of CB3b will isolate load point LP2 from SS4. This could be thought of as a dependent failure even though line 4 is still in the network. Thus, the situation resulting in FT4 on line 4 from the neighbouring line 3 at Substation 4 can be summarized as *'fault on line 3, correct operation of CB1b and CB2b at SS4, but unwanted non-selective operation of CB3b at SS4'.*

(iv) Fault on line 6 and subsequent response of primary protection system of line 6 at Substation 4:

- The main breaker of line 6 at SS4, CB1a, and the tie-breaker of line 6 at SS4, CB2a, trip to isolate the faulted line 6 from SS4. Either CB3a, the designed backup for CB2a, or

CB1b, the designed backup for CB1a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1b has no impact on line 4. The unwanted non-selective operation of CB3a will disconnect line 4 from SS4. This is a dependent failure of line 4 on account of failure of line 6. Thus, the situation resulting in FT4 on line 4 from the neighbouring line 6 at Substation 4 can be summarized as *'fault on line 6, correct operation of CB1a and CB2a at SS4, but unwanted non-selective operation of CB3a at SS4'.*

The equivalent failure rate of a line on account of its failure due to various protection system response scenarios is given as the summation of the failure rates of the identified failure modes.

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}$$

For the focus line 4, $\lambda_{Eq.(4)} = \lambda_{FT1(4)} + \lambda_{FT2(4)} + \lambda_{FT3(4)} + \lambda_{FT4(4)}$

Appendix B: Schematics of Breaker-and-a-half Substation Configuration with Instrument Transformers

According to the CIGRE Working Group Report*, *"Each of the two busbars is protected by its own protection system. The remaining middle section not covered by the busbar protection is usually protected by the feeder and breaker-failure protection. In the case where a further feeder CT is available, the middle section can be protected by a current differential protection."*

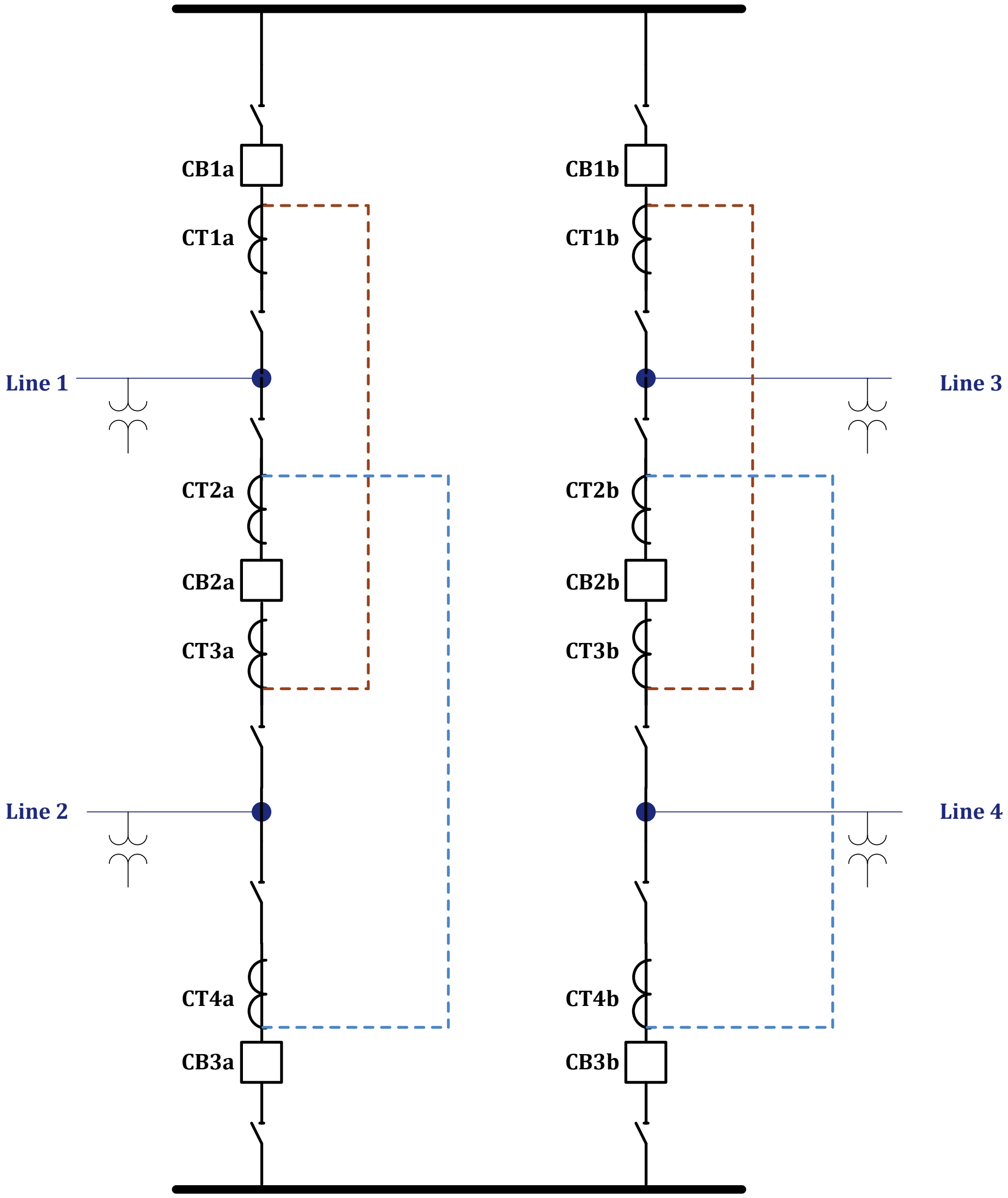

Fig. B.1. Breaker-and-a-half substation configuration: 2 diameters with instrument transformers

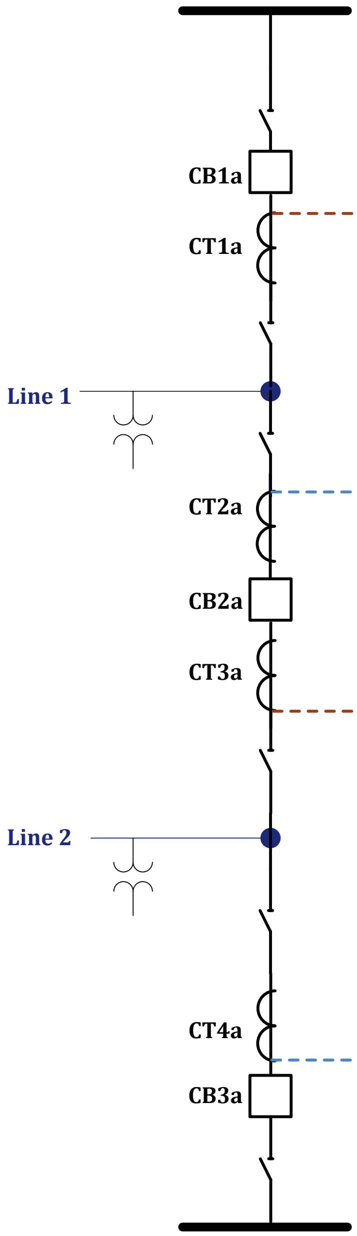

Fig. B.2. Breaker-and-a-half substation configuration: 1 diameter with instrument transformers

*S. Lindahl *et al.*, "Reliable fault clearance and back-up protection," CIGRE Working Group 34.01, Report no. 140, Apr. 1999.

APPENDIX 4

Publications

1 Vijay Venu Vadlamudi (NTNU); Oddbjørn Gjerde and Gerd Kjølle, SINTEF Energy Research:
Impact of Substation Configuration on Protection System Failure Propagation and its Effect on Reliability of Supply
18th Power Systems Computation Conference, Wroclaw, Poland, August 18-22, 2014

2 Vijay Venu Vadlamudi (NTNU); Oddbjørn Gjerde and Gerd Kjølle, SINTEF Energy Research:
Consideration of transmission protection system response in reliability of electricity supply analysis – case study
CIGRE, Paris, France, August 25-29, 2014

3 Vijay Venu Vadlamudi (NTNU); Oddbjørn Gjerde and Gerd Kjølle, SINTEF Energy Research:
Impact of Protection System Reliability on Power System Reliability: A New Minimal Cutset Approach
PMAPS, Durham, United Kingdom, July 7-10, 2014

4 Vijay Venu Vadlamudi (NTNU); Oddbjørn Gjerde and Gerd Kjølle, SINTEF Energy Research:
Dependability and Security-based Failure Considerations in Protection System Reliability Studies
4th IEEE PES, Copenhagen, Denmark, October 6-9, 2013

5 Vijay Venu Vadlamudi (NTNU); Oddbjørn Gjerde and Gerd Kjølle, SINTEF Energy Research:
Incorporation of Protection System Failure Modes in Composite Power System Reliability Studies
CIGRE, Quibec, Canada, September 24-26, 2012

6 Prepared by the PACME Working Group of the IEEE PES Reliability, Risk and Probability Applications (RRPA) Subcommittee:
Effects of Dependent and Common Mode Outages on the Reliability of Bulk Electric System – Part I: Basic Concepts
IEEE 2014

7 Prepared by the PACME Working Group of the IEEE PES Reliability, Risk and Probability Applications (RRPA) Subcommittee:
Effects of Dependent and Common Mode Outages on the Reliability of Bulk Electric System – Part II: Outage Data Analysis
IEEE 2014

Impact of Substation Configuration on Protection System Failure Propagation and its Effect on Reliability of Supply

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***Abstract*— Relatively fewer studies exist in literature on including the complex effects of transmission protection system related failure dependencies in the reliability prediction models. Usage of extensive Markov models has been usually advocated to capture the impact of protection system reliability on power system reliability. A new analytical method which makes use of approximate methods of system reliability evaluation has been recently proposed by us, which circumvents the need for Markov models. It is a unique minimal cutset-based approach for single circuit meshed transmission systems, where several basic and load/energy oriented reliability indices are obtained. The objective of this paper is to extend the procedure to examine the impact of substation configurations on protection system failure dependency propagation and its effect on bulk load point reliability indices. Preliminary investigations show a marked impact of employing a station configuration with simplified bus representation, especially in multi circuit meshed transmission systems, on the resulting reliability indices. The results of the proposed methodology are demonstrated on a suitably modified four bus illustrative test system, for cases with and without the consideration of protection system failures for a realistic station configuration.**

Keywords*— Breaker-and-a-half switching, minimal cutset; protection system; reliability; substation

I. INTRODUCTION

A transmission line can experience several failure modes on account of the various protection system response scenarios. Some of these failure modes (derivatives of missing and unwanted trips) initiate failure dependency propagation on neighbouring lines, which can have enormous consequences. In Nordic countries such as Norway and Finland, protection system misoperations at transmission and sub-transmission voltage levels were found to be the second largest contributors of Energy Not Supplied (ENS) [1]. This only impresses further on the need for including protection system related failure dependencies in the reliability prediction models [2].

There exist already in literature several notable studies, both analytical and Monte Carlo simulation based, as regards the reliability analysis of substations [3]-[10]. Active and passive failures of the various substation components for connectivity between any pair of source and load buses in the substation network are usually analysed in such works. The exclusive effects of protection system failures in various substation configurations using the concept of event trees have only been recently studied [11]. Prior to this, a methodology was proposed [12] to evaluate the effects of protection system hidden failures on bulk power system reliability; breaker-oriented substation models were integrated in the network model to consider the influence of protection systems.

An approach to performing risk assessment for the combinative system of transmission network and substation configuration was presented in [13], where it has particularly been emphasized that *"evaluating substation configurations under the constraint of a transmission network provides more accurate results than evaluating only substation configurations since the transmission network and failures of its components may have impacts on the reliability of substation configurations."* In our paper, this philosophy has been kept in mind while proposing a model and solution for studying the impact of protection system reliability on power system reliability when explicitly taking the substation configuration into account.

The objective of our paper is to examine the impact of substation configuration arrangement (breaker-and-a-half scheme) on transmission protection system failure dependency propagation and study the consequent effects on bulk load point reliability indices, using a unique minimal cutset (MC) approach. It must be noted that our paper is not about the typical stand-alone reliability analysis of substation switching configurations, e.g., contingency analysis of substation elements including busbars.

A new analytical method based on minimal cutsets, which makes use of approximate methods of system reliability evaluation, has been recently proposed by us [14]-[17], which circumvents the need for complex Markov models in analysing the impact of protection system reliability in transmission networks. This paper extends the procedure to examine the impact of substation configuration on protection system failure dependency propagation and its effect on bulk load point reliability indices.

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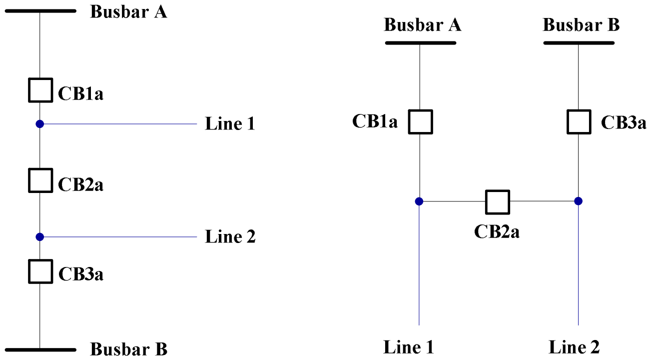
Section II provides an introduction to the significant aspects of breaker-and-a-half substation configuration. The proposed methodology of utilising a minimal cutset-based approach for the aforementioned objective of reliability analysis is outlined in Section III. Sample procedural calculations, followed by results and discussion are shown in the illustrative case study in Section IV.

II. BREAKER-AND-A-HALF SUBSTATION CONFIGURATION

There are typically six different busbar arrangements used for switching at a substation: single bus-single breaker, double bus-single breaker with bus-coupler, double bus-double breaker, main and transfer bus, double bus-one and a half breaker, and ring busbar or four-breaker mesh. Factors that influence the appropriate selection of the switching arrangement at a substation include cost, reliability, and flexibility for future expansions. The '*double bus-one and a half breaker*' busbar arrangement (also known as *breaker-and-a-half* arrangement) is shown in Fig. 1 without the isolators that usually accompany the circuit breakers, for the sake of simplicity. It has been observed [18] that this design increases the security of supply especially in cases where multiple sources are present, and has minimal bus exposure; it allows for maintenance without supply interruptions and is intended for stations serving as area hubs and/or for serving large loads that are sensitive to loss of load either because of momentary or sustained element outages. In the normal operating state, this arrangement has only 'normally closed' paths.

Two busbars A and B are interconnected by three circuit breakers CB1a, CB2a and CB3a. Line 1 is connected between CB1a and CB2a; line 2 is connected between CB2a and CB3a. Line 1 has two feeding paths – Busbar A and CB1a; Busbar B, CB2a and CB3a. Line 2 has two feeding paths – Busbar B and CB3a; Busbar A, CB1a and CB2a. Busbars A and B are mere physical buses. They are energized by means of the transmission lines or transformers connected between the breakers. The role of busbars is to merely distribute the current between the bays.



(a) 'I-depiction' of Breaker-and-a-Half Configuration (b) 'H-depiction' of Breaker-and-a-Half Configuration

Fig. 1. Typical representations of breaker-and-a-half substation configuration

A thorough understanding of the protection system backup coordination effects in a breaker-and-a-half configuration is essential for performing the necessary scenario analysis introduced later in this paper. For interrupting only line 1, the circuit breakers that need to be tripped are CB1a and CB2a, i.e., for a fault on line 1 both CB1a and CB2a must trip. For interrupting only line 2, the circuit breakers that need to be tripped are CB2a and CB3a. CB1a is referred to as the main breaker of line 1; CB2a as the tie-breaker; CB3a as the main breaker of line 2. Thus, for any problem on line '*i*', the tie-breaker must trip along with the corresponding main breaker of line '*i*'. A line and its main breaker and isolators together constitute a 'circuit'. Thus, there are two circuits in Fig. 1(a). If a breaker adjacent to one of the busbars (i.e., a main breaker) fails, then the tripping of tie-breaker does not interrupt power supply to the circuit associated with the healthy breaker (i.e., the breaker adjacent to the other busbar). Only the circuit associated with failed breaker is interrupted.

In a simple busbar configuration, one breaker is sufficient for controlling one feeder. However in this case, 3 breakers are required for controlling two feeders, and hence the name 3/2 or 1½ breaker arrangement. In a breaker-and-a-half arrangement, any circuit breaker can be removed for maintenance without affecting the service of the associated line; e.g., if CB1a is to be removed for maintenance, line 1 would still be in service through the feeding path 'Busbar B - CB2a - CB3a'. A fault on either of Busbars A and B can be isolated without interrupting service to lines 1 and 2. This arrangement has a more complicated relaying as the tie-breaker has to act on faults on any of the two circuits it is associated with. If a breaker fails to trip upon a fault, a next 'layer' of breakers is designed to trip to isolate the faulted line.

A. Basic Response Scenarios at Substation for Fault on Line

Ideally speaking, both main breaker of line 1 – CB1a and the tie-breaker – CB2a of Fig. 1 are required to trip for a fault on line 1. Three protection system response scenarios arise:

(1) Both CB1a and CB2a trip:

The faulted line 1 is disconnected from both Busbars A and B. The healthy line 2 remains unaffected.

(2) Only the main breaker CB1a trips but the tie-breaker CB2a fails to trip:

The consequence will be a loss (disconnections from the busbar) of two lines – both the faulted line 1 as well as the healthy line 2: the main breaker of the healthy line 2 – CB3a, is within the protection zone of backup relaying for circuit 1, and hence it trips to disconnect the connection of faulted line 1 from Busbar B through the closed CB2a. CB1a has already tripped and thus the faulted line 1 and Busbar A are isolated from each other.

(3) Only the tie-breaker CB2a trips but the main breaker CB1a fails to trip:

The faulted line 1 is isolated from having any impact on circuit 2. If there are other circuits connected to Busbar A, further switching action would follow because of the backup protection settings to disconnect Busbar A from the faulted line. This is illustrated in Fig. 2, which has two branches/diameters as opposed to the one branch shown in Fig. 1. For a fault on line 1, when the tie-breaker of branch 'a', CB2a, successfully trips but the main breaker of line 1, CB1a, fails to trip, CB1b – the neighbouring layer of breaker in the protection zone of line 1, from the adjacent branch 'b' – trips. This isolates Busbar A from all the remaining healthy circuits. However, the tripping of CB1b does not affect line 3, since for line 3 to be isolated, both CB1b and CB2b must be tripped. In the case of a breaker-and-a-half configuration with two branches/diameters, different permutations of the four line connections are possible. Strategic placement of these lines governs which lines get disconnected as a result of failure-to-operate state of a protection system unit and the subsequent events due to the backup protection coordination. In general, two lines sharing the circuit breakers in a branch/diameter are usually arranged such that one is connected to a source and the other to a load [19]; this source-load combination minimizes the flow of current on the busbars and the switches.

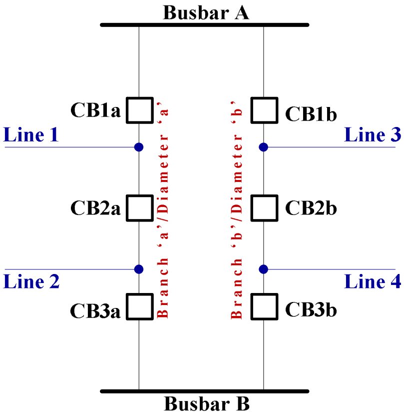


Fig. 2. Breaker-and-a-half substation configuration with two branches/diameters

III. PROPOSED METHODOLOGY

A. Equivalent Failure Rate of a Transmission Line

The various response scenarios of transmission protection systems are translated to corresponding equivalent failure modes of transmission lines by the definition and quantification of fault types (FTs) (or failure modes) as initially proposed in [15-16]. A brief generic description of such fault types for simple bus configurations is presented below.

Fault Type 1 (FT1): A fault occurs on the transmission line *i*, upon which there could be two consequent scenarios: Consequent Scenario 1 (CS1) - The fault is successfully cleared by the line's primary protection system; Consequent Scenario 2 (CS2) - The fault could not be cleared because of the unreadiness of the line's primary protection system. The failure rate of FT1 is merely the failure rate of the transmission line.

Fault Type 2 (FT2): The transmission line *i* is fault-free, but because of faulty operation of the line's primary protection system, unwanted spontaneous tripping of the circuit breaker(s) occurs. This results in isolation of the healthy line *i*. The failure rate of FT2 is the summation of unwanted spontaneous tripping rates of circuit breakers of line *i*.

Fault Type 3 (FT3): A fault occurs on one of the neighbouring transmission lines, but the faulty operation of the primary protection system of the neighbouring line results in the missing operation of a circuit breaker, because of which the faulted neighbouring line cannot be isolated by its own circuit breakers. In such a case, the protection system of line *i* acts as back-up to isolate the faulted neighbouring line. This also results in isolation of the healthy line *i*.

Fault Type 4 (FT4): A fault occurs on one of the neighbouring transmission lines, upon which the neighbouring line's primary protection system clears the fault correctly. However, because of faulty operation of either of the protection system units of line *i* or both protection system units of line *i*, unwanted non-selective tripping of line i's circuit breaker(s) occurs. This results in healthy line *i*'s isolation.

B. Types of Minimal Cutsets: Variable Failure Rates

Neighbouring lines are defined as transmission lines connected to a common bus (substation). By the same convention, parallel lines between bus pairs fall in this category. For a finer distinction in the convention, there can be a further classification of neighbouring lines as parallel neighbouring lines and non-parallel neighbouring lines. For an MC with only non-neighbouring transmission lines, the equivalent failure rate of each line in the MC is obtained by computing failure rates of FT1, FT2, FT3 and FT4 based on the description above and summing them up [15, 17].

The equivalent failure rate of a transmission line is 'variable' (not to be confused with time-dependent failure rate), depending upon the composition of the MC which it is a part of. This composition governs the way in which FT3 and FT4 are to be calculated for each of the elements. A line x when part of an MC 1 can have a different equivalent failure rate than when it is a part of MC 2. It must be noted that CS1 of FT1 on line *i* 'may' result in FT4 on neighbouring line *j*, and vice-versa. CS2 of FT1 on line *i* 'will' result in FT3 on neighbouring line *j*, and vice-versa. If neighbouring lines *i* and *j* are constituents of an MC, any of these four scenarios will result in the failure of the whole cutset. Thus, the failure rate contributions from these four scenarios form the dependency failure rate of the MC, and these contributions are duly removed from the corresponding individual equivalent failure rates of the lines.

For each line belonging to an MC, a combinatorial analysis of all possible backup coordination related interaction scenarios among its neighbouring lines is carried out (sample calculations are shown in the illustrative case study in Section IV). For each of these interaction scenarios, a failure rate contribution expression is formulated from the first principles for fault types FT3 and FT4 [15]-[17]. This is relatively straight forward for elements of MCs with constituent non-neighbouring lines. However, in the case of MCs with constituent neighbouring parallel lines or neighbouring non-parallel lines or a combination thereof, a subset of these interaction scenarios, which pertains to dependency failure among all the MC constituents are set aside. Such failure rate contributions are not included in the individual failure rate expressions of FT3 and FT4 of the elements in the MCs, but utilized only in the expressions for dependency mode failure rates of the MCs. For the sake of completeness, the relevant formulae [15] are given below:

The basic reliability indices – interruption frequency λ (number of interruptions per year), annual expected outage time U (annual interruption duration), and expected value of down time r (average interruption duration) – are obtained for delivery points. Approximate methods [14] yield the very popular set of linear relationships, for a system S consisting of i components following series reliability logic (i.e., combination of MCs), as follows:

$$\lambda_s = \sum \lambda_i;\ U_s = \sum \lambda_i r_i;\ r_s = \frac{U_s}{\lambda_s} \tag{1}$$

When the units for failure rates are in failures per year and repair times/switching times are in hours, λ (i.e., equivalent failure rate)), *U*, and *r* are obtained in terms of interruptions per year, hours per year and hours per interruption, respectively.

Subsequently, the annual power interrupted (PI), annual energy not supplied (ENS) and annual interruption costs (IC) can be computed, all based on a minimal cutset based approach. A consequence analysis of each contingency under specified operating conditions yields a system available capacity (SAC) for each delivery point due to the contingency. For each MC *j* for a given operating state:

$$\begin{aligned} P_{IN,j} &= P - SAC_j \text{ MW/interruption} \\ ENS_j &= r_j * P_{IN,j} \text{ MWh/interruption} \\ IC_j &= C(r_j) * ENS_j \text{ NOK/interruption} \end{aligned} \tag{2}$$

where *C(r)* is the specific interruption cost in currency per kWh of energy not supplied, P_{IN} is the interrupted power, and P is the load demand. Each of the expressions above is multiplied by the equivalent failure rate of MC *j* to obtain the indices on an annual basis, i.e., MW/year, MWh/year and kroners/year, respectively. For a given operating state, if there are *n* MCs, the corresponding *n* annual indices are summed up to get the net delivery point indices per operating state. If there are multiple operating states, a probability weighted equivalent failure rate of MC *j* is used as the basis for obtaining the above annual indices and summed up accordingly.

IV. TEST NETWORKS

MOPAL is a modified four-bus multi-circuit meshed OPAL test network [2] with two generators, two delivery points and six transmission lines, as shown in Fig. 3. The figure shows a simple bus configuration. The transmission network operates at 132 kV. The capacity of transmission lines is as follows: lines 1 and 4: 135 MW; lines 2, 3, 5 and 6: 67.5 MW. The two generators are assumed to be 100% reliable. Delivery point 1, LP1, has industry customers; delivery point 2, LP2 has energy-intensive industry customers. For the simplicity of illustration, one operating state (OS1), a heavy load condition is assumed to prevail throughout the duration of a year at the delivery points. In OS1, delivery point LP1 is assumed to have a constant load demand of 100 MW, and delivery point LP2 a constant demand of 75 MW. By assigning probability weightages, the effect of multiple operating states can be easily captured. Norwegian fault statistics were analysed to obtain a representative input data set for failure rate parameters and probability attributes of protection system units. Accordingly, all the protection system units ($PT_{A[i]}$, $PT_{B[i]}$ in Fig. 3) are assumed to have the same repair time of 2 h. The missing and unwanted non-selective probabilities of all the protection system units are assumed to be 0.0205 and 0.007, respectively. Failure rate of unwanted spontaneous tripping of the circuit breakers of all protection system units is 0.025 f/yr. In Fig. 3, each of the two ends of a line *i*, say A-end and B-end, has a protection system unit, PT. The subscript A or B refers to the end at which the unit is located.

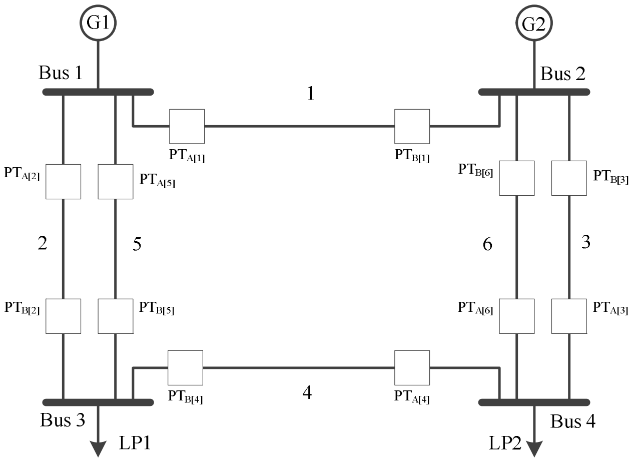


Fig. 3. MOPAL test network with a simple bus configuration

The single line diagram with breaker-and-a-half substation configuration for MOPAL network is shown in Fig. 4 in the next page. A sample explanation of the combinatorial analysis of all possible backup coordination related interaction scenarios among a line's neighbouring lines at the elemental level when substation configuration is considered, is explained below for line 5 of Fig. 4. For each of these interaction scenarios, a failure rate contribution expression is formulated from the first principles with respect to fault types FT3 and FT4 [15]-[16]. There can be as many FT3 and FT4 scenarios as are the number of neighbouring lines for a particular line.

A. Illustrative Scenario Analysis

Equivalent Failure Rate of transmission line 5 on account of the various possible transmission protection scenarios:

FT1: The failure rate of FT1 of line 5 is merely the failure rate of line 5.

$$\lambda_{FT1(5)} = \lambda_5 \tag{3}$$

FT2: There is no fault on line 5, but there is a possibility of unwanted spontaneous tripping of any of the main and tie breakers of line 5 at Substations 1 and 3, one at a time. However, a line is not disconnected from the network at a substation unless both its main and tie breakers trip at the same time. Thus, in the breaker-and-a-half substation configuration, there is no FT2.

$$\lambda_{FT2(5)} = 0 \tag{4}$$

FT3: *Situations resulting in FT3 on line 5 from the neighbouring lines:*

Scenario 1 – Fault on line 1 and subsequent response of primary protection system of line 1 at Substation 1: The two response scenarios of primary protection system of line 1 of interest are - failure of main breaker CB1b or tie-breaker CB2b of line 1 at Substation 1 (SS1). Failure of the main breaker (i.e., by failure of a breaker is meant the missing operation of protection system associated with the breaker) does not interrupt the continuity of service from G1. The designed backup for the main breaker of line 1 at SS1 is CB1a, the main breaker of connection from generator G1. Thus, when CB1a opens as a result of missing operation of CB1b, it has no adverse impact on the remaining healthy elements at SS1. Failure of line 1's tie-breaker CB2b causes its designed backup CB3b to open, which results in the isolation of line 5 from SS1. Thus, the situation resulting in FT3 on line 5 from the neighbouring line 1 can be summarized as 'fault on line 1 (quantified as λ_1) and failure of tie-breaker CB2b at SS1 (quantified as the breaker's missing probability $P_{M[CB2b@SS1]}$)'.

Thus, failure contribution from FT3 Scenario 1 of line 5 is:

$$\lambda_1 * P_{M[CB2b@SS1]} \tag{5}$$

Scenario 2 – Fault on line 4 and subsequent response of primary protection system of line 4 at Substation 3: The two response scenarios of primary protection system of line 4 of interest are - failure of main breaker CB3b or tie-breaker CB2b of line 4 at Substation 3 (SS3). Failure of main breaker CB3b will cause its designed backup CB3a to open, but this does not interrupt the continuity of service to load point 1, LP1. However, failure of the tie-breaker CB2b results in its designed backup CB1b to open, which will isolate line 5 from SS3. Thus, the situation resulting in FT3 on line 5 from the neighbouring line 4 can be summarized as 'fault on line 4 and failure of tie-breaker CB2b at SS3'.

Thus, failure contribution from FT3 Scenario 2 of line 5 is:

$$\lambda_4 * P_{M[CB2b@SS3]} \tag{6}$$

Scenario 3 – Fault on line 2 and subsequent response of primary protection system of line 2 at Substations 1 and 3: (a). For a fault on line 2, both CB2a and CB3a at Substation 1 must open to isolate the faulted line from SS1. If only CB2a fails but CB3a works, then CB2a's designed backup, CB1a, will open, as a result of which generator G1 is disconnected from SS1 in addition to the disconnection of the faulted line 2 from SS1. The isolation of G1 could be thought of as a dependent failure. But line 5 is very much in the network. If only CB3a fails but CB2a works, then CB3a's designed backup, CB3b, will open, as a result of which only line 2 is disconnected from SS1. This situation has no impact on line 5. This could be thought of as an inbuilt safeguard against the propagation of failure to the neighbouring parallel line. Even though the primary protection system of line 2 at SS1 has failed to safely remove the faulted line 2 from the network, calling for backup action from the primary protection system of the neighbouring line 5 does not affect line 5 on account of the redundancy of paths provided by this station configuration.

Thus, failure contribution from FT3 Scenario 3(a) of line 5 is:

$$\lambda_2 * P_{M[CB2a@SS1]} \tag{7}$$

(b). For a fault on line 2, CB1a and CB2a at Substation 3 must open to isolate the faulted line from SS3. If only CB2a fails but CB1a works, then Cb2a's designed backup, CB3a, will open, as a result of which load point 1, LP1, is disconnected from SS3 in addition to the disconnection of the faulted line 2. The isolation of LP1 could be thought of as a dependent failure. But line 5 is very much in the network. If only CB1a fails but CB2a works, then CB1a's designed backup, CB1b, will open, disconnecting only the faulted line 2 from the network. But line 5 is very much in the network.

Thus, failure contribution from FT3 Scenario 3(b) of line 5 is:

$$\lambda_2 * P_{M[CB2a@SS3]} \tag{8}$$

Thus, the situations resulting in FT3 on line 5 from the neighbouring line 2 can be summarized as 'fault on line 2 and failure of tie-breaker CB2a at SS1' or 'fault on line 2 and failure of tie-breaker CB2a at SS3'. Thus, the overall failure rate contribution from FT3 Scenario 3 of line 5 is:

$$\lambda_2 * P_{M[CB2a@SS1]} + \lambda_2 * P_{M[CB2a@SS3]} \tag{9}$$

FT4: *Situations resulting in FT4 on line 5 from the neighbouring lines:*

Unwanted non-selective operation is assumed to be limited to the next layer of breakers designed to trip to isolate a line if a fault had taken place on the line.

Scenario 1 – Fault on line 1 and subsequent protection system response at Substation 1: (*When a fault occurs on line 1 and its primary protection system at Substation 1 acts correctly to isolate faulted line 1 from SS1.)*

The main breaker of line 1 at SS1, CB1b, and the tie-breaker of line 1 at SS1, CB2b, trip to isolate the faulted line 1 from SS1. Either CB1a, the designed backup for CB1b, or CB3b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1a has no impact on the incoming line from generator G1. However, the unwanted non-selective operation of CB3b will isolate line 5 from SS1. Thus, the situation resulting in FT4 on line 5 from the neighbouring line 1 can be summarized as 'fault on line 1, AND correct operation of CB1b and CB2b at SS1, but unwanted non-selective operation of CB3b at SS1'.

For instance, correct operation of CB1b at SS1 is denoted as $P_{C[CB1b@SS1]}$. Its value is the probability of missing operation of CB1b at SS1 subtracted from 1. The probability of unwanted non-selective operation of CB3b at SS1 is denoted as $P_{U-Ns[CB3b@SS1]}$. Thus, failure contribution from FT4 Scenario 1 of line 5 is:

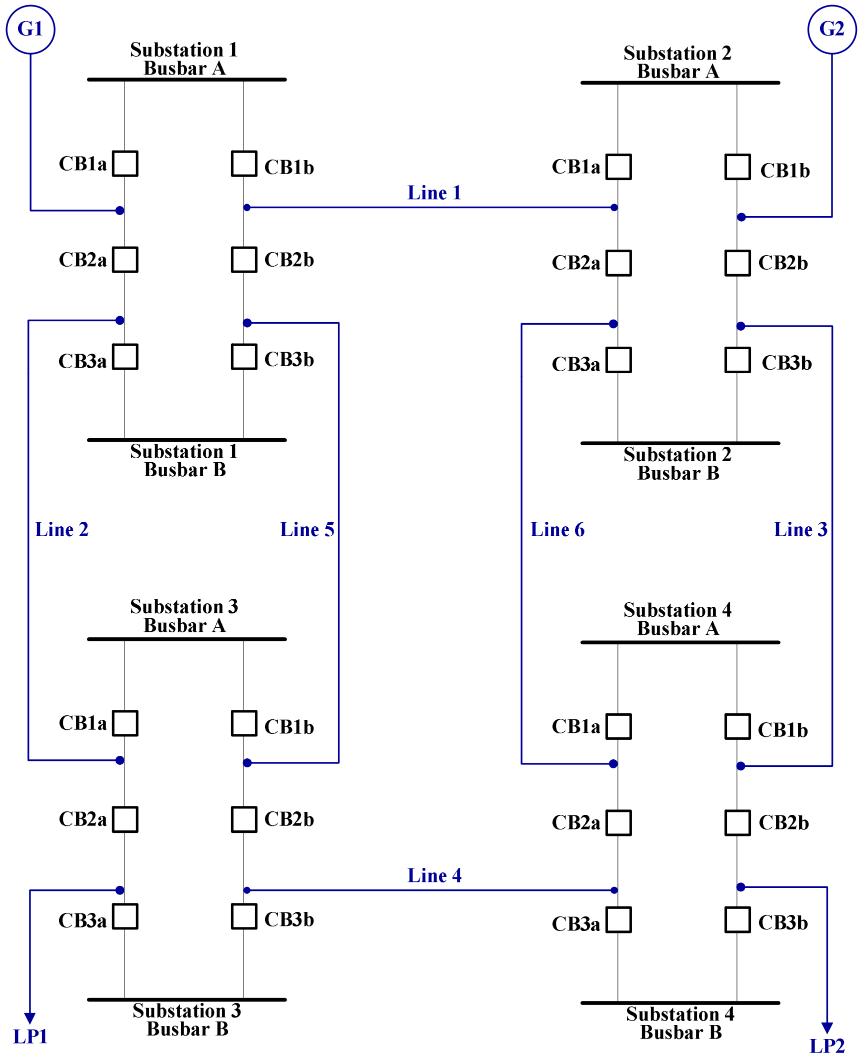


Fig. 4. Single line diagram with breaker-and-a-half substation configuration for MOPAL network

$$\lambda_1 * [P_{C[CB1b@SS1]} * P_{C[CB2b@SS1]}] * P_{U-Ns[CB3b@SS1]} \qquad (10)$$

<u>Scenario 2 – Fault on line 4 and subsequent protection system response at Substation 3</u>: (*When a fault occurs on line 4 and its primary protection system at Substation 3 acts correctly to isolate the faulted line 4 from SS3.*)

The main breaker of line 4 at SS3, CB3b, and the tie-breaker of line 4 at SS3, CB2b, trip to isolate the faulted line 4 from SS3. Either CB3a, the designed backup for CB3b, or CB1b, the designed backup for CB2b, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3a has no impact on the outgoing connection to LP1. However, the unwanted non-selective operation of CB1b will isolate line 5 from SS3. Thus, the situation resulting in FT4 on line 5 from the neighbouring line 4 can be summarized as 'fault on line 4, correct operation of CB3b and CB2b at SS3, but unwanted non-selective operation of CB1b at SS3'.

Thus, failure contribution from FT4 Scenario 2 of line 5 is:

$$\lambda_4 * [P_{C[CB3b@SS3]} * P_{C[CB2b@SS3]}] * P_{U-Ns[CB1b@SS3]} \qquad (11)$$

<u>Scenario 3 – Fault on line 2 and subsequent protection system response at Substations 1 and 3</u>: (a). At Substation 1, the primary protection system acts correctly to isolate faulted line 2 from SS1: The main breaker of line 2 at SS1, CB3a, and the tie-breaker of line 2 at SS1, CB2a, trip to isolate the faulted line 2 from SS1. Either CB3b, the designed backup for CB3a, or CB1a, the designed backup for CB2a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB3b has no impact on line 5. However, the unwanted non-selective operation of CB1a will isolate generator G1 from SS1. This could be thought of as a dependent failure. Thus, the situation resulting in FT4 on line 5 from the neighbouring line

2 at Substation 1 can be summarized as ‘fault on line 2, correct operation of CB3a and CB2a at SS1, but unwanted non-selective operation of CB1a at SS1’.

Thus, failure contribution from FT4 Scenario 3(a) of line 5 is:

$$\lambda_2 * [P_{C[CB3a@SS1]} * P_{C[CB2a@SS1]}] * P_{U-Ns[CB1a@SS1]} \tag{12}$$

(b). At Substation 3, the primary protection system acts correctly to isolate faulted line 2 from SS3: The main breaker of line 2 at SS3, CB1a, and the tie-breaker of line 2 at SS3, CB2a, trip to isolate the faulted line 2 from SS3. Either CB3a, the designed backup for CB2a, or CB1b, the designed backup for CB1a, is prone to unwanted non-selective operation. The unwanted non-selective operation of CB1b has no impact on line 5. However, the unwanted non-selective operation of CB3a will isolate load point LP1 from SS3. This could be thought of as a dependent failure. Thus, the situation resulting in FT4 on line 5 from the neighbouring line 2 at Substation 3 can be summarized as ‘fault on line 2, correct operation of CB1a and CB2a at SS3, but unwanted non-selective operation of CB3a at SS3’.

Thus, failure contribution from FT4 Scenario 3(b) of line 5 is:

$$\lambda_2 * [P_{C[CB1a@SS3]} * P_{C[CB2a@SS3]}] * P_{U-Ns[CB3a@SS3]} \tag{13}$$

In effect, the situations resulting in FT4 on line 5 from the neighbouring line 2 can be summarized as ‘fault on line 2, correct operation of CB3a and CB2a at SS1, but unwanted non-selective operation of CB1a at SS1’ or ‘fault on line 2, correct operation of CB1a and CB2a at SS3, but unwanted non-selective operation of CB3a at SS3’. Thus, the overall failure rate contribution from FT4 Scenario 3 of line 5, is the summation of Eqns. (12) and (13).

The equivalent failure rate of a line on account of its failure due to various protection system response scenarios is obtained as the summation of the failure rates of the identified failure modes. For the elemental analysis of line 5 as illustrated above,

$$\lambda_{Eq.(5)} = \lambda_{FT1(5)} + \lambda_{FT2(5)} + \lambda_{FT3(5)} + \lambda_{FT4(5)} \tag{14}$$

The equivalent failure rates of all the remaining transmission lines of Fig. 4 are obtained on similar lines. The concept of variable failure rates of minimal cutsets as explained in Section III B is then utilized accordingly. In addition to the formulae shown in Eqns. (1) and (2), for further details on the application of minimal cutset approach in obtaining the various reliability indices, the reader is referred to [15].

B. Results

Minimal cutsets of up to third order for both load points of the MOPAL network, as obtained from a contingency analysis phase, for an operating state OS1, are shown in Table I. Tables II to V provide an overview of the comparative analysis of the proposed approach of including the unreliability impact of protection and control (P&C) in the reliability assessment including the breaker-and-a-half substation configuration against the benchmark cases of perfect P&C and P&C modelled simplified bus configuration. The typical reliability indices of interest are - λ , U, and r. Subsequently, the annual power interrupted (PI) and annual energy not supplied (ENS) have been computed. It is clearly seen that simplified busbar configurations yield pessimistic results. A realistic reliability appraisal is possible only when the substation configuration is taken into account for identifying the impact of protection system reliability on power system reliability, as seen from the relative percentage changes in the comparative analysis.

As expected, the results confirm the superior reliability standard of the breaker-and-a-half substation architecture. The assumption of what constitutes a dependent failure in the scenario analyses, e.g., isolation of a load point or a generator from a substation as a consequence of the various possible switching actions in the protection system operation upon the occurrence of a line fault, has a bearing on the values of the reliability parameters.

The proposed methodology is yet to be tested on an actual system. It is however anticipated that the complexity of algorithm should not be an issue for actual systems given as how scenario analysis-related failure rate expressions are simple non-linear equations requiring direct substitutions. The usage of approximate methods for handling the MC-based reliability calculations greatly simplifies the computational burden. The procedure can be easily extended to substations with different busbar configurations, requiring only the FT3 and FT4 failure contribution expressions to be modified, from the first principles, based on the corresponding architecture.

Through the systematic MC-based approach as presented in this paper, the need for Markov models is bypassed, thus eliminating the issue of state space explosion. Future work involves a detailed sensitivity analysis of input data parameters.

TABLE I. MINIMAL CUTSETS FOR MOPAL NETWORK

OS1 LP1	**OS1 LP2**
{4, 5}, {2, 4}, {3, 5, 6}, {2, 5, 6}, {2, 3, 6}, {2, 3, 5}	{5, 6}, {4, 6}, {3, 6}, {3, 5}, {3, 4}, {2, 6}, {2, 5}, {2, 3}

TABLE II. BASIC RELIA. INDICES – COMPARATIVE ANALYSIS FOR OS1LP2

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**
Perfect P&C	0.323	6.28	2.028
P&C Modelled w/o SS	1.733	1.58	2.739
P&C Modelled with SS	1.073	2.40	2.234

TABLE III. BASIC RELIA. INDICES – COMPARATIVE ANALYSIS FOR OS1LP1

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**
Perfect P&C	0.087	5.98	0.519
P&C Modelled w/o SS	1.014	0.97	0.984
P&C Modelled with SS	0.395	1.70	0.673

TABLE IV. ADDITIONAL RELIA. INDICES – COMPARATIVE ANALYSIS FOR LP1

Method	**PI (MW/yr)**	**ENS (MWh/yr)**
Perfect P&C	2.82	16.86
P&C Modelled w/o SS	32.97	31.98
P&C Modelled with SS	12.83	21.86

TABLE V. ADDITIONAL RELIA. INDICES – COMPARATIVE ANALYSIS FOR LP2

Method	**PI (MW/yr)**	**ENS (MWh/yr)**
Perfect P&C	9.66	63.33
P&C Modelled w/o SS	45.69	81.52
P&C Modelled with SS	27.99	72.49

V. CONCLUSIONS

As evidenced by the comparative assessment of the results, comprehensive evaluation of the impact of dependent failures of lines caused by various transmission protection system events cannot be carried out if terminal stations are modelled as simplified single busbars. Due consideration must be given to the internal configuration of substations. Towards this end, a scenario analysis based methodology has been put forward in the paper to model the transmission line failure modes on account of the various protection system response scenarios, which are a function of the substation configuration. The reliability model is based on the minimal cutsets of transmission lines obtained from the information on critical contingencies leading to potential interruptions or reduced supply at various delivery points in the power system. This paper is not about the typical reliability analysis of station originated events of substations, where forced outages of generators and lines because of random failure events in the substation are analysed. As it is, there is a significant effect of reliability of protection systems on the reliability of supply, demonstrating the need for incorporating appropriate protection system reliability models in predictive power system reliability studies.

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Consideration of transmission protection system response in reliability of electricity supply analysis – case study

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SUMMARY

A realistic appraisal of reliability attributes of electricity supply must also take into account an appropriate modelling and analysis of protection system response scenarios of transmission lines. Due to the prevailing transmission line backup protection coordination schemes, there exist several functional dependencies in their operation. Transmission protection schemes are thus amenable to the propagation of failures due to such dependencies. Neglecting the failure dependency impact would be an oversimplification, leading to the consequent underestimation of the various reliability indices. The scope of studies concerning the impact of protection system reliability on power system reliability is usually restricted to the theoretical domain. This is due to the lack of a suitable methodology and the pertinent input data parameters such as protection system failure rates and probability attributes of missing and unwanted operations of protection systems. The objective of this paper is to present a practical case study based on a Norwegian power system, which effectively accounts for the due consideration of the various transmission protection system response scenarios in the reliability analysis of electricity supply. The methodological evolution towards an integrated approach is first presented. It is then followed by a brief chronicle of the theoretical developments initiated by us in this field, and the subsequent application to a practical case study.

KEYWORDS

Dependency - Failure Mode – Norwegian power system - Protection System - Reliability - Transmission Network

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1 INTRODUCTION

An integrated approach for the reliability of electricity supply analysis has been recently established [1, 2]. It is based on a contiguous deployment of a power market simulator (EMPS), a power system simulator (PSS^{TM}E), and a methodology for delivery point reliability and interruption cost assessment (OPAL). This is found to have several applications in short term and long term planning studies, and has relative advantages over the usually fragmented traditional methods of reliability analysis that mostly account for worst case scenarios. As regards the reliability analysis, the objective is to determine the reliability of supply indices for delivery points under study, i.e., to estimate the frequency and duration of interruptions, energy not supplied (ENS), and the corresponding cost of energy not supplied (CENS), e.g., in accordance with the Norwegian quality of supply regulation.

Demonstration studies conducted in this regard [3] on sample test systems have shown the robustness of the integrated methodology in obtaining the relevant reliability indices. But it has been previously identified that protection system failures could have a high impact on the reliability of supply [4]. On the basis of empirical evidence provided by a comparative review of fault statistics, efforts were initiated to capture the impact of protection system imperfections on predictive power system reliability studies. Subsequently, a comprehensive algorithmic approach was presented in [5], accounting for a more systematic way of handling dependent failures propagated by transmission protection systems. The main objective of this paper is to extend the present approach to include such considerations of transmission protection system response in the reliability of supply analysis, and bring forth the implications and study the practical constraints encountered, with recourse to alternatives. Accordingly, a case study based on a Norwegian power system is employed in this paper, encouraged by the results of a preliminary investigation carried out from a related exercise on a sample test system [6].

The results shown in this paper will ascertain that the effects of protection system response scenarios on transmission line outages are vital to the realistic appraisal of reliability attributes of electricity supply. Without taking into account the dependability and security attributes of transmission protection systems [7], the obtained reliability indices are found to be very optimistic, and lacking in credibility. Due to the prevailing transmission line backup protection coordination schemes, several functional dependencies arise, neglecting whose failure-dependency impact leads to oversimplifications and consequent underestimation of reliability indices. Hence, emphasis is laid in this paper on the identification and analysis of multiple failure modes of transmission lines arising out of the various protection system response scenarios. The approach and results are demonstrated for a case study based on a Norwegian power system, using the aforementioned integrated approach that is now made comprehensive by the inclusion of detailed protection system modelling.

Of the relatively fewer studies available in literature on the impact of protection system failures on power system reliability, usage of extensive and complex Markov models or fault trees combined with event trees has been resorted to. This renders their practical application very difficult. One of the unique features of this paper is the incorporation of protection system failure-dependency effects in the integrated reliability analysis without the need for Markov models. Also highlighted is the need for finer resolution of protection system related fault statistics in order to effectively gather the required input data requirements. Altogether, the extensions to the existing integrated methodology by incorporating transmission line protection system failure considerations is expected to enable a consistent analysis of societal impacts of risk of load curtailment and interruption costs for delivery points.

2 OVERVIEW OF THE INTEGRATED APPROACH

An integrated methodology for security of supply analysis involves three distinct phases [1-3]: power market analysis (phase 1), contingency analysis (phase 2) and reliability analysis (phase 3). This integration enables a better information exchange and interaction between the different actors of the chain of analysis.

Phase 1: In the security constrained power market analysis phase (EMPS/power flow/voltage stability), generation and power market scenarios are combined to produce a set of 'operating states.' The definition of operating state as postulated by the EPRI report on transmission system reliability methods [8] is as follows: '*a system state valid for a period of time, characterized by its load and generation composition including the electrical topological state (breaker positions etc.) and import/export to neighbouring areas.*' These operating states can be further grouped using different clustering functions to obtain representative scenarios that can significantly reduce the computational requirements [9].

Phase 2: Analytical contingency simulation of component failures due to random events is carried out using AC/DC power flow models. Minimal cutsets of transmission lines are then obtained for each operating state and delivery point. This is based on the information on critical contingencies leading to potential interruptions or reduced supply at various delivery points in the power system. Contingencies resulting in overload or voltage problems are flagged for a more detailed analysis.

Phase 3: The reliability model is based on the minimal cutsets for each delivery point. Relying on the approximate methods of system reliability evaluation, a simple yet efficient way to obtain the various reliability indices for each delivery point is then put in place –number of interruptions per year λ, annual expected interruption duration U, and expected average interruption duration r. Subsequently, the annual power interrupted (PI), annual energy not supplied (ENS) and annual interruption costs (cost of energy not supplied, CENS) are computed.

A simplified self-explanatory schematic of the integrated approach displaying phases 2 & 3 is shown in Fig. 1 in the next page.

3 RELIABILITY ANALYSIS PHASE

In the previous publications on the integrated methodology [1-3], phases 1 and 2 as mentioned above have been covered in detail. Handling of protection system failures in the reliability phase had received a rather nominal treatment. Through [1-3], the minimal cutset based reliability methodology using approximate methods of system reliability evaluation was well established in general. However, the methodology specifically pertained to the investigation of procedural conceptualization of reliability analysis for perfectly reliable protection systems. By incorporating a detailed modelling and analysis of transmission system protection scenarios into this scheme, a ***modified comprehensive integrated approach*** for the reliability of electricity supply analysis can now be established. The additional inputs required for such a reliability analysis are the information about the protection configuration, fault statistics and specific interruption costs. The reliability indices are then weighted according to the probability of the different operating states to obtain annual indices.

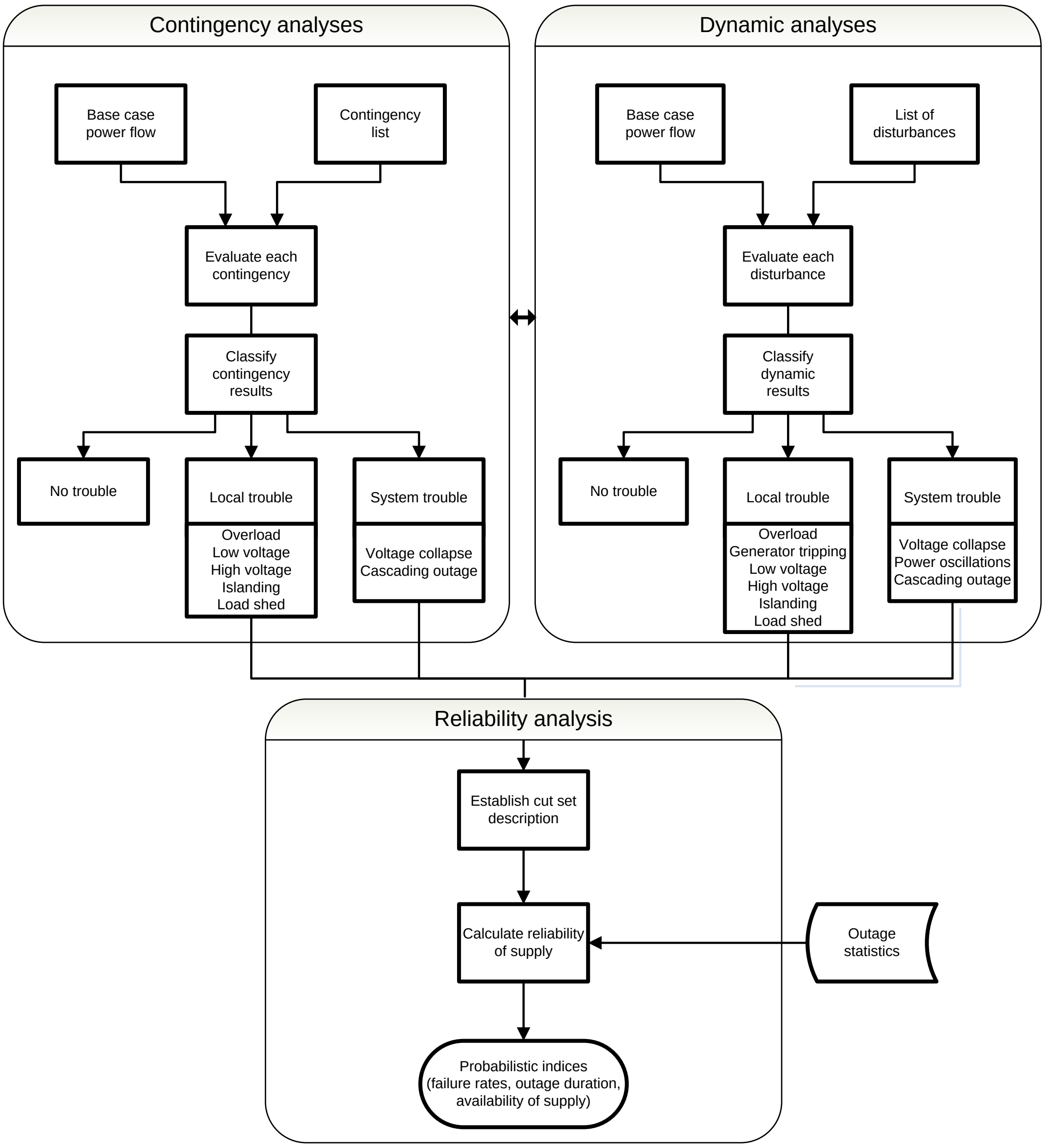

Fig. 1. Simplified schematic of the integrated approach

For the sake of a succinct overview, a consolidated description of transmission line failure modes on account of the various possible protection system response scenarios is reproduced below from [5, 6]. For the corresponding translation of these defined scenarios into mathematical models, i.e., the failure rates quantifying each of these ‘fault type’ scenarios, the reader is referred to [5, 6]. This is where the previous simple integrated methodology differs from the presented modified comprehensive integrated methodology. Once all the minimal cutsets are obtained, failure rates of the corresponding transmission lines of each minimal cutset are systematically augmented. This is done by incorporating additional failure rates that pertain to protection system response scenarios, based on the topology of the elements of a minimal cutset (i.e., based on whether the transmission line elements are neighbouring or not). For every minimal cutset, dependent mode failure rates as mandated by backup protection coordination among the neighbouring elements if any, are computed. All the minimal cutsets are duly combined using the approximate series system reliability logic.

Fault Type 1 (FT1): A fault occurs on the transmission line i, upon which there could be two consequent scenarios:
Consequent Scenario 1 (CS1): Because of the readiness of line i's primary protection system, the fault is cleared correctly. The line remains isolated from the system until its repair is complete. The outage time associated with FT1 of line i, is the same as the line's repair time.
Consequent Scenario 2 (CS2): Because of the unreadiness of line i's primary protection system, the fault cannot be cleared, and protection system unit(s) of the neighbouring lines must act to isolate the faulted line. The fault on line i cannot be cleared by the line's primary protection system on account of the one of the following conditions: Unreadiness of protection system at one end of the line; Unreadiness of protection system at the other end of the line; Unreadiness of protection systems at both ends of the line.

Fault Type 2 (FT2): The transmission line i is fault-free, but because of faulty operation of the line's primary protection system, unwanted spontaneous tripping of the circuit breaker(s) occurs. This results in isolation of the healthy line i. This situation can be remedied by auto-reclosure of the breaker associated with the corresponding protection system unit. The outage time associated with FT2 of line i, is the same as the line's protection unit's repair/replacement time.

Fault Type 3 (FT3): A fault occurs on one of the neighbouring transmission lines, but because of the faulty operation of a protection system assembly of the neighbouring line, its corresponding circuit breaker fails to act. This results in missing operation of a circuit breaker, because of which the faulted neighbouring line cannot be isolated by its own circuit breakers. In such a case, a protection system assembly of line i acts as back-up to isolate the faulted neighbouring line. This also results in isolation of the healthy line i. The outage time associated with FT3 of line i, is the same as the switching time.

Fault Type 4 (FT4): A fault occurs on one of the neighbouring transmission lines, upon which the neighbouring line's primary protection system clears the fault correctly. However, because of faulty operation of either of the protection system units of line i or both protection system units of line i, unwanted non-selective tripping of line i's circuit breaker(s) occurs. This results in healthy line i's isolation. The outage time associated with FT4 of line i, is the same as the switching time.

The equivalent failure rate of line i taking into account the significant transmission line failure modes due to the various protection system response scenarios is obtained as the summation of individual failure rates of all the above fault types. This is a valid logic since these failure mode states are mutually exclusive for line i, and elements exhibiting such multiple failure modes can be modeled using appropriate series/parallel reliability logic. A system with a component consisting of four mutually exclusive failure modes is analogous to a four component series system. Thus, the equivalent failure rate of line i is given as the summation of failure rates quantifying all the fault types mentioned above. Some of the important points to be noted about the various fault types are as follows: CS1 of FT1 on line i 'may' result in FT4 on neighbouring line j, and vice-versa; CS2 of FT1 on line i 'will' result in FT3 on neighbouring line j, and vice-versa.

Thus, both the consequent scenarios of FT1 could result in multiple transmission line isolations due to the dependency effects of back-up protection system coordination design. These scenarios are quantified and made use of as dependence mode failure rates in the reliability analysis. FT2 is the only fault type which is independent in that there is no failure propagation to the neighbouring lines at all times.

4 CASE STUDY

The modified comprehensive integrated methodology is applied for a realistic case in the middle of Norway (*Midt-Norge*), assessing the reliability of supply for two different delivery points in the 420 kV transmission grid. One is situated more or less in the centre of the grid (LP1), the other at the end of a line with single sided supply (LP2). *Midt-Norge* is represented by area “10” in the EMPS model shown in Fig. 2 below. A reliability assessment of this configuration was previously carried out in [1, 2], but by using a simple integrated methodology for the year 2010 only. The results of the application of the modified comprehensive integrated methodology for the *Midt-Norge* case study are presented in this section, with relevant sample calculations. All the data concerning the power market analysis phase and contingency analysis phase remains the same for the year 2010, i.e., the input for phase 1, the output of phases 1 and 2 are the same for both the earlier adopted simple integrated approach and the current modified comprehensive integrated approach; the procedure carried out to obtain these outputs for eventual information on minimal cutsets to be used in the reliability analysis phase is outlined below.

The system was analysed using three different operating states to represent the year 2010; these were the weeks 4, 16 and 30. Week 4 represents a heavy load situation, week 16 represents a still quite heavy load situation and hydro reservoirs running out of water, while week 30 represents light load. Power flow and market models for the year 2010 have been used as a basis with 650 MW load in LP1 and 220 MW load in LP2.

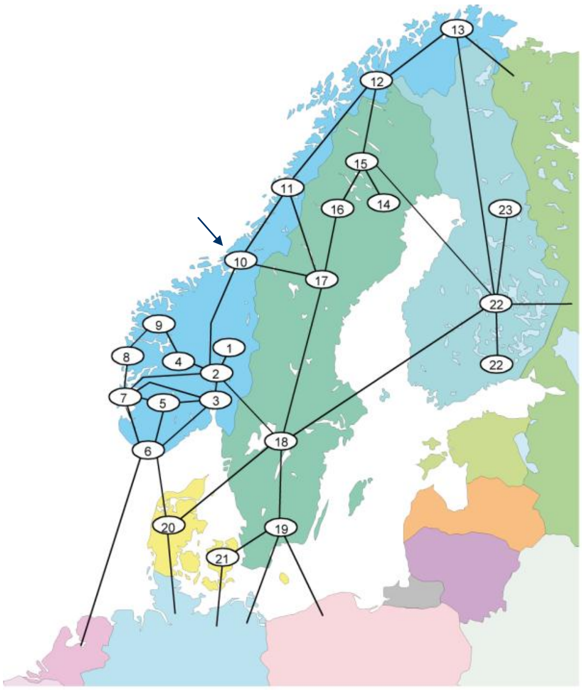

Fig. 2. The EMPS model and division of areas

Week 4 is representative of weeks 42-14; week 16 is representative of weeks 15-25; and week 30 is representative of weeks 26-41. From this information, the probability of occurrence of these three different representative operating states can be obtained.

The first analysis step was to initialize the three operating states through interaction between EMPS (market model) and PSS^{TM}E (power flow model) in a security constrained market analysis. In the estimation of transmission capacities to the neighboring areas, the limiting factor turned out to be voltage stability. The EMPS model was updated with the transmission capacities in the different operating states, and their respective probabilities of occurrence were provided as input to the contingency analysis.

In this case, TPLAN[1] was used to screen the system and provide a list of contingencies of single outages to be evaluated. Contingencies of double outages were defined manually. A total of 330 single and 46 double outages were analysed. For each of the 376 contingencies the system consequence was found. This involved deciding whether or not the contingency would lead to an interruption for the load points of interest. Voltages and overloads were checked to uncover if or not the system was within its defined limits. The simulations and consequence analysis led to lists of contingencies which caused interruptions for delivery points LP1 and LP2 in the different operating states represented by weeks 4, 16 and 30. The interruptions were due to islanding, overload or voltage deviations. No curtailment or blackout-situations were revealed for the chosen operating states.

Thus, for the calculating the reliability indices in the last phase, several minimal cuts were identified both for LP1 and LP2, depending on the operating state. Only first and second order cuts (i.e. single and double outages) were taken into account for the ensuing application of approximate methods of system reliability evaluation. Not only line faults, but also busbar faults are considered in the MCs.

In Norway, FASIT (Fault And Supply Interruption information Tool) [10], developed based on international terms and standards, e.g. IEEE Std. 859 – 1987, is widely in use by all the network companies including the TSO Statnett. It is now the national standard for collection, calculation and reporting of reliability data for all voltage levels above 1 kV [10], regulated through the Norwegian quality of supply regulation. Norwegian fault statistics were analysed to obtain a representative input data set for failure rate parameters and probability attributes of protection system units as required for the reliability analysis in phase 3.

The procedure was repeated for data pertaining to the future scenario – year 2015. Tables 1 through 4 show the end results of the various power system reliability computations for the various cases. Fig. 3 is a sample schematic of a portion of the network under study, depicting the arrangement of neighbouring transmission lines that helps in identifying the nature of composition of an MC. There are 12 buses (A to L) and 12 transmission lines (1 to 12) in the sample portion of the network. Lines 1 through 6 are 420 kV lines; lines 7 through 12 (indicated in red colour) are at lower voltage levels. Adjacent lines at different voltage levels are assumed to be non-neighbouring, so that backup protection system coordination effects are relegated to lines of similar voltage levels. For example, a fault on a line of voltage level ‘x’ will not result in unwanted non-selective operation of the protection system of the adjacent line of voltage level ‘y’. Neither will it result in the missing operation related backup actions

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[1] Transmission Planning, Siemens PTI

(such as disconnection of both lines x and y). Thus, the augmentation of each of the original failure rates of the transmission lines in an MC with equivalent failure rates of FT2, FT3 and FT4 will involve the neighbouring line topology as shown in Fig. 4.

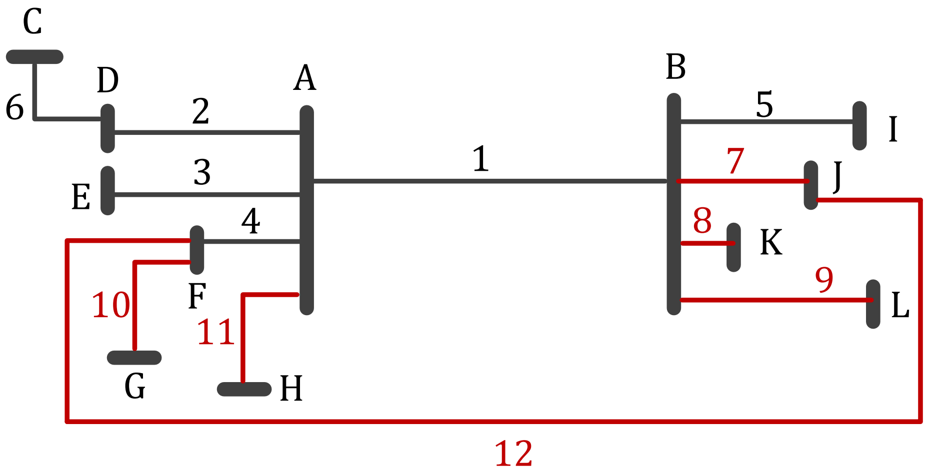

Fig. 3. Sample schematic of a portion of the network under study, depicting the arrangement of all neighbouring transmission lines

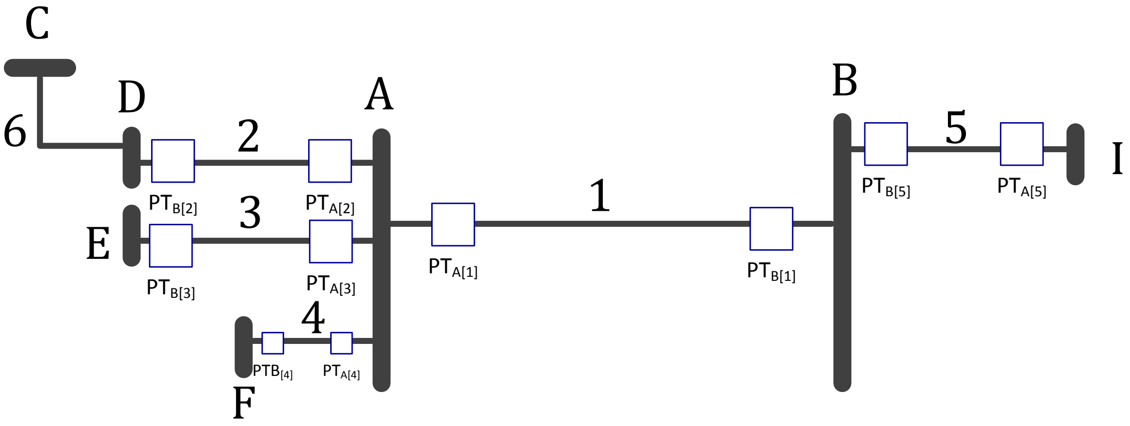

Fig. 4. Sample schematic of a portion of the network under study, depicting the arrangement of neighbouring transmission lines of 420 kV, including protection system units

One of the most important MCs for both load points LP1 and LP2 is MC {1, 4}.

Sample calculations – Scenario studies for FT3 and FT4 of MC {1, 4}:

Situations resulting in FT3 on line 1 yield the following scenarios:

Scenario 1: Fault on line 2, failure of protection system unit $PT_{A[2]}$

Scenario 2: Fault on line 3, failure of protection system unit $PT_{A[3]}$

Scenario 3: Fault on line 4, failure of protection system unit $PT_{A[4]}$

Scenario 4 : Fault on line 5, failure of protection system unit $PT_{B[5]}$

Failure rate contributions from Scenarios 1, 2 and 3 belong to the dependency mode failure rate of MC {1, 4} since the occurrence of any of these scenarios will result in the failure of MC {1, 4}.

Situations resulting in FT4 on line 1 yield the following scenarios:
Scenario 1: Fault on line 2, correct operation of $PT_{A[2]}$, but unwanted non-selective operation of $PT_{A[1]}$ or $PT_{B[1]}$ or both.
Scenario 2: Fault on line 3, correct operation of $PT_{A[3]}$, but unwanted non-selective operation of $PT_{A[1]}$ or $PT_{B[1]}$ or both.
Scenario 3: Fault on line 5, correct operation of $PT_{B[5]}$, but unwanted non-selective operation of $PT_{A[1]}$ or $PT_{B[1]}$ or both.
Scenario 4 : Fault on line 4, correct operation of $PT_{A[4]}$, but unwanted non-selective operation of $PT_{A[1]}$ or $PT_{B[1]}$ or both.
Failure rate contributions from Scenario 4 belong to the dependency mode failure rate of MC {1, 4} since the occurrence of this scenario will result in the failure of MC {1, 4}.

As regards line 4 in MC {1, 4}, situations resulting in FT3 on it yield the following scenarios:
Scenario 1: Fault on line 2, failure of protection system unit $PT_{A[2]}$
Scenario 2: Fault on line 3, failure of protection system unit $PT_{A[3]}$
Scenario 3: Fault on line 1, failure of protection system unit $PT_{A[1]}$
However, failure rate contributions from all the above three scenarios pertain to the dependency mode failure rate of MC {1, 4} since the occurrence of any of these scenarios will result in the failure of MC {1, 4}. Thus the equivalent failure rate of FT3 for line 4 in MC {1, 4} is zero. But the contributions from Scenarios 1 and 2 above have already been covered in the analysis of situations resulting in FT3 on line 1, and thus are not taken into account here in the dependency mode failure rate so as to avoid double counting.

Situations resulting in FT4 on line 4 yield the following scenarios:
Scenario 1: Fault on line 3, subsequent successful fault clearance by the protection system units of line 3, but unwanted non-selective operation of either/both of the protection system units of line 4.
Scenario 2: Fault on line 2, subsequent successful fault clearance by the protection system units of line 2, but unwanted non-selective operation of either/both of the protection system units of line 4.
Scenario 3: Fault on line 1, subsequent successful fault clearance by the protection system units of line 1, but unwanted non-selective operation of either/both of the protection system units of line 4. This scenario pertains to the dependency mode failure failure rate of MC {1, 4}.
All the individual dependency mode failure rate contributions from the relevant scenarios above are summed up to get the overall dependency mode failure rate of MC {1, 4}. Mathematical expressions from [5] are employed accordingly to evaluate the various reliability indices.

Table 1. Reliability of supply indices for the delivery points – year 2010, using the modified comprehensive integrated methodology

	Comprehensive Integrated Methodology, 2010							
	Week 4		**Week 16**		**Week 30**		**Annualized Indices**	
Indices	**LP1**	**LP2**	**LP1**	**LP2**	**LP1**	**LP2**	**LP1**	**LP2**
λ, f/yr	0.0422	1.34	0.0539	1.394	0.0539	1.394	0.0483	1.3680
U, hr/yr	0.0105	2.3584	0.0134	2.3698	0.0134	2.3698	0.0120	2.3643
r, hr	0.25	1.76	0.25	1.7	0.25	1.7	0.25	1.7282
PI, MW/yr	13.1875	141.7308	7.4195	64.8746	10.792	94.3630	31.399	300.9684
ENS, MWh/yr	3.2968	249.4462	1.8548	110.2868	2.698	160.4172	7.8497	520.1502
CENS, NOK/yr	218912	16563225	123163	7323046	179147	10651704	521223	34537975

Table 2. Reliability of supply indices for the delivery points – year 2010, using the simple integrated methodology

	Simple Integrated Methodology, 2010							
	Week 4		**Week 16**		**Week 30**		**Annualized Indices**	
Indices	**LP1**	**LP2**	**LP1**	**LP2**	**LP1**	**LP2**	**LP1**	**LP2**
λ, f/yr	0.0211	1.34	0.0329	1.373	0.0329	1.373	0.0272	1.3571
U, hr/yr	0.0052	2.3584	0.0082	2.3752	0.0082	2.3752	0.0068	2.3671
r, hr	0.25	1.76	0.25	1.73	0.25	1.73	0.25	1.7442
PI, MW/yr	6.5937	141.7307	4.5237	63.8973	6.58	92.9415	31.399	298.5696
ENS, MWh/yr	1.6484	249.4461	1.1309	110.5423	1.645	160.7888	4.4243	520.7773
CENS, NOK/yr	109456	16563224	75094	7340011	109228	10676380	293778	34579616

Table 3. Reliability of supply indices for the delivery points – year 2015, using the modified comprehensive integrated methodology

	Comprehensive Integrated Methodology, 2015							
	Week 4		**Week 16**		**Week 30**		**Annualized Indices**	
Indices	**LP1**	**LP2**	**LP1**	**LP2**	**LP1**	**LP2**	**LP1**	**LP2**
λ, f/yr	0.0118	1.352	0.0539	1.394	0.0118	1.352	0.02072	1.3608
U, hr/yr	0.0029	2.366	0.0134	2.3698	0.0029	2.366	0.0051	2.3668
r, hr	0.25	1.75	0.25	1.7	0.25	1.75	0.25	1.7391
PI, MW/yr	3.6875	143	7.4195	64.8746	2.36	91.52	13.467	299.3946
ENS, MWh/yr	0.9218	250.25	1.8548	110.2868	0.59	160.16	3.3667	520.6968
CENS, NOK/yr	61212	16616600	123163	7323046	39176	10634624	223552	34574270

Table 4. Reliability of supply indices for the delivery points – year 2015, using the simple integrated methodology

	Simple Integrated Methodology, 2015							
	Week 4		**Week 16**		**Week 30**		**Annualized Indices**	
Indices	**LP1**	**LP2**	**LP1**	**LP2**	**LP1**	**LP2**	**LP1**	**LP2**
λ, f/yr	0.0118	1.35	0.0329	1.373	0.0118	1.352	0.0162	1.3554
U, hr/yr	0.00295	2.3625	0.0082	2.3752	0.0029	2.366	0.0040	2.3662
r, hr	0.25	1.75	0.25	1.73	0.25	1.75	0.25	1.7457
PI, MW/yr	3.6875	142.7885	4.5237	63.8973	2.36	91.52	10.5712	298.2057
ENS, MWh/yr	0.9218	249.8798	1.1309	110.5423	0.59	160.16	2.6428	520.5821
CENS, NOK/yr	61212	16592019	75094	7340011	39176	10634624	175482	34566654

Analysis of results:
In order to enable an illustrative comparison of the CENS values of the proposed comprehensive integrated methodology with those of the previously postulated simple integrated methodology, a fixed specific interruption cost of 66.4 NOK/kWh of energy not supplied is utilized in all the calculations. In the comparative assessment, one can note that there is a considerable difference in the values of reliability indices obtained for LP1. However, reliability indices for LP2 are more or less similar. This is on account of the composition of MCs. Whereas a majority of MCs for LP1 have predominant interdependencies among the constituent elements, relatively fewer MCs have such interdependencies for LP2. Interruption frequencies are higher for LP2 compared to those of LP1 since LP2 has single sided supply and the single outages are decisive in the reliability computations. CENS values are also the highest for LP2, thus indicating the need for appropriate reinforcements to improve the reliability of LP2. A comparison with the case of perfect and imperfect protection systems has shown that protection system dependencies have a relatively small influence on LP2. The reliability of supply would have been practically 100% for LP1 if protection had not been taken into account since only second or higher order independent outages contribute to the unreliability.

5 CONCLUSIONS

In this paper, a systematic approach to include transmission protection system response in the reliability analysis of electricity supply has been employed to a portion of the Norwegian power system. A modified comprehensive integrated methodology for the security of supply analysis has thus been implemented. In effect, the impact of outages arising from the dependencies related to the missing and unwanted operation of protection systems has been captured. The proposed methodology is expected to enable a consistent analysis of societal impacts of risk of load curtailment and interruption costs for delivery points. Future research work includes the application of this method to consider the impact of detailed substation configurations in the backup protection system coordination.

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Impact of Protection System Reliability on Power System Reliability: A New Minimal Cutset Approach

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Abstract—**In order to capture the effect of dependent failures that could arise due to the various transmission protection system response scenarios on power system reliability, complex Markov models or fault trees combined with event trees are typically employed in the predictive reliability studies. A unique approach utilizing minimal cutsets (MC) and the approximate methods of system reliability evaluation, dispensing with the assumption of perfect protection and control, was recently postulated to obtain various power system reliability indices. The approach was basic in that it was applicable to single circuit meshed transmission systems, where only MCs up to a maximum order of two could be handled. However, the parallel structure of transmission lines in multi-circuit meshed transmission systems, in addition to resulting in possible higher order critical transmission line MCs, creates unique topological dependencies among the backup protection system coordination schemes. In this paper, a comprehensive MC approach to capture the impact of protection system reliability on power system reliability is presented, covering all such consequent dependencies. An illustrative sample case study is used to explain the salient features of the proposed methodology.**

Keywords—Dependent failure, minimal cutset; protection system; reliability; transmission network.

I. INTRODUCTION

The effect of various dependent and common mode outages on the reliability of bulk electric systems has been established to be significant enough as to warrant detailed analysis using appropriate reliability models [1]-[4]. Based on the available outage data statistics from across the world, it could be noted that one of the major causes of dependent failures in power system are transmission protection system failures and misoperations [4]. The prominent characteristic features pertaining to the effect of protection systems on bulk power reliability evaluation in the early 1990s were highlighted by the then Application of Probability Methods task force on protection systems reliability [5], and relevant studies have assumed increasing prominence ever since.

Protection systems are characterized by two attributes: the ability to trip when called for (dependability), and the ability to restrain from tripping when not called for (security). This combined ability, termed as its reliability, is brought about by introducing redundancy features in the fault clearance system that comprises the protection system [6]. But then again, though the facilitation of redundancy reduces the probability of a dependability-based protection system failure, there is a possible increase in the probability of a security-based protection system failure [7]. There are several studies which model the impact of these *basic* failure modes of protection systems on the reliability of power systems using different methodologies, notable ones being the recent propositions such as [8]-[9].

A unique algorithmic approach utilizing MCs and the approximate methods of system reliability evaluation, dispensing with the assumption of perfect protection and control, was recently postulated by us [10] to obtain various power system reliability indices. However, the methodology was applicable only for single circuit meshed transmission systems, where only MCs up to a maximum order of two could be handled. The *basic* failure modes of protection systems were expanded to reflect their effect on the consequent failure modes of transmission lines, for a rigorous analysis. Misoperations in the primary protection systems of transmission lines can lead to dependent failures of the neighbouring transmission lines because of the possible interactive response scenarios arising from the existing backup protection system coordination strategies. Quantifying this failure dependency is crucial to capture the full impact of protection system reliability on power system reliability.

The present paper includes the consideration of additional operational dependencies brought on by the parallel structure of transmission lines in multi-circuit meshed transmission systems, and also accounts for handling the possible higher order critical transmission line MCs in the reliability analysis. This yields a comprehensive MC approach to capture the impact of protection system reliability on power system reliability. The proposed new MC approach is a part of an ongoing project dealing with the development of a comprehensive integrated methodology for security of electricity supply analysis [11] to combine power market analysis with power system (contingency) analysis in the subsequent reliability studies.

II. OVERVIEW OF METHODOLOGY

The definition of MC employed in this work is the one according to the IEEE Standard 493-1997 [12]: "*A set of components that, if removed from the system, results in loss of*

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continuity to the load point being investigated and that does not contain as a subset any set of components that is itself a cutset of the system." The interruptions considered here are total interruptions and also partial interruptions, where a portion of the load at a delivery point may still be supplied. Each contingency leading to such interruptions is represented by an MC of components of the transmission system that are subject to outage. The available capacity to supply a load upon the occurrence of a contingency is termed as system available capacity (SAC).

The term 'operating state' used is in accordance with the definition in the EPRI report on transmission system reliability methods [13]: "*A system state valid for a period of time, characterized by its load and generation composition including the electrical topological state (breaker positions, etc.) and import/export to neighbouring areas.*"

From the analytical contingency simulation of random failures, all the transmission line MCs along with their corresponding SACs are first obtained for every selected operating state. Failure rates of the corresponding transmission lines of each MC are systematically augmented by incorporating additional failure rates that pertain to protection system response scenarios, based on the topology of the elements of an MC (i.e., based on whether the transmission line elements are neighbouring or not). For every MC, dependent mode failure rates as mandated by backup protection coordination among the neighbouring elements if any, are computed, and all the MCs are duly combined using the approximate series system reliability logic.

III. EQUIVALENT FAILURE RATES OF MINIMAL CUTSETS

A. Equivalent Failure Rate of a Transmission line

The various response scenarios of transmission protection systems are translated to corresponding equivalent failure modes of transmission lines by the definition and quantification of fault types (FTs) as initially proposed in [10]. A brief generic description of such fault types is presented below.

Fault Type 1 (FT1): A fault occurs on the transmission line i, upon which there could be two consequent scenarios: Consequent Scenario 1 (CS1) - The fault is successfully cleared by the line's primary protection system; Consequent Scenario 2 (CS2) - The fault could not be cleared because of the unreadiness of the line's primary protection system. The failure rate of FT1 is merely the failure rate of the transmission line.

Fault Type 2 (FT2): The transmission line i is fault-free, but because of faulty operation of the line's primary protection system, unwanted spontaneous tripping of the circuit breaker(s) occurs. This results in isolation of the healthy line i. The failure rate of FT2 is the summation of unwanted spontaneous tripping rates of circuit breakers of line i.

Fault Type 3 (FT3): A fault occurs on one of the neighbouring transmission lines, but the faulty operation of the primary protection system of the neighbouring line results in the missing operation of a circuit breaker, because of which the faulted neighbouring line cannot be isolated by its own circuit breakers. In such a case, the protection system of line i acts as back-up to isolate the faulted neighbouring line. This also results in isolation of the healthy line i.

Fault Type 4 (FT4): A fault occurs on one of the neighbouring transmission lines, upon which the neighbouring line's primary protection system clears the fault correctly. However, because of faulty operation of either of the protection system units of line i or both protection system units of line i, unwanted non-selective tripping of line i's circuit breaker(s) occurs. This results in healthy line i's isolation.

The input data required to treat these fault types in the predictive reliability assessment studies is shown in Table I.

TABLE I. INPUT DATA REQUIREMENTS

No.	**Input Data**	**Symbol**
1	Failure rate of line i	λ_i
2	Probability attributes of the protection system units (PT) of line i: Probability of missing (M) operation, probability of unwanted non-selective (U-Ns.) operation. *(Note: Each of the two ends of a line i, say A-end and B-end, has a protection system unit. The subscript A or B refers to the end at which the unit is located.)*	$P_{M(PT_{A[i]})}$
		$P_{M(PT_{B[i]})}$
		$P_{U-Ns.(PT_{A[i]})}$
		$P_{U-Ns.(PT_{B[i]})}$
3	Failure rate of unwanted spontaneous tripping of circuit breakers of line i's protection system units	$\lambda_{BE_{A[i]}}$
		$\lambda_{BE_{B[i]}}$
Note: Missing probability of a protection system unit subtracted from unity gives the conditional probability of the unit clearing a fault on a line given that a fault occurs on the line.		

The quantification of the failure rates, from the first principles, of the various fault types when there are exactly two neighbouring lines for every transmission line in single circuit meshed systems was presented in [10]. As the name of the studied transmission configuration suggests, there existed no parallel neighbouring transmission lines. Consideration of parallel configurations, as found in multi-circuit meshed transmission systems, would essentially change the formulation of failure rate quantifications for FT3 and FT4.

A simple bus arrangement is initially chosen as the basis for the ensuing modifications. Detailed station configurations are currently being addressed in the ongoing phase of research. Some of the operational aspects of a simple bus arrangement in multi-circuit meshed transmission systems are given below:

- Every time there is a fault on a parallel line, if it is not cleared, its counterpart will 'successfully' get disconnected.
- Every time a parallel line performs a back-up action, its counterpart also does the same. Implication: Calculation of FT3 changes.

- If there is unwanted non selective operation of a parallel line, it is assumed its counterpart will NOT experience the same (because of the assumption that faulty operations happen one at a time). Implication: Calculation of FT4 changes.

In the case of FT3 for a single circuit meshed transmission system, the 'net' FT3 failure rate of a transmission line was dependent upon the number of neighbouring transmission lines, i.e., there were as many 'terms' in the net FT3 failure rate of a transmission line under consideration (say, line i) as were the number of neighbouring lines. Each 'term' quantified an FT3 failure rate contribution from each neighbouring line. From the first principles, it was shown that each 'term' was a simple multiplication of the failure rate of the neighbouring transmission line (say for a neighbouring line j, λ_j) and the missing probability of an end protection system unit of the neighbouring transmission line (say if PT_A was the protection system unit at the end of the neighbouring line closest to the transmission line i under consideration, then $P_{M(PT_{A[j]})}$). Thus, the FT3 failure rate contribution to line i from a non-parallel neighbouring line j amounts to $\lambda_j * P_{M(PT_{A[j]})}$.

However, from a parallel neighbouring transmission line, say line k, the FT3 failure rate contribution will have to include the likelihood of the events that either one of the end protection system units of the parallel neighbouring line can encounter a missing operation. These are independent but not mutually exclusive events. Thus, the FT3 failure rate contribution from a parallel neighbouring line k to line i amounts to: $\lambda_k (P_{M(PT_{A[k]})} + P_{M(PT_{B[k]})} - P_{M(PT_{A[k]})} * P_{M(PT_{B[k]})})$

In the case of FT4 for a single circuit meshed transmission system, the 'net' FT4 failure rate of a transmission line was also dependent upon the number of neighbouring transmission lines, i.e., there were as many 'terms' in the net FT4 failure rate of a transmission line under consideration (say, line i) as were the number of neighbouring lines, similar to the case of FT3. Each 'term' quantified an FT4 failure rate contribution from each neighbouring line. From the first principles, it was shown that each 'term' was a simple multiplication of the failure rate of the neighbouring transmission line (say for a neighbouring line j, λ_j) multiplied by the conditional probability of the 'nearest' protection system unit of the neighbouring line successfully clearing a fault on it given that a fault occurred on it, and the probability of unwanted non-selective operation of either protection system units of the transmission line under consideration (line i). Say if PT_A was the nearest protection system unit of the neighbouring line j, then the FT4 failure rate contribution to line i from a non-parallel neighbouring line j amounts to:

$$[\lambda_j * (1 - P_{M(PT_{A[j]})})] * \begin{pmatrix} P_{U-Ns.(PT_{A[i]})} + P_{U-Ns.(PT_{B[i]})} \\ -P_{U-Ns.(PT_{A[i]})} * P_{U-Ns.(PT_{B[i]})} \end{pmatrix} \tag{1}$$

However, for a parallel neighbouring transmission line, say line k, the FT4 failure rate contribution will have to reflect the conditional probability of both protection system units of the neighbouring line acting to successfully clear the fault upon its occurrence on it. Thus, the FT4 failure rate contribution from a parallel neighbouring line k to line i amounts to:

$$\begin{gathered}[\lambda_k * (1 - P_{M(PT_{A[k]})}) * (1 - P_{M(PT_{B[k]})})] * \\ \left(P_{U-Ns.(PT_{A[i]})} + P_{U-Ns.(PT_{B[i]})} - P_{U-Ns.(PT_{A[i]})} * P_{U-Ns.(PT_{B[i]})}\right)\end{gathered} \tag{2}$$

The equivalent failure rate of line i is the summation of failure rates of all the four FTs.

B. Order of Minimal Cutsets

Theoretically, all the MCs of a power system must be analyzed for a given operating state in order to carry out accurate reliability analysis. However, keeping in mind that the probability of higher order cutsets is negligible when compared to that of lower order cutsets, for the sake of computational efficiency, reasonable approximations can be resorted to. Thus, the assessment may be limited to credible contingencies based on pre-select contingency cut-off criteria. A good rule of thumb, generally accepted, is to consider MCs up to order n+1 where n is the lowest-order MC of the system [12]. The lowest possible order being 1, it is mandatory to have a methodology in place that at least analyzes second order MCs for reliability analysis. However for n-1 secure power systems, the lowest order MC will be 2, mandating a methodology that can analyze at least third order MCs.

C. Types of Minimal Cutsets: Variable Failure Rates

Neighbouring lines are defined as transmission lines connected to a common bus. By the same convention, parallel lines between bus pairs fall in this category. For a finer distinction in the convention, there can be a further classification of neighbouring lines as parallel neighbouring lines and non-parallel neighbouring lines. For an MC with only non-neighbouring transmission lines, the equivalent failure rate of each line in it is obtained by computing failure rates of FT1, FT2, FT3 and FT4 as indicated above and summing them up.

The equivalent failure rate of a transmission line is 'variable' (not to be confused with time-dependent failure rate), depending upon the composition of the MC which it is a part of. This composition governs the way in which FT3 and FT4 are to be calculated for each of the elements. A line x when part of an MC 1 can have a different equivalent failure rate than when it is a part of MC 2. It must be noted that CS1 of FT1 on line i 'may' result in FT4 on neighbouring line j, and vice-versa. CS2 of FT1 on line i 'will' result in FT3 on neighbouring line j, and vice-versa. If neighbouring lines i and j are constituents of an MC, any of these *four* scenarios will result in the failure of the whole cutset. Thus, the failure rate contributions from these four scenarios form the dependency failure rate of the MC, and these contributions are duly removed from the corresponding individual equivalent failure rates of the lines.

For each line belonging to an MC, a combinatorial analysis of all possible backup coordination related *interaction scenarios* among its neighbouring lines is carried out (sample calculations are shown in the illustrative case study section). For each of these *interaction scenarios*, a failure rate contribution expression is formulated from the first principles with respect to fault types FT3 and FT4. This is relatively straight forward for elements of MCs with constituent non-neighbouring lines. However, in the case of MCs with constituent neighbouring parallel lines or neighbouring non-parallel lines or a combination thereof, a subset of these interaction scenarios, which pertains to dependency failure among all the MC constituents are set aside. Such failure rate contributions are not included in the individual failure rate expressions of FT3 and FT4 of the elements in the MCs, but utilized only in the expressions for dependency mode failure rates of the MCs.

D. Handling Dependencies in Minimal Cutsets

If x and y are two components of a parallel system that has a common mode/dependency mode failure, the resulting reliability block diagram (RBD) can be represented as simplified to a two component independent parallel system in series with a *component* accounting for the common mode/dependency mode failure. Such a consequent ‘series’ system can fail either when the parallel block of x and y fails independently or when there is an occurrence of a *scenario* which results in the common mode/dependency mode failure of both x and y. Similarly, if x, y and z are three components of a parallel system that has a common mode/dependency mode failure, the resulting RBD can be represented as simplified to a three component independent parallel system in series with a *component* accounting for the common mode/dependency mode failure. Such a consequent ‘series’ system can fail either when the parallel block of x, y and z fails independently or when there is an occurrence of a *scenario* which results in the common mode/dependency mode failure of all the three elements. This is shown in Fig. 1. A similar logic is applicable to MCs.

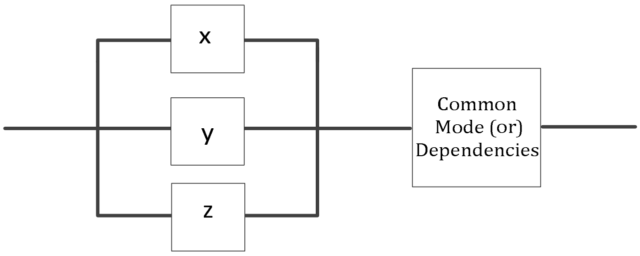

Fig. 1. Minimal cutset equivalence with RBD for handling dependencies

The dependency scenarios are obtained from the combinatorial analysis of backup coordination related interaction scenarios among the corresponding transmission lines of an MC. In the case of an MC group of 2 neighbouring parallel lines and 1 non-neighbouring line, there is no scenario which can result in the simultaneous failure of all three elements of the cutset; however there will arise a dependency scenario where two elements can fail because of dependency. If x and y are neighbouring lines, and y is a non-neighbouring line, the partial dependency scenario is handled using a decomposition technique as shown in Fig. 2.

From the approximate methods of reliability evaluation for a parallel system [14] consisting of three components without dependent failures, basic reliability indices are given in Equations (3)-(5). These can be modified suitably to incorporate dependency mode failure rates.

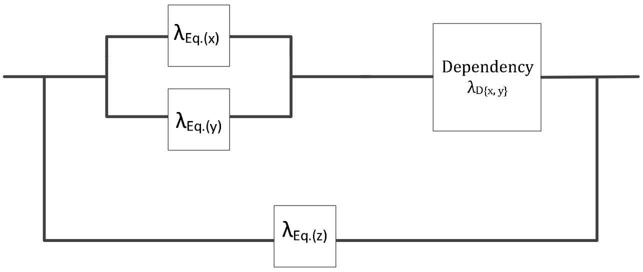

Fig. 2. Minimal cutset equivalence with RBD for handling partial dependency. $\lambda_{D(x,y)}$ is the dependency mode failure rate of cutset {x, y}; $\lambda_{Eq.(x)}$ is the equivalent failure rate of element x, and so on.

$$\lambda_{Eq.\{x,y,z\}}=\frac{\left(\lambda_{Eq.(x)}*\lambda_{Eq.(y)}*\lambda_{Eq.(z)}\right)\left(r_{(x)}r_{(y)}+r_{(y)}r_{(z)}+r_{(z)}r_{(x)}\right)}{8760*8760}\ f/yr \tag{3}$$

$$r_{\{x,y,z\}}=\frac{r_{(x)}*r_{(y)}*r_{(z)}}{r_{(x)}r_{(y)}+r_{(y)}r_{(z)}+r_{(z)}r_{(x)}}\ h \tag{4}$$

$$U_{\{x,y,z\}}=\frac{\lambda_{Eq.\{x,y,z\}}*r_{\{x,y,z\}}}{8760*8760}\ h/yr \tag{5}$$

When the units for failure rates are in failures per year and repair times/switching times are in hours, $\lambda_{Eq.}$ (interruption frequency (equivalent failure rate)), *U* (annual interruption duration (expected annual outage time)) and *r* (average interruption duration (equivalent outage time) are obtained in terms of failures (interruptions) per year, hours per year and hours per failure (interruption), respectively.

Once all the MCs for every selected operating state are obtained, they are combined using the approximate methods for a series system S consisting of i components (MCs) following series reliability logic, as follows:

$$\lambda_s=\sum\lambda_i;\ U_s=\sum\lambda_i r_i;\ r_s=\frac{U_s}{\lambda_s} \tag{6}$$

Additional indices such as annual power interrupted (API), annual energy not supplied (AENS) and annual interruption costs (AIC) can be subsequently derived from these basic indices [10]. In fact, the computation of unavailability U for the series combination of MCs is on the lines of obtaining the upper bound for the probability of system failure using the inclusion-exclusion principle [15]-[16] for MCs. As mentioned in [16], the assumption of independence in evaluating the individual terms of the inclusion-exclusion based union of MCs can give quite close results for the dependent case if the component reliabilities are high enough.

IV. ILLUSTRATIVE CASE STUDY

MOPAL is a modified four-bus multi-circuit meshed OPAL test network [17] with two generators, two delivery points and six transmission lines, as shown in Fig. 3. The transmission network operates at 132 kV. The capacity of transmission lines is as follows: lines 1 & 4 - 135 MW; lines 2, 3, 5 & 6 – 67.5

MW (i.e. 135/2 MW). The two generators are assumed to be 100% reliable. Delivery point 1, LP1, has industry customers; delivery point 2, LP2 has energy-intensive industry customers. For the simplicity of illustration, one operating state (OS1), a heavy load condition is assumed to prevail throughout the duration of a year at the delivery points. In OS1, delivery point LP1 is assumed to have a constant load demand of 100 MW, and delivery point LP2 a constant demand of 75 MW. By assigning probability weightages, the effect of multiple operating states can be easily captured. All the protection system units have the same repair time of 2 h. The missing and unwanted non-selective probabilities of all the protection system units are assumed to be 0.0205 and 0.007, respectively. Failure rate of unwanted spontaneous tripping of the circuit breakers of all protection system units is 0.025 f/yr. The MCs obtained for OS1 at LP1 and LP2 from the contingency analysis are shown in Figs. 4 and 5, respectively.

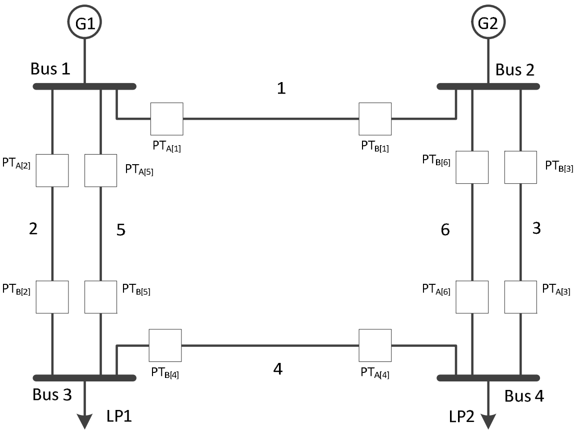

Fig. 3. MOPAL test network

<u>Sample calculation:</u> Consider the MC {2, 5} for the case of OS1LP2. At the elemental level, for line 2, which has lines 1, 4 and 5 as its neighbouring lines, a combinatorial analysis of backup coordination related interaction scenarios is carried out as follows. There are three scenarios resulting in FT3 on line 2. (i). Fault on line 1 and dependability-based failure (DBF) of $PT_{A[1]}$. Failure rate contribution of this scenario to the equivalent failure rate of FT3 of element 2 is $\lambda_1 * P_{M(PT_{A[1]})}$ (ii). Fault on line 4 and DBF of $PT_{B[4]}$. Failure rate contribution of this scenario to the equivalent failure rate of FT3 of element 2 is $\lambda_4 * P_{M(PT_{B[4]})}$ (iii). Fault on line 5 and DBF of $PT_{A[5]}$ or $PT_{B[5]}$ or both. Failure rate contribution of this scenario to the equivalent failure rate of FT3 of element 2 is $\lambda_5 (P_{M(PT_{A[5]})} + P_{M(PT_{B[5]})} - P_{M(PT_{A[5]})} * P_{M(PT_{B[5]})})$.

If the MC of which line 2 is a constituent were not to contain in it any neighbouring transmission lines, the equivalent failure rate of FT3 of line 2 would be the summation of all the above failure rate contributions from the different scenarios. However, in analyzing the MC {2, 5}, scenario (iii) above would result in a dependent failure of line 2 because of failure of protection systems of line 5 (because of the prevailing backup protection coordination strategy). Thus, this contribution is set aside to be included in the dependency mode failure rate of the MC {2, 5}, and is excluded from the equivalent failure rate of FT3 of line 2. On conducting a similar scenario analysis for element 5, a particular contribution would be set aside to be included in the dependency mode failure rate of the MC {2, 5}. On similar lines, scenario analysis for FT4 for each of the elements 2 and 5 is carried out, and the corresponding failure rate contributions of scenarios leading to dependent failures of lines 2 and 5 are included in the dependency mode failure rate of the MC {2, 5}. Once the equivalent failure rates of elements 2 and 5, and the dependency mode failure rate are thus obtained, the MC is analyzed using the approximate methods of system reliability evaluation as explained earlier.

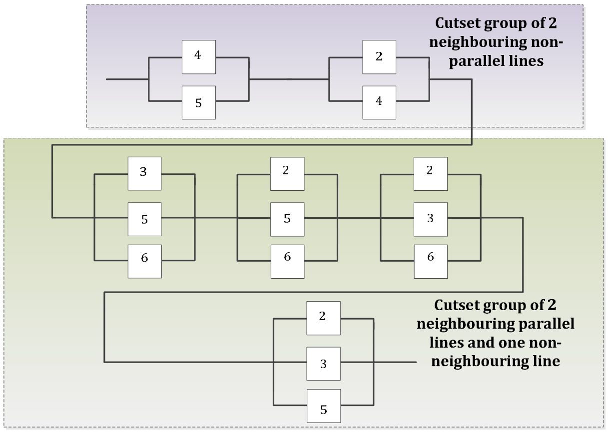

Fig. 4. Minimum cutsets for OS1LP1

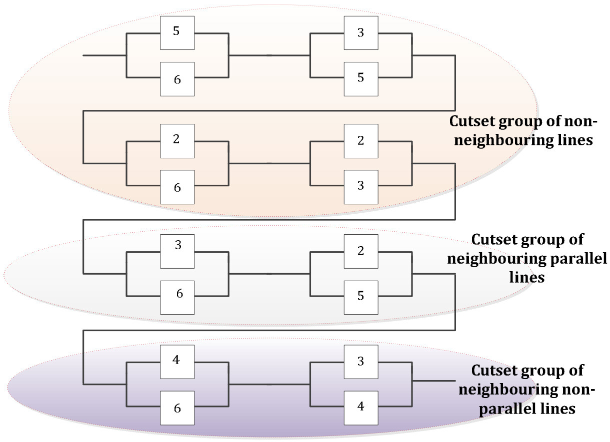

Fig. 5. Minimum cutsets for OS1LP2

Tables II to V provide an overview of the comparative analysis of the proposed approach of including the unreliability impact of protection and control (P&C) in the reliability assessment against the benchmark case of perfect P&C. For the example case of LP2, noticeably, there is a 436% increase in the failure frequency on account of protection system failure modes when compared to the case of perfect protection and control; a 35% increase is observed in the annual interruption duration. Further, the comparative values of the consequence indices - the annualized values of API and AENS highlight the impact of P&C imperfections. Compared to the earlier studies conducted on OPAL test network (i.e., MOPAL test network without the parallel transmission structure) [10], there is a 25% increase in the % increase in the failure frequency from the case of perfect protection systems to that of imperfect protection systems. This indicates the vulnerability of parallel transmission lines to more dependent failures in simple station configurations on account of protection system unreliability.

TABLE II. BASIC RELIA. INDICES – COMPARATIVE ANALYSIS FOR OS1LP2

Method	λ (f/yr)	r (h)	U (h/yr)
Perfect P&C	0.323	6.28	2.028
P&C Modelled	1.733	1.58	2.739

TABLE III. BASIC RELIA. INDICES – COMPARATIVE ANALYSIS FOR OS1LP1

Method	λ (f/yr)	r (h)	U (h/yr)
Perfect P&C	0.087	5.98	0.519
P&C Modelled	1.014	0.97	0.984

TABLE IV. ADDITIONAL RELIA. INDICES – COMPARATIVE ANALYSIS FOR LP1

Method	API (MW/yr)	AENS (MWh/yr)
Perfect P&C	2.82	16.86
P&C Modelled	32.97	31.98

TABLE V. ADDITIONAL RELIA. INDICES – COMPARATIVE ANALYSIS FOR LP2

Method	API (MW/yr)	AENS (MWh/yr)
Perfect P&C	9.66	63.33
P&C Modelled	45.69	81.52

For OS1LP2, the MCs are all of second order. Even though there are third order MCs for OS1LP1, none of them have all neighbouring lines. The only protection system dependencies affecting the indices are of second order. For the case of perfect protection systems, this third order 'redundancy' in the MCs leads to very low unavailability. However, the dependent mode failures of protection systems are responsible for unavailability that is almost five hundred times worse when compared to the corresponding benchmark case of perfect protection systems. As regards the validation, for now, comparisons have been made with the validated results of work carried out on the OPAL test network [10].

V. CONCLUSIONS

A new minimal cutset approach has been presented, complementing an ongoing project dealing with the development of a comprehensive integrated methodology for security of electricity supply analysis. The project seeks to combine power market analysis with power system (contingency) analysis in the subsequent reliability studies that include transmission protection system reliability considerations. The uniqueness of the proposed minimal cutset approach lies in its ability to model the impacts of transmission protection system failures on power system reliability without the need for complex Markov models, by using the approximate methods of system reliability evaluation. However, the applicability of approximate methods must be evidenced by substantiation as not all cases will yield acceptable results. Approximate methods are applicable only when individual component availabilities are high. Their usage in handling system MCs in is in fact an acceptable study of mere upper bounds of system failure probability and associated indices. Such upper bound approximate results when compared with the corresponding exact system reliability evaluation results are very much a function of the component reliabilities. Work including the detailed considerations of station configurations for a more realistic reliability appraisal of the effects of backup protection coordination strategies is presently underway, following which the comprehensive methodology would be applied to a Norwegian power system.

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Dependability and Security-based Failure Considerations in Protection System Reliability Studies

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Abstract— **The reliability of protection systems has a considerable effect on the reliability of supply, and hence appropriate protection system reliability models must be incorporated in power system reliability studies. These studies assume increasing prominence, especially in the wake of influx of smart grid technologies, making it imperative to handle the accompanying failure dependencies in detail. This paper presents the results of one such related investigation carried out to incorporate the impact of transmission line failure modes on account of various protection system response scenarios on supply reliability indices. In addition to the basic frequency and duration indices, indices such as annual power interrupted, annual energy not supplied, and annual interruption costs are computed, built on a minimal cut set based approach. The approach presented circumvents the need for complex Markov models to include protection system reliability considerations. An illustrative case study is employed to draw attention to the impact of identified comprehensive failure scenarios in protection and control equipment on power system reliability. Comparisons are made with an existing simplified method, and also with a case where protection system reliability is assumed to be perfect. The results bring forward the emphasis to be placed on initiatives to include the study of impact of reliability of protection systems on reliability of supply.**

Index Terms-- **Cutset, protection system, reliability, smart grid, transmission network.**

I. INTRODUCTION

The study of existence of sufficient generation, transmission and distribution facilities to ensure continuity of supply to customers with designated quality features is the goal of power system reliability assessment. A majority of studies conducted in this realm [1], [2] assume perfectly reliable protection systems, and hence do not take into account the effects of failure scenarios in their operation.

The IEEE Standard C37.100-1992 outlines the characteristic features a protection system must possess – dependability and security [3]. Missing and unwanted operations of protection systems constitute the reasons for shortfall in these attributes, respectively. An unwanted operation is said to occur if a protection system acts in response to the conditions it is not designed to react to. A missing operation is said to occur if a protection system fails to act in response to the conditions it is designed to react to. Studies of Swedish, Norwegian and Finnish fault statistics [4], [5] revealed the significant impact of various transmission protection failure modes on supply reliability as being associated with the dependability and security features of transmission protection systems. The need for a balance between the competing requirements of dependability and security features of protection systems has been specially highlighted in a North American Electric Reliability Council (NERC) report [6]. Even special protection schemes, also known as remedial action schemes, which are considered to be viable alternatives to transmission system expansion planning in a smart grid environment, are found to have an impact on power system reliability on account of inadequate dependability and security attributes [7]. A generic framework for handling the consequent failure dependencies is mandated. Thus, modeling the failure modes in protection systems associated with their dependability and security features is an essential exercise for comprehensive evaluation of power system reliability. The results of power system reliability studies that take into account the protection system unreliability impacts would provide more realistic inputs to the system reinforcement measures. Yet, there are relatively fewer works in the literature on power system reliability accounting for the impact of protection system unreliability. Complex Markov models [8] or fault trees combined with event trees [9] are the only means in vogue that model protection system reliability impacts on supply reliability.

The main objective of our research is to create a structured framework which captures the impact of various transmission protection system failure mode scenarios on supply reliability, founded on a minimal cutset (MC) based approach. This complements the recently initiated methodology for reliability of supply assessment, termed as OPAL (Norwegian abbreviation for optimization of reliability of supply) [10], [11], which estimates the frequency and duration of customer interruptions, energy not supplied, and the corresponding cost of energy not supplied. Reliability modeling of the various protection system response scenarios at the component level is first described. Mathematical expressions for deducing the equivalent failure modes corresponding to these failure modes/fault types were previously described in [12]. Based on these inputs, approximate methods of system reliability

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evaluation [1] are then employed. Reliability modeling at the system level, using the concept of minimal cutsets is then explained. In the process, handling dependencies arising out of back-up protection system coordination strategies is taken into account while employing the approximate methods. Sections II and III outline the requisite mathematical foundation for the overall reliability analysis, followed by an illustrative case study in Section IV.

II. MATHEMATICAL MODELING OF FAILURE MODES

A protection system on a transmission line consists of fault clearance system (relay and communication units) and circuit breakers. Failure of a transmission line (i.e., isolation from the network) is on account of different protection system response scenarios. Thus, a transmission line can have several failure modes, *also referred to as fault types.* Several protection system failure modes, which are derivates of the basic missing and unwanted operations (associated with dependability and security features, respectively), identified in [12] are revised, and their mathematical modeling applicable to single circuit meshed transmission systems is subsequently extended and employed in this paper. The dependency effects due to failure modes of a transmission line on the failure modes of adjacent transmission lines are included in the overall analysis. Line i is protected by two protection system units at its either ends. The nomenclature used here (with respect to line i) is listed below.

λ_i : Failure rate of transmission line i.

r_i : Outage/repair time of transmission line i.

$\mathrm{PT}_{\mathrm{A[i]}}, \mathrm{PT}_{\mathrm{B[i]}}$: Protection system units at each of the ends A and B of transmission line i.

$\lambda_{BE_{A[i]}}$: Failure rate of unwanted spontaneous tripping of the circuit breakers of protection system unit at the A-end of transmission line i. Similar interpretation for $\lambda_{BE_{B[i]}}$.

$P_{U-Ns.(PT_{A[i]})}$: Probability of unwanted non-selective operation of protection system unit at the A-end of transmission line i. Similar interpretation for $P_{U-Ns.(PT_{B[i]})}$.

$P_{M(PT_{A[i]})}$: Probability of missing operation of protection system unit (missing probability) at the A-end of transmission line i. Similar interpretation for $P_{M(PT_{B[i]})}$.

$P(PT_{A-i})$: Conditional probability of protection system unit at the A-end of transmission line i clearing a fault, given that a fault occurs on line i. It is the missing probability of the unit subtracted from unity. Similar interpretation for $P(PT_{B-i})$.

Fault Type 1 (FT1): A fault occurs on the transmission line i, upon which there could be two consequent scenarios:

Consequent Scenario 1 (CS1): Because of the readiness of line i's primary protection system, the fault is cleared correctly. The line remains isolated from the system until its repair is complete. The outage time associated with FT1 of line i, is the same as the line's repair time.

Consequent Scenario 2 (CS2): Because of the unreadiness of line i's primary protection system, the fault cannot be cleared, and protection system unit(s) of the neighbouring lines must act to isolate the faulted line. The fault on line i cannot be cleared by the line's primary protection system on account of the one of the following conditions: Unreadiness of protection system at one end of the line; Unreadiness of protection system at the other end of the line; Unreadiness of protection systems at both ends of the line. The failure rate of FT1 of line i is expressed as follows:

$$\lambda_{FT1(i)} = \lambda_i \tag{1}$$

Fault Type 2 (FT2): The transmission line i is fault-free, but because of faulty operation of the line's primary protection system, unwanted spontaneous tripping of the circuit breaker(s) occurs. This results in isolation of the healthy line i. This situation can be remedied by auto-reclosure of the breaker associated with the corresponding protection system unit. The outage time associated with FT2 of line i, is the same as the line's protection unit's repair/switching time.

$$\lambda_{FT2(i)} = [\lambda_{BE_{A[i]}} + \lambda_{BE_{B[i]}}] \tag{2}$$

Fault Type 3 (FT3): A fault occurs on one of the neighbouring transmission lines, but because of the faulty operation of a protection system assembly of the neighbouring line, its corresponding circuit breaker fails to act. This results in missing operation of a circuit breaker, because of which the faulted neighbouring line cannot be isolated by its own circuit breakers. In such a case, a protection system assembly of line i acts as back-up to isolate the faulted neighbouring line. This also results in isolation of the healthy line i. The outage time associated with FT3 of line i, is the same as the switching time. The following expression quantifies this fault type when there is only one neighbouring line, say line j, adjacent to line i at one end; and also only one neighbouring line, say line k, adjacent to line i at its other end.

$$\lambda_{FT3(i)} = \lambda_j * P_{M(PT_{A[j]})} + \lambda_k * P_{M(PT_{B[k]})} \tag{3}$$

Fault Type 4 (FT4): A fault occurs on one of the neighbouring transmission lines, upon which the neighbouring line's primary protection system clears the fault correctly. However, because of faulty operation of either of the protection system units of line i or both protection system units of line i, unwanted non-selective tripping of line i's circuit breaker(s) occurs. This results in healthy line i's isolation. The outage time associated with FT4 of line i, is the same as the switching time. Thus,

$$\begin{aligned} \lambda_{FT4(i)} = & \left([\lambda_j * P(PT_{A-j})] + [\lambda_k * P(PT_{B-k})]\right) * \\ & \left(P_{U-Ns.(PT_{A[i]})} + P_{U-Ns.(PT_{B[i]})} - P_{U-Ns.(PT_{A[i]})} * P_{U-Ns.(PT_{B[i]})}\right) \end{aligned} \tag{4}$$

The equivalent failure rate of line i taking into account the significant transmission line failure modes due to the various protection system response scenarios is obtained as the summation of individual failure rates of all the above fault types. This is a valid logic since these failure mode states are mutually exclusive for line i, and elements exhibiting such multiple failure modes can be modeled using appropriate series/parallel logic. A system with a component consisting of four mutually exclusive failure modes is analogous to a four component series system. Thus, the equivalent failure rate of line i is given as follows:

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)} \tag{5}$$

Some of the important points to be noted about the various fault types are as follows:

- CS1 of FT1 on line i 'may' result in FT4 on neighbouring line j, and vice-versa.

$$\lambda^{*}_{CS1FT1(i)} = [\lambda_i * P(PT_{A(or)B-i})] * \begin{pmatrix} P_{U-Ns.(PT_{A[j]})} + P_{U-Ns.(PT_{B[j]})} \\ -P_{U-Ns.(PT_{A[j]})} * P_{U-Ns.(PT_{B[j]})} \end{pmatrix} \tag{6}$$

- CS2 of FT1 on line i 'will' result in FT3 on neighbouring line j, and vice-versa.

$$\lambda^{*}_{CS2FT1(i)} = \lambda_i * P_{M(PT_{A(or)B[i]})} \tag{7}$$

Thus, both the consequent scenarios of FT1 could result in multiple transmission line isolations due to the dependency effects of back-up protection system coordination design. These scenarios are quantified and made use of as dependence mode failure rates in the reliability analysis. FT2 is the only fault type which is independent in that there is no failure propagation to the neighbouring lines at all times.

III. RELIABILITY ANALYSIS

According to the basic procedure set down in the OPAL methodology [10], [11], the input to the reliability analysis consists of information about which delivery points will experience interruptions or reduced supply on account of critical contingencies. Minimal cutsets of up to second order are deduced from the contingency analysis phase. The following is the postulated algorithmic approach for obtaining the various reliability indices:

(i) Obtain MCs for each operating state of each load point from the contingency analysis phase.

(ii) Analyse each and every MC:

(a) For each MC, obtain the equivalent failure rate of each of its elements. It must be noted that the equivalent failure rate of an element is dependent upon the composition of the MC, i.e., whether there are neighbouring lines or non-neighbouring lines present in the MC.

(b) Analyse the combination of all elements of the MC using the approximate methods of system reliability evaluation for parallel systems.

(iii) Analyse the combination of all MCs for each operating state of each load point using the approximate methods of system reliability evaluation for series systems.

(iv) Accumulate the reliability indices for each operating state of each load point.

(v) Use relevant weightage factors (probabilities of occurrences of operating states) to obtain overall reliability indices for each load point.

Approximate methods [1] yield the very popular set of linear relationships, for a system S consisting of i components following series reliability logic, as follows:

$$\lambda_s = \sum \lambda_i;\ U_s = \sum \lambda_i r_i;\ r_s = \frac{U_s}{\lambda_s} \tag{8}$$

When the units for failure rates are in failures per year and repair times/switching times are in hours, $\lambda_{Eq.}$ (interruption frequency (equivalent failure rate)), U (annual interruption duration (expected annual outage time)) and r (average interruption duration (equivalent outage time)) are obtained in terms of failures (interruptions) per year, hours per year and hours per failure (interruption), respectively.

<u>*Analysis of MC{x, y} where x & y are non-neighbouring lines*</u>:

$$\left.\begin{aligned} \lambda_{Eq.\{x,y\}} &= \frac{\lambda_{Eq.(x)} * \lambda_{Eq.(y)} (r_{(x)} + r_{(y)})}{8760}\ f/yr \\ r_{\{x,y\}} &= \frac{r_{(x)} * r_{(y)}}{r_{(x)} + r_{(y)}}\ h \\ U_{\{x,y\}} &= \lambda_{Eq.\{x,y\}} * r_{\{x,y\}}\ h/yr \end{aligned}\right\} \tag{9}$$

<u>*Analysis of MC{x, y} where x and y are neighbouring lines*</u>:

Dependencies due to back-up protection system coordination can be modeled the same way common-mode failures are modeled in the reliability block diagram of a two-component active parallel redundant system, where an additional 'component' characterizing the common-mode failure rate is connected in series with the parallel configuration of elements, for analysis purposes.

$$\left.\begin{aligned} \lambda_{Eq.\{x,y\}} &= \frac{\lambda'_{Eq.(x)} * \lambda'_{Eq.(y)} (r'_{(x)} + r'_{(y)})}{8760} + \lambda_D\ f/yr \\ U_{\{x,y\}} &= \left(\frac{\lambda'_{Eq.(x)} * \lambda'_{Eq.(y)} * r'_{(x)} * r'_{(y)}}{8760} \right) + (\lambda_D * r_D)\ h/yr \\ r_{\{x,y\}} &= \frac{U_{\{x,y\}}}{\lambda_{Eq.\{x,y\}}}\ h \end{aligned}\right\} \tag{10}$$

λ_D is the dependence mode failure rate of cutset {x, y}, and r_D is the restoration time taken for the switching action (switching time). λ_D is obtained as a suitable summation of the terms $\lambda^{*}_{CS1FT1(x)}$, $\lambda^{*}_{CS1FT1(y)}$, $\lambda^{*}_{CS2FT1(x)}$ and $\lambda^{*}_{CS2FT1(y)}$. $\lambda'_{Eq.(x)}$ differs from $\lambda_{Eq.(x)}$ in that the corresponding terms figuring in the dependence mode failure rate are removed so as to avoid double counting.

IV. CASE STUDY

The OPAL test network has been used as a benchmark for testing the integrated methodology of incorporating power market analysis via power flow and contingency analysis to delivery point reliability analysis [10], [11]. The fundamental theoretical basis for MC-based reliability analysis was initially established with the OPAL test network structure as a yardstick. Norwegian fault statistics were analysed to obtain a representative input data set for failure rate parameters and probability attributes of protection system units. This framework was subsequently used for a realistic case in the middle of Norway, where the reliability of supply for two different delivery points in the 420 kV transmission grid was investigated [13]. Hence, as a logical extension of improvisations in the methodology proposed, the test network has been retained for illustrative purposes in this paper. The insights gleamed from the sensitivity analysis are currently being built into investigations underway on a large Norwegian power network.

OPAL is a four-bus test network with two generators, two delivery points and four transmission lines, as shown in Figure 1 [10]. The transmission network operates at 132 kV. The capacity of each of the transmission lines is 135 MW. The two generators are assumed to be 100% reliable. Delivery point 1, LP1, has industry customers; delivery point 2, LP2 has energy-intensive industry customers. Two uniform loading conditions are assumed to prevail throughout certain duration of a year at a delivery point. In a ‘heavy’ load condition (designated as Operating State 1 (OS1)), delivery point LP1 is assumed to have a constant load demand of 100 MW, and delivery point LP2 a constant demand of 75 MW. In a ‘light’ load condition (designated as Operating State 2 (OS2)), delivery point LP1 is assumed to have a constant load demand of 60 MW, and delivery point LP2 a constant demand of 30 MW. By assigning probability weightages, the effect of multiple loading conditions can be easily captured. For a twelve month period (December through November) OS2 is assumed to last for 9 months (March to November) a year. Hence, the probability of occurrence of light load condition is 9/12=0.75. OS1 is assumed to last for 3 months (December, January and February) and thus, the probability of occurrence of heavy load condition is 3/12=0.25. All the protection system units have the same repair time of 2 h. The missing and unwanted non-selective probabilities of all the protection system units are assumed to be 0.0205 and 0.007, respectively. Failure rate of unwanted spontaneous tripping of the circuit breakers of protection system unit is 0.025 f/yr.

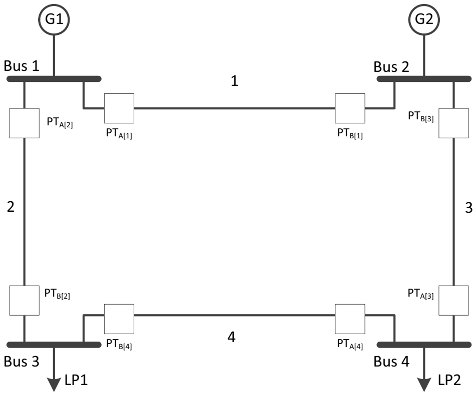


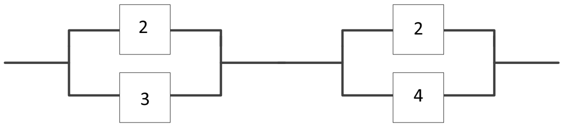
Figure 1. Single line diagram of the OPAL test network [10].

A. Results

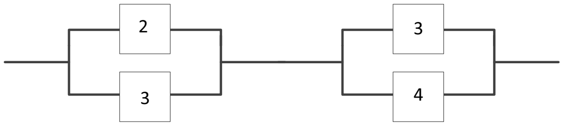
To illustrate the application of the proposed methodology, the basic reliability indices – failure frequency λ (number of interruptions per year), annual expected outage time U (annual interruption duration), and expected value of down time r (average interruption duration) – are obtained for delivery points LP1 and LP2. Subsequently, the annual power interrupted (API), annual energy not supplied (AENS) and annual interruption costs (AIC) are computed, all based on a minimal cutset based approach [10]. A consequence analysis of each contingency under specified operating conditions yields a system available capacity (SAC) for each delivery point due to the contingency. For each MC *j* for a given operating state,

$$\left.\begin{aligned} P_{IN,j} &= P - SAC_j \text{ MW/interruption} \\ ENS_j &= r_j * P_{IN,j} \text{ MWh/interruption} \\ IC_j &= C(r_j) * ENS_j \text{ NOK/interruption} \end{aligned}\right\} \quad (11)$$

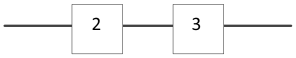
where *C(r)* is the specific interruption cost in currency per kWh of energy not supplied, P_{IN} is the interrupted power, and P is the load demand. Each of the expressions above is multiplied by the equivalent failure rate of MC *j* to obtain the indices on an annual basis, i.e., MW/year, MWh/year and NOK (Norwegian Kroners)/year, respectively. For a given operating state, if there are *n* MCs, the corresponding *n* annual indices are summed up to get the net delivery point indices per operating state. If there are multiple operating states, a probability weighted equivalent failure rate of MC *j* is used as the basis for obtaining the above annual indices and summed up accordingly. The MCs for the OPAL test network are as shown in Figure 2.



(a) Minimal cutsets for heavy load (OS1), and light load (OS2) conditions at LP1



(b) Minimal cutsets for light load (OS2) condition at LP2



(c) Minimal cutsets for heavy load (OS1) condition at LP2

Figure 2. Minimal cutsets for the OPAL test network.

Tables I to V provide an overview of the comparative analysis of the proposed approach of including the unreliability impact of protection and control (P&C) in reliability assessment against the benchmark case of perfect P&C. For the example case of LP1, noticeably, there is a 347% increase in the failure frequency on account of protection system failure modes when compared to the case of perfect protection and control; a 27% increase is observed in the annual interruption duration. These figures highlight the sample impact of P&C imperfections.

There is an almost 28% increase in the AENS and 20% increase in the AIC for LP1 due to the various protection system response scenarios as against the case of a perfect response scenario. But for LP2, the corresponding increase is just under 1%. This is so because the reliability indices are dominated by higher order outages for LP1. There is no single contingency forming a minimal cutset for LP1, and hence the dependent double contingencies originating from protection system faults on neighbouring lines play an important role.

TABLE I. BASIC RELIABILITY INDICES – COMPARATIVE ANALYSIS FOR OS1LP2

Method	λ (f/yr)	r (h)	U (h/yr)
Perfect P&C	7	13.285	93
Proposed Methodology	7.578	12.329	93.439

TABLE II. BASIC RELIABILITY INDICES – COMPARATIVE ANALYSIS FOR OS1LP1 (SAME FOR OS2LP1)

Method	λ (f/yr)	r (h)	U (h/yr)
Perfect P&C	0.08	6.324	0.506
Proposed Methodology	0.358	1.798	0.644

TABLE III. BASIC RELIABILITY INDICES – COMPARATIVE ANALYSIS FOR OS2LP2

Method	λ (f/yr)	r (h)	U (h/yr)
Perfect P&C	0.087	5.97	0.52
Proposed Methodology	0.399	1.697	0.678

TABLE IV. ADDITIONAL RELIABILITY INDICES – COMPARATIVE ANALYSIS FOR LP1

Method	API (MW/yr)	AENS (MWh/yr)	AIC (million NOK/yr)
Perfect P&C	5.6	35.328	~1.779
Proposed Methodology	25.07	45.084	~2.137

TABLE V. ADDITIONAL RELIABILITY INDICES – COMPARATIVE ANALYSIS FOR LP2

Method	API (MW/yr)	AENS (MWh/yr)	AIC (million NOK/yr)
Perfect P&C	71.96	941.688	~14.737
Proposed Methodology	84.774	949.652	~14.842

The approximate methods provide pessimistic estimates, and in fact yield only upper bounds for the reliability indices. The proposed method of handling dependencies is not well suited for obtaining lower bounds, in which case Markov models must be resorted to. However, the obtained information is deemed sufficient enough for practical uses, taking into account the tradeoff. In terms of validation, the proposed methodology of handling protection system imperfections in power system reliability calculations for the OPAL test system yields near identical results as those of the preliminary results of [10]. The applicability of approximate methods itself in general, has been first established by comparisons with the accurate analytical state space method. It must be pointed out that the algorithmic approach as posited in the paper is comprehensive, and accounts for a more systematic way of handling dependencies, forming the basis for arriving at generic expressions for more complex real life transmission networks. Future work includes the extension of the proposed methodology to multi circuit meshed transmission systems, and consequent application to a Norwegian system with varied substation configurations.

V. CONCLUSIONS

The results show significant effect of reliability of protection systems on the reliability of supply, demonstrating the need for incorporating appropriate protection system reliability models in power system reliability studies. The generic framework for handling failure dependencies can be expanded to include similar dependencies in smart grid technologies such as special protection schemes. The uniqueness of the proposed approach lies in its ability to model the impacts of transmission protection system failures on power system reliability without the need for complex Markov models, while accounting for the complex dependency effects, using the approximate frequency and duration methods. Existing input data collection schemes for protection system attributes are not standardized across the world and present inherent practical difficulties due to varied interpretations. This issue is currently being addressed by the IEEE taskforce on probability applications for common mode events (PACME).

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Incorporation of Protection System Failure Modes in Composite Power System Reliability Studies

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SUMMARY

Reliability of protection systems of the transmission network is found to have significant impact on the supply reliability. Quantifying the impact of protection system imperfections on power system reliability entails the identification of multiple failure modes of transmission lines arising out of the various protection system response scenarios. In this paper, analytical expressions are developed that characterize the effective failure rates of the significant fault types on a transmission line. These expressions are in terms of the two different types of essential probability attributes of protection system units (viz., missing probability and unwanted probability), and the failure rates of protection system units and transmission lines, taking into account the coordination strategy of neighbouring back-up protection systems. A cutset based procedure is then employed to obtain the relevant reliability indices. The uniqueness of the proposed approach lies in its ability to model the impacts of transmission protection system failures on power system reliability without the need for complex Markov models, while accounting for the dependency effects. A simple case study involving the calculation of basic delivery point reliability indices, with and without the consideration of protection system failures, is illustrated on a four-bus OPAL[1] test network.

KEYWORDS

Cutset - Dependency - Failure Mode - Protection System - Reliability - Transmission Network

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[1] OPAL = Optimization of reliability of supply (Norwegian abbreviation)

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1 INTRODUCTION

Research on composite power system reliability studies is well documented in literature. Numerous analytical and simulation methods to assess the reliability of supply are in vogue, based on mathematical models of varying degrees of complexity [1, 2]. Several assumptions underline these methods with a view to tractability, depending on the specific goals of such studies. The generic assumption of perfectly reliable transmission protection systems is no longer valid, as seen from the studies on fault statistics of power systems across the world that point to failures in protection systems as being one of the major contributors to unreliability of power systems [3-5]. The North American Electric Reliability Corporation (NERC) System Protection and Control Task Force recently outlined protection system reliability requirements for bulk electric systems that ensure adequate levels of bulk system reliability [6]. However, relatively fewer studies have been conducted on incorporating the impact of protection system failures on power system reliability. Those reported in literature thus far have mainly relied on extensive and complex Markov models [7] or fault trees combined with event trees [8]. The latest development in this field includes an elaborate Markov model-based composite power system reliability evaluation, where the impact of two main types of hidden protection failures, namely, undesired-tripping mode and fail-to-operating tripping mode, on system reliability has been investigated.

Recently, a new methodology for reliability of supply assessment, termed as OPAL [10], has been initiated and is currently being improvised to provide inputs for long term planning purposes [11]. The basic objective is to "*determine the reliability of supply indices for the delivery points under study, i.e., to estimate the frequency and duration of interruptions (or reduced supply), energy not supplied, and the corresponding cost of energy not supplied"*. The reliability model is based on the minimal cutsets for each delivery point. It takes into account both interruptions due to primary faults on the power system components and protection system faults that render isolation of the faulted power system components ineffective. Earlier, based on the Norwegian fault statistics, key failure modes of transmission line protection failures have been identified and their impact considered for a specific case on the reliability of supply [12]. In this paper, we build on the initial conceptualizations of [12], and present a generic procedure of including the impact of protection system imperfections on supply reliability by considering four uniquely identified fault types that result on account of the various protection system response scenarios. The uniqueness of the proposed approach lies in its ability to model the impacts of transmission protection system failures on power system reliability without the need for complex Markov models, while accounting for the dependency effects. It is shown how this feature can be incorporated in the general minimal cutset structure of the OPAL methodology. It can be tailored to develop different standard expressions for different protection coordination schemes, though emphasis is laid only on the distance protection scheme in this paper. Sample results are illustrated on a four bus OPAL test network [10].

2 METHODOLOGY

In the first phase of our research, a single-circuit meshed transmission system – OPAL network, is used as a reference case. Based on this, generic expressions for failure rates are developed for similar meshed systems to account for the four uniquely identified fault types (failure modes) that a transmission line could experience because of the various associated protection system response scenarios. The task of obtaining generic expressions that can capture the more complex effects of back-up protection coordination schemes of multi-circuit meshed transmission configurations will be addressed in the later phase of our research.

2.1 Assumptions

- The circuit breaker and its associated relay and communication units together constitute the protection system assembly (unit). Each line is protected by a protection system unit at both its ends.
- Repair of protection systems is faster than that of the corresponding protected components.
- All circuit breakers have similar switching times; all protection system units have similar repair times.
- Neighbouring lines are defined as transmission lines connected to the common bus bar.

2.2 Nomenclature

Say, line i is protected by two protection system units, each at either end of the line. One end of the line is termed as A-end, and the other end as B-end. The unit at the A-end of line i is denoted by $PT_{A[i]}$, and the unit at the B-end of line i is denoted by $PT_{B[i]}$. Both the protection units together constitute primary protection system of the line.

$\lambda_{PT_{A[i]}}$ is the failure rate of the protection system unit at the A-end of line i;

$\lambda_{PT_{B[i]}}$ is the failure rate of protection system unit at the B-end of line i;

$P_{missing(PT_{A[i]})}$ and $P_{missing(PT_{B[i]})}$ are the probabilities of missing operation of protection system units $PT_{A[i]}$ and $PT_{B[i]}$, respectively, of line i;

$P_{unwanted(PT_{A[i]})}$ and $P_{unwanted(PT_{B[i]})}$ are the probabilities of unwanted operation of protection system units $PT_{A[i]}$ and $PT_{B[i]}$, respectively, of line i. Further, there could be a finer resolution of these unwanted probability input parameters:

- probability of unwanted spontaneous operations of the circuit breaker of a protection system unit (i.e., failure frequency of mal-tripping of the circuit breaker independent of faults in neighbouring lines) - $P_{unwanted-Sp.(PT_{A[i]})}$ and $P_{unwanted-Sp.(PT_{B[i]})}$, and
- probability of unwanted non-selective operations of the circuit breaker of a protection system unit (failure frequency of mal-tripping of the circuit breaker conditional upon faults in neighbouring lines) - $P_{unwanted-Ns.(PT_{A[i]})}$ and $P_{unwanted-Ns.(PT_{B[i]})}$.

For the purpose of ease of analysis, transmission lines are labeled in the single line diagram of the network in such a manner that similar ends (A-ends or B-ends) of neighbouring lines are connected to the common bus. This convention is used in the OPAL test network as shown below in Fig. 1. More about the test network is explained in the next section.

Lines adjacent to line i (neighbouring lines) are classified into two sets: Set J and Set K.

- J_i is the set of lines connected to the bus nearest to the A-end of line i.
- K_i is the set of lines connected to the bus nearest to the B-end of line i.

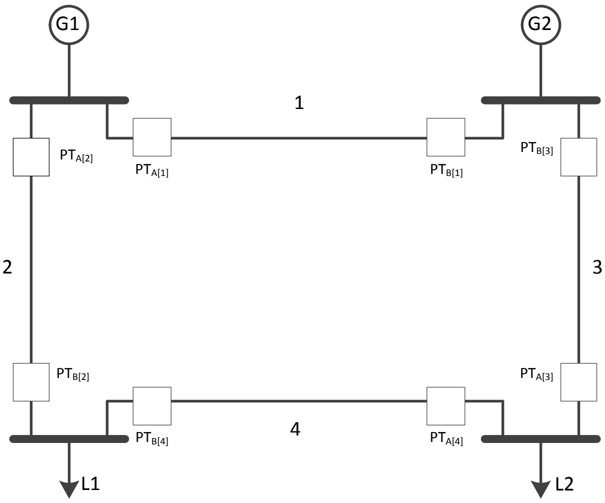

Fig. 1. Single line diagram of OPAL network [10]

2.3 Analysis of Failure Modes (Fault Types)

Based on the Norwegian fault statistics, the following dominant failure modes of transmission lines due to the various protection system response scenarios could be identified and analyzed. These modes are assumed to be representative of a vast majority of practical occurrences, in general. Additional failure modes can be included if necessary.

Fault Type 1 (FT1): A fault occurs on the transmission line i, upon which there could be two consequent scenarios:

> **Consequent Scenario 1 (CS1):** Because of the readiness of the line i's primary protection system, the fault is cleared correctly.
>
> **Consequent Scenario 2 (CS2):** Because of the unreadiness of line i's primary protection system, the fault cannot be cleared, and protection system unit(s) of the neighbouring lines must act to isolate the fault.

Irrespective of the consequent scenarios, the expression for failure rate of line i is merely its original failure rate. The outage time associated with FT1 of line i, $r_{FT1(i)}$, is the same as the line's repair time. Thus,

$$\lambda_{FT1(i)} = \lambda_i \tag{1}$$

Fault Type 2 (FT2): The transmission line i is fault-free, but because of faulty operation of the line's primary protection system, unwanted spontaneous tripping of the circuit breaker(s) occurs. This results in isolation of the healthy line i.

In order to obtain the equivalent failure rate pertaining to FT2, the failure rate of the series connected (reliability-logic wise) protection system units at both ends of the line is multiplied by a weightage probability, which is the probability of failure of the primary protection system of line i due to unwanted operations. Failure rate of series connected protection system ends is obtained as $[\lambda_{PT_{A[i]}} + \lambda_{PT_{B[i]}}]$.

The probability of failure of the primary protection system of line i due to unwanted operations is given as: P[(unwanted operation of $PT_{A[i]}$) ∪ (unwanted operation of $PT_{B[i]}$)], which is $[P_{unwanted-Sp.(PT_{A[i]})} + P_{unwanted-Sp.(PT_{B[i]})} - [P_{unwanted-Sp.(PT_{A[i]})} * P_{unwanted-Sp.(PT_{B[i]})}]]$. Thus,

$$\lambda_{FT2(i)} = \left(\begin{array}{l} [\lambda_{PT_{A[i]}} + \lambda_{PT_{B[i]}}]* \\ \quad [P_{unwanted-Sp.(PT_{A[i]})} + P_{unwanted-Sp.(PT_{B[i]})} - [P_{unwanted-Sp.(PT_{A[i]})} * P_{unwanted-Sp.(PT_{B[i]})}]] \end{array} \right) \tag{2}$$

The outage time associated with FT2 of line i, $r_{FT2(i)}$, is the same as the line's protection unit's repair time.

Fault Type 3 (FT3): A fault occurs on one of the neighbouring transmission lines, but because of the faulty operation of a protection system assembly of the neighbouring line, its corresponding circuit breaker fails to act. This results in missing operation of a circuit breaker, because of which the faulted neighbouring line cannot be isolated by its own circuit breakers. In such a case, a protection system assembly of line i acts as backup to isolate the faulted neighbouring line. This also results in isolation of the healthy line i.

FT3 'may' occur whenever there is a fault on a neighbouring line. The rate at which FT3 occurs would be the same as the failure rate of the neighbouring line if and only if it occurs every time there is a fault on the neighbouring line. Instead, the rate at which FT3 occurs is characterized by the weighted failure rate of the neighbouring line, the weightage factor being the probability of missing operation of the protection system assembly of the neighbouring line nearest to the common bus. Thus,

$$\lambda_{FT3(i)} = \left(\sum_{\forall j \in J_i} (\lambda_j * P_{missing(PT_{A[j]})}) \right) + \left(\sum_{\forall k \in K_i} (\lambda_k * P_{missing(PT_{B[k]})}) \right) \tag{3}$$

This simplifies to the following expression when there is only one neighbouring line, say line j, adjacent to line i at one end; and also only one neighbouring line, say line k, adjacent to line i at its other end.

$$\lambda_{FT3(i)} = \lambda_j * P_{missing(PT_{A[j]})} + \lambda_k * P_{missing(PT_{B[k]})} \tag{4}$$

The outage time associated with FT3 of line i, $r_{FT3(i)}$, is the same as the switching time.

Fault Type 4 (FT4): A fault occurs on one of the neighbouring transmission lines, upon which the neighbouring line's primary protection system clears the fault correctly. However, because of faulty operation of either of the protection system units of line i or both protection system units of line i, unwanted non-selective tripping of line i's circuit breaker(s) occurs. This results in isolation of the healthy line i.

FT4 'may' occur on line i whenever there is a fault on a neighbouring line and is cleared successfully by the neighbouring line's primary protection system. The rate at which this FT occurs would be the same as the *'successful fault clearance rate'* of the neighbouring line if and only if it occurs every time there is successful fault clearance instance on the neighbouring line. Instead, the rate at which FT4 occurs is characterized by the successful fault clearance rate of the neighbouring line's nearest protection system unit (or summation of successful fault clearance rates of the nearest protection units of neighbouring lines, in the case of more than one neighbouring line) weighted by the probability of unwanted non-selective operation of the primary protection system of line i. Thus,

$$\lambda_{FT4(i)} = \left(\left(\sum_{\forall j \in J_i} [\lambda_j * P(PT_{A-j})] + \sum_{\forall k \in K_i} [\lambda_k * P(PT_{B-k})] \right) * \left(P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} - P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \right) \right) \quad (5)$$

This simplifies to the following expression when there is only one neighbouring line, say line j, adjacent to line i at one end; and also only one neighbouring line, say line k, adjacent to line i at its other end.

$$\lambda_{FT4(i)} = \left(\left([\lambda_j * P(PT_{A-j})] + [\lambda_k * P(PT_{B-k})] \right) * \left(P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} - P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \right) \right) \quad (6)$$

where $P(PT_{A-j})$ is the probability of successful fault clearance by the protection system unit at the A-end of line j, given by:

$$P(PT_{A-j}) = [1 - P_{\text{missing}(PT_{A[j]})} - P_{unwanted-Sp(PT_{A[j]})}] \quad (7)$$

and $P(PT_{B-k})$ is the probability of successful fault clearance by the protection system unit at the B-end of line k, given by:

$$P(PT_{B-k}) = [1 - P_{\text{missing}(PT_{B[k]})} - P_{unwanted-Sp(PT_{B[k]})}] \quad (8)$$

$\lambda_j * P(PT_{A-j})$ is the successful fault clearance rate of protection system unit at the A-end of line j, and $\lambda_k * P(PT_{B-k})$ is the successful fault clearance rate of protection system unit at the B-end of line k. It must be noted that the convention used is such that line j is the neighbouring line connected to the bus nearest to the A-end of line i; line k is the neighbouring line connected to the bus nearest to the B-end of line i.

The outage time associated with FT4 of line i, $r_{FT4(i)}$, is the same as the switching time.

The equivalent failure rate of line i is obtained as the summation of individual failure rates of all the above fault types.

$$\lambda_{Eq.(i)} = \lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)} \quad (9)$$

where $\lambda_{FT1(i)}, \lambda_{FT2(i)}, \lambda_{FT3(i)}$ and $\lambda_{FT4(i)}$ are as described by Equations (1), (2), (3) and (5), respectively.

Some of the important points to be noted about the various fault types are as follows:

- CS1 of FT1 on line i ‘may’ result in FT4 on neighbouring line j, and vice-versa.
- CS2 of FT1 on line i ‘will’ result in FT3 on neighbouring line j, and vice-versa.

Thus, both the consequent scenarios of FT1 could result in multiple transmission line isolations due to the dependency effects of back-up protection system coordination design. FT2 is the only fault type which is independent in that there is no failure propagation to the neighbouring lines at all times.

2.4 Reliability Analysis

Based on results of the system contingency analysis phase [10, 12], minimal cutsets of lines whose contingency results in load interruptions at delivery points are identified. As a rule of thumb, the required resolution of minimal cutsets is restricted to second order only.

Once the minimal cutsets are deduced, for every element (transmission line) of each of the cutsets, the equivalent failure rate as derived in Equation (7) is calculated. Further, a three-tiered analysis is carried out at the following levels with the application of approximate frequency and duration (F&D) methods of reliability evaluation.

a) Element level
b) Cutset level
c) Delivery point level

The basic reliability parameters of interest – interruption frequency (equivalent failure rate) $\lambda_{Eq.}$, annual interruption duration (expected annual outage time) U, and average interruption duration (equivalent outage time) r – are calculated at each of these levels, as shown below. When the units for failure rates are in failures per year and repair times/switching times are in hours, $\lambda_{Eq.}$, U and r as given in the subsequent equations are obtained in terms of failures per year, hours per year and hours per interruption, respectively.

a) Element level: Employing the logic of approximate F&D method applied for series systems,

$$U_{(i)} = \lambda_{FT1(i)} r_{FT1(i)} + \lambda_{FT2(i)} r_{FT2(i)} + \lambda_{FT3(i)} r_{FT3(i)} + \lambda_{FT4(i)} r_{FT4(i)} \ \textit{h/yr} \tag{10}$$

$$r_{(i)} = \frac{U_{(i)}}{\lambda_{Eq.(i)}} \ h \tag{11}$$

b) Cutset level: If the cutset is of first order, $\lambda_{Eq.}$, U and r are the same as obtained at the element level. The composition of second order cutset may be such that the two elements could be either non-neighbouring or neigbouring transmission lines.

Case (i): Cutset {x, y} where x and y are non-neighbouring lines: Employing the logic of approximate F&D method applied for parallel systems,

$$\lambda_{Eq.\{x,y\}} = \frac{\lambda_{Eq.(x)} * \lambda_{Eq.(y)} (r_{(x)} + r_{(y)})}{8760} \ \textit{f/yr} \tag{12}$$

$$r_{\{x,y\}} = \frac{r_{(x)} * r_{(y)}}{r_{(x)} + r_{(y)}} \ h \tag{13}$$

$$U_{\{x,y\}} = \lambda_{Eq.\{x,y\}} * r_{\{x,y\}} \ \textit{h/yr} \tag{14}$$

Case (ii): Cutset {x, y} where x and y are neighbouring lines: Since the required resolution of minimal cutsets is restricted to second order, the dependency effects of consequent scenarios of FT1 between the two neighbouring lines in a minimal cutset could result in multiple transmission line isolations. This can be modeled the same way common-mode failures are modeled in the reliability block diagram of a two-component active parallel redundant system, where an additional 'component' characterizing the common-mode failure rate is connected in series with the parallel configuration of elements, for analysis purposes. Thus, employing the logic of approximate F&D method applied for parallel-series systems,

$$\lambda_{Eq.\{x,y\}} = \frac{\lambda'_{Eq.(x)} * \lambda'_{Eq.(y)} (r'_{(x)} + r'_{(y)})}{8760} + \lambda_D \ \textit{f/yr} \tag{15}$$

$$U_{\{x,y\}} = \left(\frac{\lambda'_{Eq.(x)} * \lambda'_{Eq.(y)} * r'_{(x)} * r'_{(y)}}{8760} \right) + (\lambda_D * r_D) \ \textit{h/yr} \tag{16}$$

$$r_{\{x,y\}} = \frac{U_{\{x,y\}}}{\lambda_{Eq.\{x,y\}}} \ h \tag{17}$$

where

$$\lambda'_{Eq.(x)} = \lambda_{FT1(x)} + \lambda_{FT2(x)} + \lambda'_{FT3(x)} + \lambda'_{FT4(x)} \tag{18}$$

$$\lambda'_{Eq.(y)} = \lambda_{FT1(y)} + \lambda_{FT2(y)} + \lambda'_{FT3(y)} + \lambda'_{FT4(y)} \tag{19}$$

λ_D is the dependency-mode failure rate of cutset {x, y}, and r_D is the restoration time taken for the switching action (switching time).

$\lambda'_{FT3(x)}$ is a portion of $\lambda_{FT3(x)}$ that does not contain parameters related to the neighbouring line y present in the cutset being analyzed. $\lambda'_{FT4(x)}$ is a portion of $\lambda_{FT4(x)}$ that does not contain parameters related to the neighbouring line y present in the cutset being analyzed. These subtractions are done to avoid double counting when evaluating λ_D. $\lambda'_{FT3(y)}$ and $\lambda'_{FT4(y)}$ are defined on similar lines.

$$\begin{aligned} \lambda'_{FT3(x)} &= \lambda_{FT3(x)} - \lambda_y * P_{missing(PT_{A[y]})} \ \ if\, y \in J_x \\ &= \lambda_{FT3(x)} - \lambda_y * P_{missing(PT_{B[y]})} \ \ if\, y \in K_x \end{aligned} \tag{20}$$

$$\begin{aligned} \lambda'_{FT3(y)} &= \lambda_{FT3(y)} - \lambda_x * P_{missing(PT_{A[x]})} \ \ if\, x \in J_y \\ &= \lambda_{FT3(y)} - \lambda_x * P_{missing(PT_{B[x]})} \ \ if\, x \in K_y \end{aligned} \tag{21}$$

$$\begin{aligned} \lambda'_{FT4(x)} &= \lambda_{FT4(x)} - \left(\left(\lambda_y * P(PT_{A-y})\right) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} \\ -P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \end{pmatrix} \right) \ if\, y \in J_x \\ &= \lambda_{FT4(x)} - \left(\left(\lambda_y * P(PT_{B-y})\right) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} \\ -P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \end{pmatrix} \right) \ if\, y \in K_x \end{aligned} \tag{22}$$

$$\begin{aligned} \lambda'_{FT4(y)} &= \lambda_{FT4(y)} - \left(\left(\lambda_x * P(PT_{A-x})\right) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} \\ -P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \end{pmatrix} \right) \ if\, x \in J_y \\ &= \lambda_{FT4(y)} - \left(\left(\lambda_x * P(PT_{B-x})\right) * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[i]})} + P_{unwanted-Ns.(PT_{B[i]})} \\ -P_{unwanted-Ns.(PT_{A[i]})} * P_{unwanted-Ns.(PT_{B[i]})} \end{pmatrix} \right) \ if\, x \in K_y \end{aligned} \tag{23}$$

$r'_{(i)}$ is obtained on the lines of Equations (10) and (11) with $\lambda'_{FT3(i)}$ and $\lambda'_{FT4(i)}$ substituted for the existing $\lambda_{FT3(i)}$ and $\lambda_{FT4(i)}$, respectively therein.

Dependency-mode failure rate of cutset {x, y} can be quantified as explained below.

CS2 of FT1 on line x will result in FT3 on line y, and vice-versa (i.e., CS2 of FT1 on line y results in FT3 on line x). These two events are mutually exclusive.

In general, the rate of occurrence of CS2 of FT1 on line i, $\lambda_{CS2FT1(i)}$, can be expressed as:

$$\lambda_{CS2FT1(i)} = \lambda_i[P_{missing(PT_{A[i]})} + P_{missing(PT_{B[i]})} - [P_{missing(PT_{A[i]})} * P_{missing(PT_{B[i]})}]] \tag{24}$$

CS2 of FT1 on line x results in FT3 on all the neighbouring lines. What is of interest in the cutset analysis is only the proportion of CS2 of FT1 on line x which results in FT3 on only that neighbouring line which belongs to the cutset.

The proportional $\lambda_{CS2FT1(x)}$ of interest, $\lambda^*_{CS2FT1(x)}$ is given as:

$$\begin{aligned} \lambda^*_{CS2FT1(x)} &= \lambda_x * P_{missing(PT_{A[x]})} \ \ if\ y \in J_x \\ &= \lambda_x * P_{missing(PT_{B[x]})} \ \ if\ y \in K_x \end{aligned} \tag{25}$$

At this rate, there will be a common-cause failure of lines x and y on account of failure of line x. Similary, the rate at which the other mutually exclusive event – CS2 of FT1 on line y resulting in FT3 on line x – occurs can be expressed as:

$$\begin{aligned} \lambda^{*}_{CS2FT1(y)} &= \lambda_{y} * P_{missing(PT_{A[y]})} \;\; if \;\; x \in J_{y} \\ &= \lambda_{y} * P_{missing(PT_{B[y]})} \;\; if \;\; x \in K_{y} \end{aligned} \tag{26}$$

Thus, $\lambda^{'}_{D}$, the dependency-mode failure rate of cutset {x, y} because of CS2 of FT1 on a line that will result in FT3 on the neighbouring line present in the cutset, is given as the summation of $\lambda^{*}_{CS2FT1(x)}$ and $\lambda^{*}_{CS2FT1(y)}$.

$$\lambda^{'}_{D} = \lambda^{*}_{CS2FT1(x)} + \lambda^{*}_{CS2FT1(y)} \tag{27}$$

$\lambda^{*}_{CS2FT1(x)}$ is the same as $\lambda^{*}_{FT3(y)}$, where $\lambda^{*}_{FT3(y)}$ is only that part of the expression for $\lambda_{FT3(y)}$ which contains parameters (line/protection system) of line x. This is so because the dependency propagation from line x due to the failure of its primary protection system to neighbouring lines other than line y is inconsequential to the dependency-mode failure rate of cutset {x, y}. Similarly, $\lambda^{*}_{CS2FT1(y)}$ is the same as $\lambda^{*}_{FT3(x)}$, where $\lambda^{*}_{FT3(x)}$ is only that part of the expression for $\lambda_{FT3(x)}$ which contains parameters (line/protection system) of line y.

$$\lambda^{*}_{FT3(y)} = \lambda_{FT3(y)} - \left(\left(\sum_{\substack{\forall j \in J_i \\ j \neq x}} (\lambda_{j} * P_{missing(PT_{A[j]})}) \right) + \left(\sum_{\substack{\forall k \in K_i \\ k \neq x}} (\lambda_{k} * P_{missing(PT_{B[k]})}) \right) \right) \tag{28}$$

$$\lambda^{*}_{FT3(x)} = \lambda_{FT3(x)} - \left(\left(\sum_{\substack{\forall j \in J_i \\ j \neq y}} (\lambda_{j} * P_{missing(PT_{A[j]})}) \right) + \left(\sum_{\substack{\forall k \in K_i \\ k \neq y}} (\lambda_{k} * P_{missing(PT_{B[k]})}) \right) \right) \tag{29}$$

CS1 of FT1 on line x ‘may’ result in FT4 on line y, and vice-versa. (i.e., CS1 of FT1 on line y ‘may’ result in FT4 on line x). These two events are mutually exclusive. This is a ‘probable’ effect on the dependency-mode failure rate of the cutset as opposed to the ‘certain’ effect of CS2 of FT1 on a line resulting in FT3 on the neighbouring line in the cutset.

$\lambda^{*}_{CS1FT1(x)}$ is the successful fault clearance rate of line x on account of the protection system unit of line x nearest to the neighbouring line y weighted by the probability of unwanted non-selective operation of the primary protection system of line y.

$$\begin{aligned} \lambda^{*}_{CS1FT1(x)} &= [\lambda_{x} * P(PT_{A-x})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \; if \;\; x \in J_{y} \\ &= [\lambda_{x} * P(PT_{B-x})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[y]})} + P_{unwanted-Ns.(PT_{B[y]})} \\ -P_{unwanted-Ns.(PT_{A[y]})} * P_{unwanted-Ns.(PT_{B[y]})} \end{pmatrix} \; if \;\; x \in K_{y} \end{aligned} \tag{30}$$

$\lambda^{*}_{CS1FT1(y)}$ is the successful fault clearance rate of line y on account of the protection system unit of line y nearest to the neighbouring line x weighted by the probability of unwanted non-selective operation of the primary protection system of line x.

$$\begin{aligned} \lambda^{*}_{CS1FT1(y)} &= [\lambda_{y} * P(PT_{A-y})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{pmatrix} \; if \;\; y \in J_{x} \\ &= [\lambda_{y} * P(PT_{B-y})] * \begin{pmatrix} P_{unwanted-Ns.(PT_{A[x]})} + P_{unwanted-Ns.(PT_{B[x]})} \\ -P_{unwanted-Ns.(PT_{A[x]})} * P_{unwanted-Ns.(PT_{B[x]})} \end{pmatrix} \; if \;\; y \in K_{x} \end{aligned} \tag{31}$$

Thus, $\lambda_D^{"}$, the dependency-mode failure rate of cutset {x, y} because of CS1 of FT1 on a line that will result in FT4 on the neighbouring line present in the cutset, is given as the summation of $\lambda^*_{CS1FT1(x)}$ and $\lambda^*_{CS1FT1(y)}$.

$$\lambda_D^{"} = \lambda^*_{CS1FT1(x)} + \lambda^*_{CS1FT1(y)} \tag{32}$$

The net dependency-mode failure rate of cutset {x, y} is given as:

$$\lambda_D = \lambda_D^{'} + \lambda_D^{"} \tag{33}$$

c) Delivery point level: Based on results obtained at the cutset level, all minimal cutsets which lead to interruptions at delivery points are analyzed together using the logic of approximate F&D method applied for series systems. If there are n minimal cutsets $\{x, y\}_1$, $\{x, y\}_2$, … $\{x, y\}_n$,

$$\lambda_{Eq.(Dp)} = \sum_{i=1}^{n} \lambda_{Eq.\{x,y\}_i} \text{ f/yr} \tag{34}$$

$$U_{(Dp)} = \sum_{i=1}^{n} \left(\lambda_{Eq.\{x,y\}_i} * r_{\{x,y\}_i} \right) \text{ h/yr} \tag{35}$$

$$r_{(Dp)} = \frac{U_{(Dp)}}{\lambda_{Eq.(Dp)}} \text{ h} \tag{36}$$

3 CASE STUDY

OPAL is a four-bus network with two generators, two delivery points and four transmission lines, as shown in Fig. 1 [10]. The transmission network operates at 132 kV. The capacity of each of the transmission lines is 135 MW. The two generators are assumed to be 100% reliable. Delivery point 1, L1, has industry customers; delivery point 2, L2 has energy-intensive industry customers. The network data is given in Table I.

Table I. OPAL network data [10]

Line No.	Failure Rate (f/yr)	Repair Time (h)
1	2	20
2	3	15
3	4	12
4	5	10

All the protection system units have the same failure rate of 0.025 f/yr and repair time of 2 h. The missing and unwanted (both spontaneous and non-selective) probabilities of all the protection system units are assumed to be 0.0205 and 0.007, respectively. Multiple operating states (loading conditions) are prevalent for different durations in a year.

For the sample illustration of the proposed methodology, a uniform loading condition is assumed to last the whole duration of a year at a delivery point. Delivery point L1 is assumed to have a constant load demand of 100 MW, and delivery point L2 a constant demand of 75 MW, all pertaining to a ‘heavy’ load condition. By assigning probability weightages, the effect of multiple loading conditions can be easily captured. Different loading conditions result in different minimal cutsets during the system contingency analysis.

The basic reliability indices are obtained for delivery point L1 to illustrate the application of the proposed methodology. Performing a contingency analysis to identify the interrupted power at delivery point L1 for the heavy load condition yields the following minimal cutsets: $\{x, y\}_1$:{2, 3} and $\{x, y\}_2$:{2, 4}as shown in Fig. 2.

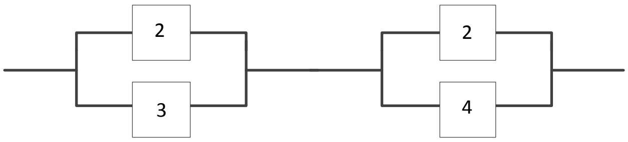

Fig. 2. Minimal cutsets for heavy load condition at L1

{2, 3} has non-neighbouring transmission lines as its constituent elements and {2, 4} has neighbouring transmission lines as its constituent elements. Employing the methodology proposed in Section 2.4, the following basic reliability indices as shown in Table II are obtained.

Table II. Basic reliability indices for delivery point L1

Reliability Parameter	**Value**
λ (f/yr)	0.357
U (h/yr)	0.642
r (h)	1.798

Table III provides an overview of the comparative analysis of methods that include the impact of protection and control (P&C) in power system reliability assessment against the benchmark of delivery point reliability at L1 with perfectly reliable P&C. Difference between the values of basic reliability indices obtained using the detailed mathematical modeling of the proposition in this paper and the methodology of the requirement specification document (RSD) [10] is brought forward. A different notational scheme than the one used in the RSD has been used this paper, with implications in the way some input data parameters have been interpreted. Clearly, there is a marked effect of the reliability of protection systems on the reliability of supply. From these basic indices, other indices such as annual interrupted power, annual energy not supplied and annual interruption costs could be obtained [10].

Table III. Comparative analysis of different reliability evaluation methods for L1

Method	**λ (f/yr)**	**r (h)**	**U (h/yr)**	**% Change in 'λ' w.r.t Perfect P&C**	**% Change in 'r' w.r.t Perfect P&C**	**% Change in 'U' w.r.t Perfect P&C**
Perfect P&C	0.08	6.32375	0.5059	-	-	-
With P&C (RSD)	0.302	2.049	0.6188	277.50	-67.60	22.32
Proposed Methodology	0.357	1.798	0.642	346.25	-71.57	26.90

Approximate F&D methods of reliability assessment are known to give pessimistic results. However, their application circumvents the need for complex Markov model-based solutions in incorporating the effects of protection system reliability on power system reliability. Future work includes the investigation of the applicability of dynamic reliability block diagrams to capture the complex effects of back-up protection coordination schemes of multi-circuit meshed transmission configurations.

4 CONCLUSIONS

There is a considerable effect of reliability of protection systems on the reliability of supply, and hence appropriate protection system reliability models must be incorporated in power system reliability studies. A detailed mathematical modelling of the dominant failure modes of transmission lines due to various protection system response scenarios has been provided in this paper. The uniqueness of the proposed approach lies in its ability to model the impacts of transmission protection system failures on power system reliability without the need for complex Markov models, while accounting for the dependency effects, using the approximate frequency and duration methods. Sample delivery point indices based on the proposition have been calculated for the OPAL test network. The developed procedure of incorporating protection system failure modes in reliability studies allows for the inclusion of additional failure modes if necessary, and is generic.

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Effects of Dependent and Common Mode Outages on the Reliability of Bulk Electric System – Part I: Basic Concepts

Prepared by the PACME Working Group of the
IEEE PES Reliability, Risk and Probability Applications (RRPA) Subcommittee

Abstract—**This paper is the first part of a two-part paper based on the ongoing activity carried out by the Task Force (TF) of the Working Group (WG) on Probability Applications for Common Mode Events (PACME) in electric power systems under the Reliability, Risk and Probability Applications (RRPA) Subcommittee. The primary objectives of this work are to (1) review and discuss the basic definitions of dependent, common-mode and cascading outage events, (2) identify the major causes of common-mode, dependent and cascading outages, (3) recognize the effects of protection system failures and misoperations on the Bulk Electric System (BES), and (4) assess the impact of weather related outages and extreme events on the performance of the BES. The scope of Part I is limited to the basic concepts on common-mode and dependent outages. The overall goal of the two papers is to assist the wider efforts within the industry in practically assessing the effects of dependent and common-mode outages on the reliability of BES.**

***Index Terms*-- Common mode outage, dependent outage, extreme event, outage data, transmission system reliability.**

I. NOMENCLATURE

Terminology for definitions in this section comes from the IEEE Standards 346 and 859 [1] - [2] and NERC Glossary Terms [3].

A. Terms Related to Dependent Outages

Primary outage: An outage occurrence within a related multiple outage event which occurs as a direct consequence of the initiating incident and is not dependent on any other outage occurrence.

Secondary outage: An outage occurrence which is the result of another outage occurrence.

Secondary outages may be caused by components or units requiring physical clearance during the repair process, failure of a circuit breaker to clear a fault, or a protective relay system operating incorrectly and overreaching into the normal tripping zone of another unit. Some secondary outages are solely the result of system configuration; for example, two components in series will always go out of service together. At present, primary outages are referred to in the industry as independent outage occurrences, and secondary outages as dependent or related outage occurrences.

Failure of response function: The inability of a component to perform a function which is required as a response to system conditions or to a manually or automatically initiated command.

Exposure (Operations): The number of operations during which a component or components within a unit are exposed to failure of response functions.

B. Terms Related to Common Mode Outages

A Common mode outage refers to simultaneous outages of multiple components due to a common cause

Common-mode outage event: A related multiple outage event consisting of two or more primary outage occurrences initiated by a single incident or underlying cause where the outage occurrences are not consequences of each other.

Primary outage occurrences in a common-mode outage event are referred to as common-mode outage occurrences or simply common-mode outages. The common mode outages could be momentary or sustained outages. The components involved in common mode outages could be returned to service at the same time or at different times. Traditionally, common mode outages are regarded as small probability events. They are assigned small or even zero weighting values and mostly ignored. Although the probability of a common mode failure may be small relative to the probability of independent outages, the probability of system failure can dramatically increase upon taking the possibility of common mode outage into consideration.

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Cascading: It is the uncontrolled successive loss of system elements triggered by an incident at any location. Cascading results in widespread electric service interruption that cannot be restrained from sequentially spreading beyond an area predetermined by studies.

Adverse reliability impact: It is the impact of an event that results in BES instability or Cascading.

II. INTRODUCTION

The panel session on the practical aspects of PACME at the 2012 IEEE PES General Meeting included papers [4]-[6] that provided a review of the fundamental concepts in the modeling of common mode and dependent outages in BES. Among the discussions that ensued were challenges in obtaining useful practical data concerning such outages that is required to support the existing models to carry out predictive reliability assessment studies. This two-part paper set is a result of the consequent efforts initiated by the PACME Working Group in identifying and addressing the relevant challenges.

Section III presents an overview of the causes and effects of common-mode and dependent outages, including the emergent deployment of cyber devices. Weather related outages are covered exclusively in Section IV. Cascading outages are dealt with in Section V.

III. CAUSES OF COMMON-MODE AND DEPENDENT OUTAGES

The common-mode and dependent outages belong to a category of multiple-outage events that have a significant impact on system reliability but have received only a limited attention. Assessing the likelihood of these events has always been a challenge for utility planning and operation departments. They are influenced by a number of factors such as: failure of equipment (often due to ageing), malfunctioning of protective devices, weather conditions (wind, lighting), natural disasters (hurricanes, earthquakes), loading conditions, power transfers, maintenance, human error, etc. Usually, an initiating event for common-mode or dependent outage propagates via different mechanisms beyond the initial outage to multiple outages, which might sometimes result in cascading failures. The recent NERC State of Reliability (SOR) reports [7] show that 20-25% of all sustained automatic outages belong to a category of common-mode or dependent events. This section describes the various causes of common-mode and dependent outages.

A. Common-Mode Outages

Most common mode outages occur on the transmission lines outside of the substations. The collapse of a transmission line tower supporting more than one circuit is a straightforward example. Most component failures resulting in common mode failures outages cause a fault on one or more phases of two or more different transmission circuits, either because those phases are displaced sufficiently to come into contact with the ground, or because a grounded item such as a static wire contacts a phase or phases of both lines.

Many experts do not consider an incident to be common mode where two circuits are impacted by a single storm or other disturbance, but the damaged components are not common to both circuits and do not come in contact with each other. An example would be the destruction of two parallel lines on separate towers by a tornado. Additional justification for this classification is found in the repair processes being largely independent; repairing the components of line 1 does nothing to restore line 2, and vice versa.

B. Protection System Failures and Misoperations

Dependent outages are frequently caused by relay protection system and circuit breaker failures and misoperations. Old, but still descriptive, terms for these are “stuck breaker” and “overreach”. These dependent outages are caused by response failures: the failing component has an assigned response function following some class of faults, and has failed to perform the function or was not selective enough in doing it. Protection system failures and misoperations do not cause a fault on the power system but may allow it to continue longer than intended, with adverse consequences of greater damage to equipment or possibly, allowing a generating unit to pull out of synchronism (instability).These failures also result in back up breakers to operate generally leading to a wider outage than if the main protection had operated correctly.

The salient features pertaining to the effect of protection systems on bulk power reliability evaluation in the early 1990s were highlighted by the then Application of Probability Methods (APM) task force on protection systems reliability [8]. *Dependability* and *security* are the two attributes a transmission protection system must possess to be reliable. Missing operation (failure to operate when called upon to clear a fault) and unwanted operation (spurious/unwanted operation in the absence of faults or due to faults outside the protection zone) of protection systems [9], termed as *misoperations*, are responsible for the weakening of these attributes, respectively. If the power system is operated according to the n-1 criterion, an unwanted trip does not cause system problems; it results in the isolation of a healthy line, which situation can be remedied by auto-reclosure of the breaker associated with the corresponding protection system unit. On the other hand, missing trips are responsible for failure dependency propagation. For example, because of unreadiness of a line’s protection system, a fault on the line cannot be cleared, and protection system unit(s) of the neighboring lines designed to act as backup, must act to isolate the faulted line. In the process, the healthy neighboring line is isolated from the system as well until further appropriate switching action is executed. Recent studies such as [10] – [11] include the comprehensive effect of such protection system dependencies in the power system reliability modeling and analysis. However, the level of specificity involved in obtaining the relevant protection system input data parameters for such models is found to be a hindrance to the realization of corresponding reliability indices, and hence the need for consolidated protection system failures related data collection efforts. In Nordic countries such as Norway and Finland, protection system misoperations were found to be the second largest contributors of Energy Not Supplied (ENS) at transmission and subtransmission voltage levels [12]. This only impresses further on the need for including protection system related failure dependencies in the reliability prediction models. The relationship between protection system, the system protected and the impact of various factors on failure to respond is modeled and analyzed in [13].

C. Substation Related Outages

There are numerous components within substations which can cause a fault. Most such components are part of a single transmission unit and their failure normally causes only that unit to be tripped out of service. Examples are lightning arresters, disconnect switches, current transformers, voltage transducers, insulators and bus conductors. Such a component failure is classified as independent from a probabilistic standpoint if only the unit of which the failed component is a part is affected, but common mode if multiple units are affected. Occasionally such a component fails with sufficient violence to propel debris into components belonging to another unit, or causes debris to fall on a portion of a unit at a lower level. It must be noted that a circuit breaker is inherently a component of the two units between which it is the interface, and its failure is common mode if both are outaged. Most circuit breakers have current transformers on their bushings which form the ends of the sensing zones for faults on the two units, and a fault on the circuit breaker will be within the overlap of those zones.

D. Failures of Cyber Devices and Cyber Attacks

Cyber devices have come into common use controlling power systems, and do not have a one to one correspondence to transmission "units". A transmission unit may be controlled by one or multiple cyber devices or none, and several units may be controlled by a single cyber device. The control relationships are neither explicitly shown nor implied by the one-line diagrams which have traditionally been used to describe the configuration of a power system. Thus it is difficult to quantify the exposure, for instance in years or number of operations, and calculate a failure rate. Most cyber device failures neither cause nor exacerbate a power system fault.

Modern electric power systems are increasingly built with more command and control functionalities that come with supporting infrastructure such as communication networks and substation automation systems [14]. These infrastructures are complex and cause interdependencies between physical energy systems and cyber network systems. Besides the protection and substation system hardware failures, failures of cyber devices can cause related multiple outage events with a much wider impact to power system reliability.

Cyber threats that cause devices' malfunction and failures can be of different forms such as denial of service, malware, authentication, spoofing, etc [14]. Once the cyber devices fail to function as expected, power systems operation will be affected and could possibly lead to power outages. The impact of cyber devices to the system can be classified to three levels; generation, transmission, and distribution [14]. The impact to generation will be in the form of automatic voltage regulator control, governor control, and protection. The cyber attacks at the transmission level will affect VAR compensation, state estimation, and protection. The impact at the distribution level will be mostly in the form of protection malfunction. The common concern across these three levels is in the protection systems.

The cyber part of power systems is recently being recognized as a potential contributing factor in triggering power outages [15]. The severity of the impact as a result of cyber devices failures can be classified into three groups, namely, catastrophic, degrading, and local effects [15]. The catastrophic effect refers to the situation when a failure of cyber devices causes the system operator to mishandle or inadequately handle contingencies that will lead to cascading failures and eventually blackouts. The degrading effect refers to the condition when the failures of cyber devices cause the inefficient utilization of resources that would lower the overall system efficiency but do not cause widespread outages. The local effect is when the failure of cyber devices blocks non-critical functionality within limited duration and place. This type of effect is of the minimal impact to the overall system but will cause some limited inconvenience to the end customer.

Although the severity of cyber device failures and impact varies, the resulting effect may still cause the simultaneous outages of multiple components. This type of failures should therefore be considered as one of the causes of common-mode and dependent outages. Examples of cyber failures in a substation causing common mode failures are given in [16]. An example of a major manifestation of this dependency is Italian blackout of September 2003 – a failure in a power station led to a failure of the communication network, which in turn caused additional failures of power stations [17].

IV. WEATHER RELATED OUTAGES

This section describes the characteristics of various common-mode and dependent outages related to the weather. The typical joint representation of common mode and weather related outages is presented in [5]. Reference [4] extends this model to three classifications of weather conditions – normal, adverse and major adverse.

Much of the data pertaining to outage events in the USA is available from the GADS (Generating Availability Data System) and the TADS (Transmission Availability Data System) that are maintained by the NERC. Although the GADS dates back to 1982, it includes data collected since

1963. However, the TADS provides comprehensive transmission outage data only since 2008. Prior to this, there was no uniform practice in transmission outage data collection across the US, although the NERC regions maintained their own regional databases, and analyses and reports such as those in [18] have been published. The Canadian utilities have had more consistent transmission data collection practices for many decades, and this data is available at the CEA web site [19], although unlike the NERC data the CEA data is not freely available.

The NERC web site provides a glossary defining all terms including dependent and common mode outages, as well as instructions for data collection. The TADS data contains considerable discrimination between outage types, causes and modes: among others, it distinguishes between momentary and sustained outages, between outages caused by lightning and weather excluding lightning, between common mode and common mode initiating events, and so on. However, the statistics reported within each cause code (such as weather related) are not broken down into independent, dependent, common mode, etc.

V. CASCADING EVENTS

An extreme category of dependent mode outage events is presented in this section. Cascading describes a general type of dependence between events in which the events that have already occurred have weakened the system so that subsequent events are more likely. Long, complicated cascades of outages are an important cause of large blackouts. Cascading often involves unusual and complicated interactions between events because common and straightforward interactions have already been mitigated by engineers.

Cascading is challenging to study because of the many different mechanisms and types of failure involved. In particular, cascading events can include a variety of common mode and secondary failure mechanisms. The reason for lumping together so many different mechanisms into the general category of cascading is that it appears that the general characteristics of cascading can be described and quantified at a bulk level of analysis without detailed consideration of each of the mechanisms. The quantitative study of cascading at a bulk level of analysis is much less developed than other areas of risk analysis, and is complementary to, and no way a substitute for, the risk analysis of detailed failure mechanisms.

In cascading analysis, a cascade is considered to have initial primary events that then propagate into a series of further events. The primary events can be analyzed by standard risk analysis. Each further event is a secondary event in the sense that it is caused in some way by the previous events, but there are often multiple causes or no single cause that can be clearly described. Instead of trying to ascertain the causes, the cascading analysis characterizes the overall tendency for the events to propagate.

In particular, given samples of cascading line outages, the outages in each cascade can be grouped into successive generations and the total number of outages in each generation can be summed over all the cascades. Then the ratio of the total number of outages in successive generations gives the average propagation. For example, if in one year of cascading data there are a total of 1000 outages in generation 1 and 500 outages in generation 2, then the average propagation from generation 1 to generation 2 is 0.5. That is, on average, one outage in generation 1 produces 0.5 outages in generation 2. The average propagation can be used to estimate the probability distribution of the total number of outages due to cascading from some assumed initial failures using a branching process model [20].

Cascades are viewed as initial primary events followed by propagation, and the challenge is to quantify and manage the propagation to characterize and mitigate cascading. Of course, reducing the frequency and severity of the primary events is also of key importance in mitigating cascading. The potential for the new bulk cascading analysis to describe and mitigate cascading events will become clearer as research progresses.

The next section describes the challenges in modeling of common mode and dependent outages.

VI. CHALLENGES IN MODELING COMMON MODE AND DEPENDENT OUTAGES

Traditionally, the basic indices of modeling common mode or dependent outages are outage frequency, repair (recovery) time and unavailability. These indices are calculated by classifying into groups in terms of equipment types (such as overhead lines, transformers, etc.) and voltage levels (such as 500 kV, 230 kV, etc.). However, a variety of common mode and dependent outages presents difficulties in data classification and modeling. The following issues are a few examples [21]:

- The equipment components in a common mode or dependent outage may not be the same type. For instance, an overhead line and a transformer can fail due to a common cause (such as protection action or personnel incident). There are too many combinations of different equipment types in a common mode or dependent outage.
- The equipment components in a common mode or dependent outage may be associated with different voltage levels. For example, a 500 kV overhead line and a 230 kV line can be tripped due to a common cause (such as lighting). There are also too many such combinations.
- In the traditional common mode modeling, one single repair (recovery) time is assumed. It has been observed in actual data collection [19], however, that two or more components in a common mode outage may have different repair times in many cases.

The above issues present the challenges on how to classify data of common mode or dependent outages, how to calculate their indices according to the classed equipment groups, and how to model their repair times in system reliability evaluation.

VII. CONCLUSION

This paper, Part I of the two-paper set, is an overview of the causes and effects of common mode and dependent outages in bulk electric systems. It is intended to lay the necessary foundation for understanding their impact on the reliability of BES. The subsequent outage data analysis, based on the industry practice in North America and parts of Europe is described in the companion paper (Part II).

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Effects of Dependent and Common Mode Outages on the Reliability of Bulk Electric System – Part II: Outage Data Analysis

Prepared by the PACME Working Group of the
IEEE PES Reliability, Risk and Probability Applications (RRPA) Subcommittee

Abstract—**A companion paper (Part I) presents the basic concepts of dependent and common mode outages, the causes for their origins in the bulk electric system (BES) and the subsequent effects from a reliability perspective. This paper describes the practical outage data collection efforts in vogue in North America and parts of Europe, with particular emphasis on outage data statistics corresponding to dependent and common mode outages. The goal is to eventually be able to obtain standard, representative reliability indices for typical transmission elements such as lines and transformers from the available outage data.**

Index Terms-- **Common mode outage, dependent outage, extreme event, outage data, transmission system reliability.**

I. INTRODUCTION

Interest in data collection and analysis is perhaps as old as the development of models and methods. Like the papers dealing with models, the early literature on data reporting does not mention multiple failures due to dependent and common mode failure phenomenon. In early references, the reliability performance of the system was primarily based on independent failure rates of individual system elements. In [1] – [4], it is shown that major outage events are often caused by multiple outages related to a common environment such as storm, common-mode failure, or dependent failures such as failure or misoperation of relays, stuck breaker conditions. The outage data of transmission elements collected by various collection schemes is used to evaluate historical performance and to perform predictive reliability analyses. A careful reading of the literature reveals considerable difference of opinion interpreting whether outages are common mode. Perhaps the two characteristics which are agreed upon are that there is a single cause and that the outages overlap in time.

II. REVIEW OF OUTAGE DATA COLLECTION SYSTEMS

The review of outage data collection systems in general establishes a context for the core focus of the paper on dependent and common mode outages. A selective overview of such schemes prevalent in North America and parts of Europe is provided in this section.

A. United States

a. TADS – NERC

The Transmission Availability Data System (TADS) was launched with the establishment of a TADS task force by the North Electric Reliability Corporation (NERC) Planning Committee in 2006. In 2007, the NERC Board of Trustees approved the collection of automatic transmission outage data beginning in the calendar year 2008 (Phase I). Subsequently, in 2008, the NERC Board of Trustees approved the collection of non-automatic outage data beginning in the calendar year 2010. Based on previous work and experiences on transmission outage data collection, TADS implemented a uniform approach to reporting and measuring transmission availability, performance and other related reliability information. Consistency across the NERC footprint includes types of transmission availability data, performance metrics that are calculated from the reported data: refinements and improvements, such as changes to definitions, cause codes, outage modes, transmission elements, etc. More specific details regarding the NERC TADS collection system can be found in [2] and [5].

b. WECC Transmission Reliability Data (TRD)

WECC is the regional entity responsible for coordinating and promoting BES reliability in the Western Interconnection. WECC is geographically the largest and most diverse of the eight NERC regions. The TRD transmission outage data collection system includes both forced and scheduled outages for all circuits configured ≥ 200 kV (transmission lines and transformers). More specific details regarding the WECC TRD system can be found in [4] – [5]. The TRD database contains both outage data history and inventory data for each WECC participating member utility. The TRD data, collected since 2006, are primarily used to support WECC Reliability Criteria, and Performance Category Upgrade Request Process (PCUR). WECC has incorporated probabilistic analysis within reliability standards in 1997. The WECC Performance Table W-1 [4], applicable to WECC member utilities, incorporates performance criteria and outage probabilities for the current NERC contingency categories B – D.

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B. Canada

a. CEA

The transmission segment of the Canadian Electricity Association (CEA) Equipment Reliability Information System (ERIS) program was initiated in 1978 and the subsequent annual ERIS program reports include transmission equipment outage statistics for equipment with operating voltages of 60 kV and above. The reports include outage data on major transmission system components in addition to transmission line statistics [6]. The component forced outage and common mode outage definitions used in ERIS are consistent in principle with those stated in the IEEE Standard 346-1973. The ERIS program captures common mode events using unique and individual event identification numbers. The outages of major components associated with a common mode event are linked to the appropriate common mode event identification number. The existing specification and data collection system provides the ability to conduct a wide range of outage data analysis studies.

b. BC Hydro

The Reliability Decision Management System (RDMS) was initiated at BC Hydro in 2004 and put in operation in October 2005. The main purpose of building and using RDMS is to help BC Hydro meet business requirements in reliability management. Reports of both system and equipment performance are provided to the British Columbia Utilities Commission, CEA, WECC and NERC. In addition, RDMS provides input data for reliability studies and probabilistic analysis in system planning, asset outage information for maintenance scheduling, data analytics (benchmark study, trend analysis and outage cause investigation), and corporate targets of key performance indices. RDMS creates various reports on reliability indices for 23 types of equipment from 60 kV to 500 kV, and bulk system at delivery points. The reliability indices include outage frequency, duration, probability, severity and energy-related metrics. For equipment indices, both independent and dependent outages are covered. Common mode and other dependent outage indices are calculated and reported separately. Hourly load curve information at individual delivery points is available to calculate energy-related indices such as Delivery Point Unreliability Index (DPUI). More details about RDMS can be found in [7].

C. Europe

a. Great Britain (GB)

GB does not have a national data repository for transmission level data that is similar to North American databases. An analysis of fault data was published as part of the recent Fundamental Review of the GB Security and Quality Supply Standard [8]. This includes breakdowns by year, network owner, level of outage (N-1, N-2, etc) and whether the outage was permanent or transient. The GB distribution industry which includes voltage levels up to 132 kV has a more formal data collection system – the National Fault and Interruption Reporting Scheme (NAFIRS), managed by the Energy Networks Association [9]. The statistics distinguish between faults which do and which do not disconnect customers, and severity of outage (N-1, N-2); mean repair times are also reported. No distinction is made between genuine common mode failures, and other double outages (e.g., failure of a second circuit during repair of the first, whether coincidental or due to higher loading). It is estimated that about 25% of double failures are true common mode.

b. Nordic Countries

Nordel was an organization for co-operation among the Transmission System Operators (TSOs) of the Nordic countries (Denmark, Finland, Iceland, Norway and Sweden) until 2009, primarily aimed at creating an effective harmonized Nordic electricity market. Nordel operational tasks have now been transferred to the European Network of Transmission System Operators for Electricity (ENTSO-E). It must be pointed out that only the transmission grids of Finland, Sweden, Norway and the eastern part of Denmark are synchronously connected together, forming the Nordel interconnected grid. The Grid Disturbance Group (STÖRST), under the aegis of the Nordel's Operations Committee was responsible for preparing guidelines to be used for collecting transmission fault and disturbance statistics of the Nordic countries [10]. Accordingly, the transmission grid fault and disturbance statistics were published by Nordel from 1999-2008 [10]. From 2009, the fault statistics of the Nordic countries continue to be published by ENTSO-E [11]. TSOs providing the required statistical data are Energinet.dk in Denmark, Fingrid Oyj in Finland, Landsnet in Iceland, Statnett in Norway and Svenska Kraftnät in Sweden. Other ENTSO-E countries are encouraged to participate in similar reporting.

Objectives that the Nordel statistics support include the assessment and prediction of the reliability of the transmission system. They are limited to transmission units in commercial operation with a voltage of at least 100 kV. Grid disturbances are grouped by seven different fault causes [12]. The number of faults in lines and cables, as well as other components such as power transformers, instrument transformers, circuit breakers and control equipment, divided by cause, for each of the voltage levels, is reported. The consequences of the various disturbances are eventually presented in the form of estimated Energy Not Supplied (ENS). Each of the Nordic countries has its own way of gathering data according to fault causes based on the common Nordic cause allocation guidelines [10]. Work intended to establish common guidelines for founding a common Scandinavian fault database for voltage levels above 1 kV has also been recently initiated [12]. In Norway, FASIT (Fault And Supply Interruption information Tool) [13], developed based on international terms and standards, e.g. IEEE Std. 859 – 1987, is widely in use by all the network companies including the TSO Statnett. It is now the national standard for collection, calculation and reporting of reliability data for all voltage levels above 1 kV [13], regulated through the Norwegian quality of supply regulation.

The next section presents a sample analysis of some of the failure statistics on common mode and dependent outages in North America.

III. OUTAGE DATA ANALYSIS

A. *Common Mode and Dependent Outage Parameters in TADS, CEA and TRD*

For information collected by TADS from 2008 through 2012, including momentary and sustained outages at voltages ≥ 200 kV, over 70% of sustained and momentary automatic outages are single mode, resulting in the loss of just one transmission element (N-1). However, a significant percent of automatic outages are multiple element outages, categorized as either dependent or common mode. On a NERC-wide basis, an average of two percent of events per year contain between three or more momentary and sustained automatic element outages, some of which meet the TPL (transmission planning) standards requirements, while other events went beyond the N-1 events (known as a NERC Category B events) commonly used in planning and daily operations.

A study based on CEA data [3] conducted for the period 2006 – 2010 indicated that the majority of common mode events are associated with two or three major component outage occurrences. The study also indicated that approximately 47% of transmission line related common mode events resulted from common tower outages, and identified the integral subcomponents of the transmission line that contributed to tower-line common mode outages. Less than one quarter of these outages are associated with the line terminals. The study indicates that although common mode outages on transmission lines are commonly considered to be relatively rare, the results show that actual common mode outage occurrences constitute approximately 8% of all transmission line forced outage occurrences and when these events occur on the tower-line they constitute approximately 6% to the unavailability of transmission lines. It was found that common mode outages attributed to line terminal equipment contributed very little to transmission line unavailability. A substantial portion of transmission line related common mode events are due to adverse weather. The noted study [3] showed that adverse weather in the months of June, July and August were the dominant causes of transmission line common mode events with defective equipment being a distant secondary cause.

A study based on WECC TRD outage data [4] conducted for the period 2008 – 2010 indicated that common mode and dependent outages account for approximately 10% of all outages in WECC system. The study also indicated that approximately 66% of all common mode outages involved two lines being out. It was found that the most dependent mode outages occurred in the summer months due to heavy loading conditions and severe weather related factors such as wind, fires, lighting, etc. Three dominant causes of dependent mode outages were identified to be "weather excluding lighting", "lightning" and "failed substation equipment". Reference [14] provided a comprehensive analysis of TRD data by taking into account the random nature of outages and fifteen various factors/ variables. The particular emphasis was placed on analysis of various types of explanatory variables such as voltage class, length, number of conductors per phase, number of terminals, circuits per structure, insulator type, structure, terrain and elevation.

The Western Electricity Coordinating Council (WECC) has established a Performance Category Upgrade Request (PCUR) process for adjusting performance requirements for two lines on a common corridor based on outage probability. Historical outage performance as well as expected future performance from a class of similar facilities is used in performing the required analysis. A few utilities, including Bonneville Power Administration (BPA) have applied their historical outage behavior of transmission lines over a time period to compute the mean time between failures (MTBF) of two lines on a common corridor [15]

B. *Typical Data of a Utility in North America*

Typical reliability metrics calculated from the outage data of a utility in North America are provided in Tables I and II. The calculated reliability metrics have been classed into line-related and terminal-related categories since these two categories require different calculation methods. The line-related events are associated with line length, while the terminal-related events are not. These metrics cannot cover all common cause outage types. For example, a common cause outage can include different equipment types (such as a line and a transformer) or different voltage levels (such a line at 500 kV and another at 230 kV). Such common cause outage events cannot be accounted in a form of average metrics normalized by length or classed by equipment type. Four notes below Tables I and II provide more details.

Table I .Sustained Common Cause Outage Metrics (line-related)

Voltage (kV)	Frequency (events/yr/100 km)	Recovery Time (hr/event)	Unavailability (per 100 km)
500	0.1894	1.2575	0.000027
230	0.6893	0.3899	0.000031
138	0.8088	17.332	0.001600
60	4.4077	14.900	0.007497

Table II. Sustained Common Cause Outage Metrics (terminal-related)

Voltage (kV)	Frequency (events/yr)	Recovery Time (hr/event)	Unavailability
500	0.6364	1.6243	0.000118
230	0.3636	0.4045	0.000017
138	0.3636	0.4825	0.000020
60	0.6167	0.0909	0.000006

Notes:

1. Tables I and II indicate the common cause outage metrics of overhead lines based on the typical statistics of a utility in North America during 2003 to 2012. The statistics are dynamic data and vary over years.
2. A common cause outage may be associated with different equipment types (such as a line and a transformer) or different voltages (such as a line at 500 kV and another line at 230 kV). These common outage data cannot be expressed as normalized average metrics according to equipment type or voltage level.
3. The outage frequency and unavailability in Table I have been normalized in a form of per 100 km. Note that the 60 kV lines associated with common cause outages in the table have an average length of much shorter than 100 km.
4. The line-related common cause outages refer to the line outages caused by non-substation factors (such as lightning, tree falling, foreign objects, etc.), whereas the terminal-related common cause outages refer to the line outages caused by substation component factors (such as protection, personnel incident, RAS operation, etc.)

C. Recommendations

Based on the observation of some of the data collection practices, we propose the following recommendations:

1. It is necessary for utilities to use a computerized database with automatic functions in data collection, storage, processing and analysis.
2. More work is required for utilities and organizations to establish uniform definitions, calculation methods and procedures in common cause outage data.
3. Some special issues should be further addressed. For example, components in a common cause outage group have different recovery times; a common cause outage may be associated with different equipment types and different voltage levels. In these cases, an average index cannot be calculated or the model of common cause outage may need a modification.
4. The data should be checked and every effort should be made to include the causes of an outage. The best time to check and provide outage details is right after an incident has occurred. Drop down menus with auto fill, whenever possible, is quite convenient to enter the information.
5. The various databases, models and processes should talk to each other so that all parties including regulators, mangers, planners, operators and maintenance crew can use the outage data to extract information relevant to them.

IV. IMPACT OF OTHER FACTORS

This section presents a brief overview on statistical analysis of events pertaining to a specific class of dependent mode failures, i.e., protection system related dependencies. Such failures can be clearly seen to be different from common-mode failures. A brief note on extraordinary events such as cascading failures is also provided, for completeness.

A. Protection System Failures and Misoperations

A recent misoperations report from NERC, prepared by its Protection System Misoperations Taskforce [16], outlined the data collection schemes required to analyze protection system misoperations related reliability issues. The emphasis of this analysis was primarily on investigation into the possible root causes of such misoperations and recommending the relevant risk mitigating strategies. The general trend observed was that unwanted protection system operations were much higher than missing protection system operations. Approximately 94% of misoperations in the study period resulted in unnecessary trips. Only 6% or less resulted in a failure to trip or slow trip. Approximately 65% of misoperations were found to be due to one of these three reasons/cause-codes: incorrect settings/logic/design errors, relay failures/malfunctions, and communication failures. NERC uses a Severity Risk Index (SRI) [17] to measure risk impact from events resulting in transmission loss, generation loss, and load loss. Protection system misoperations were found to have a statistically significant correlation with Transmission Outage Severity, a measure which is based on the SRI transmission severity component. The relative risk of misoperations is found to be the highest among all cause codes, excluding weather and unknown initiating causes.

The Nordel statistics from the Nordic countries,provide systematic fault and disturbance statistics, but are limited in information on protection system misoperations [18]. A joint comparative study conducted by Norway and Finland [18] – [19], based on their respective internal mechanisms of recording protection system fault statistics for the years 1999-2004, yielded empirical evidence of the effect of protection system reliability on power system reliability. This was revealed by a marked impact of protection system misoperations on the estimated Energy Not Supplied (ENS). In fact, protection system misoperations were found to be the second largest contributor of ENS at transmission and subtransmission voltage levels. In Norway, the unwanted trips accounted for 60% of the total number of incorrect trips, whereas in Finland, they constituted 84% of the total number of incorrect trips. As in the case of the NERC studies, the unwanted protection system operations were also found to be much higher than the missing protection system operations in the Norway-Finland joint study.

It is not only missing operations that result in the failure dependency propagation, but also unwanted operations due to faults outside the protection zones that result in dependent failure modes of the transmission lines [20]. This level of finer resolution in data collection is usually not resorted to. However, if one were to use predictive models for reliability assessment, such data would be needed. Presently in Norway, further research on FASIT databases is being conducted to include comprehensive protection system failure statistics.

In both NERC and Nordel studies, the statistics on misoperations can be used to compute only the prevailing protection system reliability attributes – dependability, and security [18]. However, further research is warranted to put forward a standardized way of computing the necessary input parameters such as protection system failure rates and probability attributes of missing and unwanted operations, so that, say, recent mathematical models in vogue [20] – [21] can be employed in predictive studies to capture the impact of protection system reliability on power system reliability.

B. Cascading Events

Cascading analysis has been recently developed to describe the number of transmission lines outaged in cascading events [22]. The average propagation of automatic line outages is estimated from the TADS data. The average propagation increases from 0.2 to approximately 0.7 as the cascades progress. (Propagation of 0.2 means that each line outage causes, on average, 0.2 further line outages.) Then a Galton-Watson branching process model of cascading uses the average propagation and the statistics of the initial outages to estimate the probability distribution of the total number of line outages. This initial analysis suggests a way to quantify the effect of cascading in propagating initial outages from one year of TADS data for a large utility.

V. CONCLUSIONS

This two-part paper is based on the ongoing activity carried out by the Task Force (TF) of the Working Group (WG) on Probability Applications for Common Mode Events (PACME) in electric power systems under the Reliability, Risk and Probability Applications (RRPA) Subcommittee. Beginning with an overview of the causes and effects of the dependent and common mode outages in Bulk Electric Systems, the focus is centered on gaining an insight into the corresponding outage data collection efforts across the industry, with a view to establish necessary benchmarks. The results presented show that there is a definitive need for collective effort from academia and industry in not only recommending procedures for data collection and monitoring but also in obtaining representative indices from the collected data by making use of appropriate predictive reliability models and tools. An awareness of various international data collection practices and systems will support efforts to converge these systems. Convergence of these systems will, in turn, provide benefits for benchmarking and comparing performances of different practices.

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