RNR: Reliability oriented Network Restructuring

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***Abstract*—This paper is about an application of optimal power flow calculation for considering how interconnections of microgrids affect the reliability of the system and the need of network reconfiguration. For this purpose reliability indicators for power system restructuring are presented. A reliability oriented network restructuring (RNR) mathematical optimization model is proposed for solving power grid expansion decisions with non-linear AC-OPF. The microgrid structures are derived from the standard IEEE-14 bus system architecture. The proposed reliability framework is implemented with the set of reliability indicators for measuring the system performance. The model was solved using outer approximation algorithm. The analysis is conducted to investigate the importance of restructuring in an investment decision for the expansion. The results with a comparison between investment and investment with restructuring are outlined. Consequently, the expansion considering the restructuring is found to be practical and feasible.**

***Index Terms*—power system expansion, reliability and vulnerability, optimal power flow, microgrids, non-linear system of equations, outer approximation algorithm**

I. Introduction

THERE is an energy transition from "top-to-bottom" to "bottom-to-top" flow of energy. The conventional generator is at the top in the former and multiple renewable energy based generators are at the bottom in the latter. The increased share of renewable energy resources (RES) in the power generation mix is one of the primary reasons for the transition. With this transition the macro-grid is sub-divided in to multiple micro-grids with distributed and renewable energy technologies. However integrated, intermittent and distributed generations have increased the risk of security of supply as their utilization grows in distribution networks. Micro-grid (MG) is more sensitive to power quality issues when it is maintained on local resources. Voltage imbalance, voltage drops, between generation and load are serious issues which are caused by connection of single-phase loads and sources. The objective of the modern network operator is to employ the smart grid technologies to plan, operate and maintain a modern power system economically stable and with an acceptable level of reliability.

Optimal power flow (OPF) is a central operational tool for power systems. The direct current (DC) version is mostly used for the high-voltage networks for transmission of bulk power. The alternating current (AC) version is primarily used in case of distribution networks, especially in the distribution grid problems such as grid planning, optimal controls, reactive power dispatch and unit commitment. Primary objective of OPF is to maintain the system stability while minimizing the cost of operations and maintenance. Investment decisions considering power system constraints are closer to practical. OPF in its original form is a highly non-linear problem. The non-linearity of the system of equation is usually solved using iterative Gauss-Siedel or Newton-Rapson method. Moreover OPF is a non-convex optimization problem. It is also a NP-hard problem (see [1], [2]) to find a solution for radial networks. To solve such a problem literature suggests a) approximation- with relaxed physical properties of OPF b) non-linear optimization methods c) heuristics/meta-heuristics d) convexification. The power system mostly consists of radial networks. In literature a lot of work is done to linearise and relax the constraints. The models can be broadly classified as a) original OPF (O-ACOPF), b) augmented OPF (A-ACOPF), c) augmented-relaxed (AR-ACOPF) OPF [3]. In literature there are exact numerical solutions provided through distributed optimization based on alternative direction method of multipliers and semi-definite relaxations for radial and non-radial networks [3]–[8]. However, only numerical proofs for specific grids are portrayed in place of generalized exact proof of the relaxation of the problem. In this paper we use a feasible and near-optimal outer approximation algorithm to solve the non-li/near ACOPF problem. Keeping the physical properties of the power distribution system intact we focus on the OPF in IEEE 14 bus network with power injection of intermittent and non-dispatch able generations at multiple edges of the distribution network. The model considers the two-port pi network for the transmission line representation. The model is tested over three microgrids with an IEEE-14 bus radial network configuration.

Distribution system expansion or in this case MG expansion is often an optimal investment and operational decision. However most of the investment models lack power system aspect of expansion. Treated problem on a high level prospective. The contribution of this paper is to investigate how expansion decisions affect the reliability of the system, and therefore the importance of restructuring in power network expansion. A reliability oriented network restructuring (RNR) framework is presented.

II. Reliability Oriented Network Decision-Making

Due to power system regulation power quality and reliability issues, concerning many management businesses, many utilities try to rationalize their network and optimize the total life cycles costs of the components [9]. Many municipality

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owned utilities have been privatized, where the new owners are mainly considering profitable investments, therefore to avoid power quality's reduction, various regulation models have been issued. Given models enforce network utilities to optimize their operations without compromising the reliability nor the safety of the network. Reliability analysis are one of the ways to inspect the optimal asset management. Similar analysis has been developed in Tampere University of Technology, in the 1980's, where the reliability analysis has been utilized to evaluate optimal dis-connector locations. In the analysis [10], the failure rates are constant for similar components, where those components are influenced by many different mechanical, environmental and electrical stresses. Usually in component failure model's reliability calculations are based on exponent distribution and failure rates are considered as constants. However the constant failure rate is an inadequate approach, therefore many models for estimating component failure rates have to be used. In some cases, Monte Carlo simulation is utilized to take into account effects of the surrounding or enhanced component failure models, which are based on constant component failure rates to evaluate environmental and component related aspects in reliability analysis. Another modelling approach is done as a proportional hazard method, where it can consider age and various additional information, such as weather and the information surrounding the components. These models require lots of data to find essential dependencies affecting the component reliability to fail, therefore these models are not commonly used. Sometimes Markov Models are also used, where the component failure modelling is done by estimating the effects of the component faults for the system [11], [12]. Usually complex system models are needed, because there is a large amount of possible transitions needed for each component, such as for different weather conditions. Main requirement for RNR is to have estimates of failure rates considering main stress factors and the possibility to have first estimates from incomplete data and update values when more improved data are available. Components of distribution networks must be modelled separately, therefore component failure rate is dependent on different factors.

In this study the distribution network has been divided into five main components: aerial lines, cables, transformers and switches. For each component it has been determined the main reasons for permanent faults and auto re-closings. Separate failure rates for each component types are based on the failure reasons, e.g. transformers overall failure rate is dependent on lightning, animals and other fault causes. For all the reasons, the main stress factors which affect the failure rate have been determined. All the stress factors are classified into appropriate classes, for instance the location can be a forest a place near the road or a field. For all classes a weight has been defined, which represents the effect of a certain class to on the failure rate. For total failure rate, permanent and temporary faults can be calculated. A practical approach in component modelling is to use the idea that it should be possible to affect the parameters used in failure rate modelling, with selected planning strategies. The weather pattern is not considered directly in failure rate evaluation but included in the apparatus condition, for instance in the stress tolerance. The age factor is included in condition weight information. Voltage dip analysis is also used for examining short interruption, where each component is defined based on permanent and temporary short circuit failures. Dip rates are used to define number and depth of dips in the network. Voltage dip can be analyzed by adding information of total short circuit ratio to every separate failure rate. Failure rate parameters must be determined before modelling methods can be used.

The statistics, in this paper, have been collected by Finnish network companies, where the used statistics are based on population and outages. The analyzed data consists of 2400 faults, where about 60% of those were aerial line faults. The population covers about 11,000 km of cables and aerial lines and about 12,500 transformers for several years' time period. General failure rate of components were calculated as a weighted mean from failure rates of separate companies. Defined parameter groups are used to calculate the separate failure rates. The basic input data set is the component information, i.e. type, failure rate, and the network topology, also some other information are needed which are affecting results of the analysis, such as repair times and automation devices installed. In the enhanced radial reliability analysis, network is analyzed with feeders and zones, where zone refers to a part of feeder. In the given analysis, the expected amount of permanent and temporary failures and voltage dips in a zone are calculated as a sum of the individual network component failures. Determination of repair time is done by analyzing the possibilities to isolate load points from the faulted component and then restore the load points with dis-connectors. For a temporary fault, the whole feeder is experiencing the same short interruption. In given analysis, experienced permanent and temporary faults and voltage dips are defined for each load point. Cost information is based on total interruption times in certain area, permanent and temporary fault and voltage dip occurrences defined with the radial network reliability analysis [13]. Utility outage costs is based on the value of non-distributed energy and fault repair costs. Other costs, such as losses in production are considered in defining inconvenience costs for the customer. The expected permanent outage annual costs are caused by a fault in the zone under study. Thus RNR framework can be expressed as an asset management model considering the Life Cycle Assessment (LCA) of power system equipment. Combined with OPF, it is a complete one-stop solution network management and planning platform. Reliability of reconfiguration by replacing overhead lines and underground cables, is evaluated considering environmental, consumer preference, n-1 contingency and DSO objectives while minimizing the investment cost.

The reconfiguration of networks is primarily done to accommodate new consumers. This is achieved by extending the connection of an existing node through a new arc. Secondly it is done by replacing some existing lines. Network utilities can adjust the failure rate and reliability parameters with their

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own network information. A Switch Gear (SG) can identify the fault region of the feeder and update it with secure supply of energy from the same power network. Reliability indices mainly include measures of outage duration and its frequency, the amount of power or energy which is not supplied, and the number of customers involved in outages. IEEE has defined reliability indices, such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Energy Not Supplied (ENS) [14]–[17]. Such index are system and customer average interruption of frequency and duration, and energy-based index, referred to as energy not supplied. Indicators are determined over a predefined period of time.

III. Reliability indices

A. Node reliability indices

1) Expected load not served (ELNS): The ELNS measures the average amount of energy not supplied to loads as a result of load shedding events. As its own name indicates, the expected load not served is a weighted average energy value accounting for both the probability of contingencies and the damage that these contingencies cause to the system in terms of lost load.

2) Loss-of-load probability (LOLP): The LOLP is computed as the probability that failure events lead to load shedding. As opposed to the ELNS, however, the loss-of-load probability is a dimensionless number that does not provide any information on the severity of the disturbance, i.e., on the energy not supplied. This lack of a clear physical meaning makes the LOLP a less intuitive metric to work with by system operators.

$$ENS = \sum_{e} P_e r_e \tag{1}$$

Where e interruption event, r_e- restoration time for interruption event e, and P_e average load interrupted by each event e.

3) loss-of-load expectation (LOLE): The LOLE assesses the expected number of hours during which loss-of-load events could happen. As the LOLP, the loss-of-load expectation fails to provide an estimation of the damage done to the system by contingencies. From a mathematical viewpoint, both the LOLE and the LOLP require the use of binary variables to be considered within a mixed-integer linear programming problem, [16, 57]. On the contrary, the ELNS can be expressed linearly, without binary variables, as follows:

$$LOLE = \sum_{o} P_o t_o \tag{2}$$

Where o is the capacity outage, p_o is individual probability of the capacity outage, t_o is the time interval based on the difference in the capacity outage magnitude due to loss of load.

B. Arc reliability indices

The arc reliability indices are summarized in the table I. This table presents the main properties of cables, overhead lines, transformers, switch-gears, consumption, generation, terrain, probability of fault and maintenance faults. In addition product description with manufacturer references are provided.

IV. OPF with Restructuring Mathematical Model

This section will outline the mathematical model developed for the reliability oriented network restructuring analyses considering AC-OPF for a distribution network. The model has been developed in AIMMS and solved using the Outer Approximation Algorithm [27] that is suitable for solving non linear non convex models like the OPF.

A. Objective Function

$$\min C^{op} + C^{inv} \tag{3}$$

$$C^{op} = \sum_{t,i,g} (P_{g,i,t} + Q_{g,i,t}) * C_g \qquad \forall t, i, g \tag{4}$$

$$\begin{aligned} C^{inv} &= \sum_{i,j,c} CRF_c * Y_{i,j,c} * C_c + \sum_{i,j,c} CRF_c * R_{i,j,c} * C_c \\ &+ \sum_{i,j} \Big(C_{i,j} * (1 - \sum_{c} R_{i,j,c}) \Big) + C^{SVC} * D_i \end{aligned} \tag{5}$$

The Objective function 3 minimises the total operational costs and investment costs. Operational costs in 4 are related to conventional generator costs due to fuel consumption. The investment costs in 5 are described by four terms: the cost of installation of new potential cables where a connection still do not exist, the cost of replacing existing obsolete cables with new ones, a representative cost of keeping existing cables as they are and the cost of installing Static Var Compensator (SVC) devices in certain nodes. The cost of existing cables is a representative cost that incorporates all the costs that a company should face to keep a cable as it is: this cost is calculated according to the history of the cable, its maintenance requirements, failures and issues and represented by the parameter Maintenance cost listed in Table II.

B. Conventional Generators, Wind Plants and Batteries

$$P_{g,i,t} \leq \overline{P}_{g,t} * W_{g,i,t} \qquad \forall g, i, t \tag{6}$$

$$Q_{g,i,t} \leq \overline{Q}_{g,t} * W_{g,i,t} \qquad \forall g, i, t \tag{7}$$

$$P_{w,i,t} \leq \overline{P}_{w,i,t} \qquad \forall w, i, t \tag{8}$$

$$Q_{w,i,t} \leq \overline{Q}_{w,i,t} \qquad \forall w, i, t \tag{9}$$

$$B^{SOC}_{b,i,t} \leq B^{cap}_{b} \qquad \forall b, i, t \tag{10}$$

$$B^{SOC}_{b,i,t} = B^{SOC}_{b,i,t} - P^{out}_{b,i,t} * \frac{1}{B^{eff}_{b}} + P^{in}_{b,i,t} \qquad \forall b, i, t \tag{11}$$

$$\frac{1}{B^{eff}_{b}} * (P^{out}_{b,i,t})^2 + (Q^{out}_{b,i,t})^2 \leq (B^{rate}_{b} * B^{cap}_{b})^2 \qquad \forall b, i, t \tag{12}$$

$$(P^{in}_{b,i,t})^2 + (Q^{in}_{b,i,t})^2 \leq (B^{rate}_{b} * B^{cap}_{b})^2 \qquad \forall b, i, t \tag{13}$$

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TABLE I: Explanation of relibility indicators in RNR

Cable	In this study we concentrate on three different voltage levels, with each having one or two different types of cables, therefore five different cables are evaluated. Cables are picked based on their suitable voltage level, cable diameter, and the conductor and the insulation type. In the [18], [19] cable line weight parameters are evaluated as normalized values between 0...1. The [18], [19] gives the possibility to pick a certain transmission line type [18]–[23] with fixed parameters. There are proposed five types of different cables and overhead-lines. For instance, for a transmission line of 6 kV or 10 kV with a length 9 km, a three-core cable is proposed with diameter of $3 * 70\ mm^2$. This cable weights 5400 kg/km and as tables has proposed we may choose a given conductor and the insulation, although steel conductors do not have insulation in this thesis. Cable indices in a network recuntroction evaluation are the cable's conductor and insulation. In the example, conductor weight is calculated as the diameter of the conductor (i.e, Al conductor diameter = 9.8 mm) multiplied with conduction material density (Al density = 8.89 kg/km). i.e, Cable, which weighs 5400 kg/km has an aluminium conductor which weighs 567 kg/km and insulation of 3699 kg/km [18], [19].
Overhaed lines	As mentioned above, there are different types of transmission lines depicted and some of the named are overhead-lines (OHL). The same evaluation planning in [18], [19] is used as in [18], [19] with the firstly mentioned being dependent also on [18], [19]. OHL indices as before mentioned line conductor and the insulation weight, with additional indices covering the OHL poles. The poles are picked to be suitable for each voltage. For instance, 35 kV OHL usually uses poles which span across 80 m. The number of poles needed are calculated by the tension and the sag of the line. After calculating the needed tension (tension at pole related to tension at the maximum deflection) and sag (tension related to the span of the poles) the number of poles is found with relation to line length (including the sag) and the span length of two poles.
Transformer	Transformers (Trfo) used in this study are ideal and listed in [18]–[23] , without having to relate to the criterium N-1 (in case one transformer is interrupted, the energy flow continues on). Therefore, only one transformer is depicted for a substation, with an exception of two substations which have two transformers because there are four voltage levels, which are distributed. Furthermore, the transformers used in this study are assumed to be almost equal to the ones provided by the companies. i.e. for a 110/10 kV substation, 220/15,6 kV transformer is used. Transformers are depicted as such with transmission line types. The needed indices are conductor (copper wire + profile) and insulation (transformer oil) weight at manufacturing and use phase.
Switch-gear	Switch-gears (SG) used are described in [18]–[23] . In this network, in the node points combination of different switchgears are used, based on their operating voltage levels. For this instance, 4 different combinations are made. SG indices are based on the sum of their emissions per one transformer. Main emissions listed are Climate change (GWP, kg CO2/Trfo), Acidification (AP, molh/Trfo), Eutrophication (NP, kg O2/Trfo), and SF6 % of all emissions. The needed indices' values are calculated with the minimum and the maximum emission values [18], [19].
Consumption	The evaluated network consists of two main types of consumers, residential (0-25 kWh), and commercial (25-50 kWh). It is assumed that around a substation there are 5-10 residential buildings and 1-3 commercial buildings, because the evaluated network is put together mainly by the residential areas, rather than commercial. The needed weight value is comprised the sum of the total energy demand in a node related to the minimum and maximum energy consumption in a node.
Generation	A single distributed generation source is assumed to generate 1000 kWh of electrical energy, although the submarine cable is assumed to have a smaller value because of the losses in transmission.
Terrain	To differentiate the nodes and the arcs, additionally to electrical aspects, environmental indices are used to evaluate a network.
Probability of fault & maintenance costs	As mentioned above not only electrical indices are used, also economical characteristics of a network are needed to be assessed. For the total maintenance costs [24]–[26] , the repair costs and a probability of fault is needed to be assessed for the transmission line and the substation. For this fault value is assumed based on the terrain influence on the probability of fault. Maintenance costs = Cost of repair * Probability of fault value [24]–[26]

This group of constraints define the main properties of conventional generators, wind plants and batteries. Upper limits on active and reactive power from conventional generators and wind plants are defined in constraints 6, 7, 8 and 9. While constraints 10, 11, 12 and 13 control the battery operations in terms of capacity, State of Charge (SOC), rating in and rating out respectively.

C. Grid Restructuring

$$P_{i,j,t} \leq (P^A - P^B + P^C) \qquad \forall_{i,j,t} | X_{i,j} = 0; A_{i,j} = 0 \tag{14}$$

$$P_{i,j,t} \leq \sum_c (1 - R_{i,j,c}) * (P^A - P^B + P^C) + \sum_c R_{i,j,c} * (P^D - P^E + P^F) \qquad \forall_{i,j,t} | X_{i,j} = 1 \tag{15}$$

$$P_{i,j,t} \leq \sum_c Y_{i,j,c} * (P^D - P^E + P^F) \qquad \forall_{i,j,t} | A_{i,j} = 1 \tag{16}$$

$$P^A = K_{i,j} * \Big(\frac{V_{i,t}}{T^{tr}_{i,j}}\Big)^2 \qquad \forall_{i,j,t} \tag{17}$$

$$P^B = \Big(\frac{V_{i,t}}{T^{tr}_{i,j}}\Big) * V_{j,t} * K_{i,j} * \cos(\delta_{i,t} - \delta_{j,t}) \qquad \forall_{i,j,t} \tag{18}$$

$$P^C = S_{i,j} * \sin(\delta_{i,t} - \delta_{j,t}) \qquad \forall_{i,j,t} \tag{19}$$

The traditional OPF equations are defined in this group of constraints in a way that incorporates the possibility to reconfigure the network. Constraint 14 defines the active power as the sum of three terms P^A, P^B and P^C that contains the power flow equations as described in constraints 17, 18 and 19. Constraint 15 defines how reconfiguration can happen: if an existing cable is not replaced with a new one of type c, then the binary variable $R_{i,j,c}$ will be equal to 0, therefore the second term of constraint 15 will be equal to zero and the active power will be defined as in 14. On the other hand, if an existing cable is replaced with a new one of type c, then the binary variable $R_{i,j,c}$ will be equal to 1, therefore the first term of constraint 15 will be equal to zero and the active power equation will be equal to the second term of constraint 15. The terms P^D, P^E and P^F are formulas equal to P^A, P^B and P^C respectively, where the parameters of existing cables $K_{i,j}$ and $S_{i,j}$ are replaced by the correspondent parameters of new available new cables K_c and S_c. The model has therefore the ability to choose if it is necessary to dismantle and replace an existing cable by choosing a new one among a list of cables with different properties and costs.

Constraint 16 defines how the installation of new cables where no existing connections are available can happen. In

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TABLE II: Reliability indices for RNR

Arc	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Node x	1	2	3	3	6	6	12	7	9	7	9	10	13	4	4
Node y	2	4	4	5	11	12	13	9	14	8	10	11	14	7	9
Transmission length, km	2	3	2	5	4	8	3	3.00	5.00	6.00	3.00	3.00	3.00	2.00	2.00
Transmission voltage,kV	10	110	35	110	110	110	110	10.00	10.00	110.00	110.00	110.00	110.00	110.00	35.00
Line type[1,2,3,4,5]	1	3	4	5	5	3	5	1	1	5	3	5	5	5	2
Life expectancy value (years)	0.1	0.1	1	1	1	0.1	1	0.10	0.10	1.00	0.10	1.00	1.00	1.00	1.00
Conductor type [1 · 5]	1	1	3	3+5	3+5	1	3+5	1	1	3+5	1	3+5	3+5	3+5	2
Line weight value, kg/km	0.36	0.81	0.33	0.00	0.00	0.36	0.00	0.36	0.36	0.00	0.81	0.00	0.00	0.00	0.43
Conductor weight value,kg/km	0.06	0.10	0.06	0.00	0.00	0.10	0.00	0.06	0.06	0.00	0.10	0.00	0.00	0.00	0.29
Insulation weight value,kg/km	0.38	1.00	0.40	-	-	1.00	-	0.38	0.38	-	1.00	-	-	-	0.00
OHL pole value, pcs	-	-	0.00	0.60	0.60	-	1.00	-	-	0.60	-	1.00	1.00	1.00	-
Terrain types	0.38	0.38	0.50	0.50	0.38	0.88	1.00	0.38	0.50	0.25	0.75	1.00	0.50	0.38	0.50
Proportional Faults/year	0.75	0.75	0.88	0.88	0.75	0.25	1.00	0.75	0.88	0.63	0.50	1.00	0.88	0.38	0.88
AIT value	0.51	0.31	0.73	0.41	0.74	0.36	0.51	0.79	0.59	0.00	0.54	1.00	0.82	0.85	0.69
AIF Value	0.51	0.55	0.69	0.79	0.63	0.00	1.00	0.71	0.97	0.57	0.39	1.00	0.74	0.17	0.83
AID value	0.22	0.13	0.17	0.05	0.21	1.00	0.00	0.18	0.03	0.03	0.33	0.10	0.17	0.80	0.10
Maintenance costs value (M €/km)	0.46	0.47	0.82	0.84	0.67	0.00	1.00	0.46	0.59	0.55	0.23	0.98	0.82	0.20	0.58

particular, if a new cable of type c is going to be installed between two nodes, the binary variable $Y_{i,j,c}$ will be equal to 1 and the active power will be equal to the terms P^D, P^E and P^F that have been explained above. On the other hand, if no cables are going to be installed, the binary variable $Y_{i,j,c}$ will be equal to 0 and no power flow will be allowed between the two nodes.

Similarly, for reactive power the same thoughts above can be applied as shown in constraints 20, 21, 22, 23, 24, 25. In this case Q^D, Q^E and Q^F are formulas equal to Q^A, Q^B and Q^C respectively, where the parameters of existing cables $K_{i,j}$, $S_{i,j}$ and $S^{sh}_{i,j}$ are replaced by the correspondent parameters of available new cables K_c, S_c and S^{sh}_c.

$$Q_{i,j,t} \leq -Q^A - Q^B + Q^C \qquad \forall_{i,j,t} | X_{i,j} = 0; A_{i,j} = 0 \tag{20}$$

$$\begin{aligned} Q_{i,j,t} \leq & \sum_c (1 - R_{i,j,c}) * (-Q^A - Q^B + Q^C) \\ & + \sum_c R_{i,j,c} * (-Q^D - Q^E + Q^F) \qquad \forall_{i,j,t} | X_{i,j} = 1 \end{aligned} \tag{21}$$

$$Q_{i,j,t} \leq \sum_c Y_{i,j,c} * (-Q^D - Q^E + Q^F) \qquad \forall_{i,j,t} | A_{i,j} = 1 \tag{22}$$

$$Q^A = \Big(S_{i,j} + \frac{S^{sh}_{i,j}}{2}\Big) * \Big(\frac{V_{i,t}}{T^{tr}_{i,j}}\Big)^2 \qquad \forall_{i,j,t} \tag{23}$$

$$Q^B = \frac{V_{i,t}}{T^{tr}_{i,j}} * V_{j,t} * K_{i,j} * \sin(\delta_{i,t} - \delta_{j,t}) \qquad \forall_{i,j,t} \tag{24}$$

$$Q^C = S_{i,j} * cos(\delta_{i,t} - \delta_{j,t}) \qquad \forall_{i,j,t} \tag{25}$$

It is straightforward that the above formulation allows also the possibility to simply dismantle existing cables without replacing them. In this case it is enough to provide a list of cables that contains also a type c with K_c, S_c and S^{sh}_c equal to zero. If chosen, this will simply correspond to absence of connection.

Reconfiguration and new potential connections can happen only in those arcs that the operator is willing to check. Not all the arcs of the grid will be subjected to such decision, therefore binary parameters $X_{i,j}$ and $A_{i,j}$ are used to select which arcs to reconfigure and which new connections to evaluate respectively.

D. Grid General Management

$$\begin{aligned} & \sum_g P_{g,i,t} + \sum_w P_{w,i,t} - \sum_j P_{i,j,t} + \sum_j P_{j,i,t} \\ & + \sum_s P^{out}_{b,i,t} - \sum_s P^{in}_{b,i,t} = P^L_{i,t} \qquad \forall_{i,t} \end{aligned} \tag{26}$$

$$\begin{aligned} & \sum_g Q_{g,i,t} + \sum_w Q_{w,i,t} - \sum_j Q_{i,j,t} + \sum_j Q_{j,i,t} \\ & + \sum_s Q^{out}_{b,i,t} - \sum_s Q^{in}_{b,i,t} = Q^L_{i,t} \qquad \forall_{i,t} \end{aligned} \tag{27}$$

$$Z_{i,j,t} = \frac{1}{\sqrt{3}} * V_{i,t} * \sqrt{(P_{i,j,t})^2 + (Q_{i,j,t})^2} \qquad \forall_{i,j,t} \tag{28}$$

$$P_{i,j,t} \leq BigM * dir_{i,j,t} \qquad \forall_{i,j,t} \tag{29}$$

$$P_{j,i,t} \leq BigM * (1 - dir_{i,j,t}) \qquad \forall_{i,j,t} \tag{30}$$

$$Q_{i,j,t} \leq BigM * dir_{i,j,t} \qquad \forall_{i,j,t} \tag{31}$$

$$Q_{j,i,t} \leq BigM * (1 - dir_{i,j,t}) \qquad \forall_{i,j,t} \tag{32}$$

$$\sum_c Y_{i,j,c} \leq 1 \qquad \forall_{i,j} \tag{33}$$

$$\sum_c R_{i,j,c} \leq 1 \qquad \forall_{i,j} \tag{34}$$

$$\underline{V} \leq V_{i,t} \leq \overline{V} + V^{SVC} * D_i \qquad \forall_{i,t} \tag{35}$$

$$\underline{\delta} \leq \delta_{i,t} \leq \overline{\delta} \qquad \forall_{i,t} \tag{36}$$

$$\underline{Z} \leq Z_{i,t} \leq \overline{Z} \qquad \forall_{i,j,t} \tag{37}$$

This set of constraints describe the main properties to take into account for the grid management. In particular flow balance for active and reactive power is defined in 26 and 27 respectively; the current is defined in 28; the flow direction is described through constraints 29, 30, 31 and 32; constraints33 and 34 limit the choice of new cables to 1; finally constraints 35, 36 and 37 define limits on the voltage, phase angle and current. Regarding constraint 36, the voltage upper limit is linked to the decision of installing a SVC device. In particular, when a SVC device is installed on a node i, the binary variable D_i is equal to 1 and the voltage upper limit increases of a value V^{SVC}. This can make a difference in the decision of dismantling a cable or installing a SVC device.

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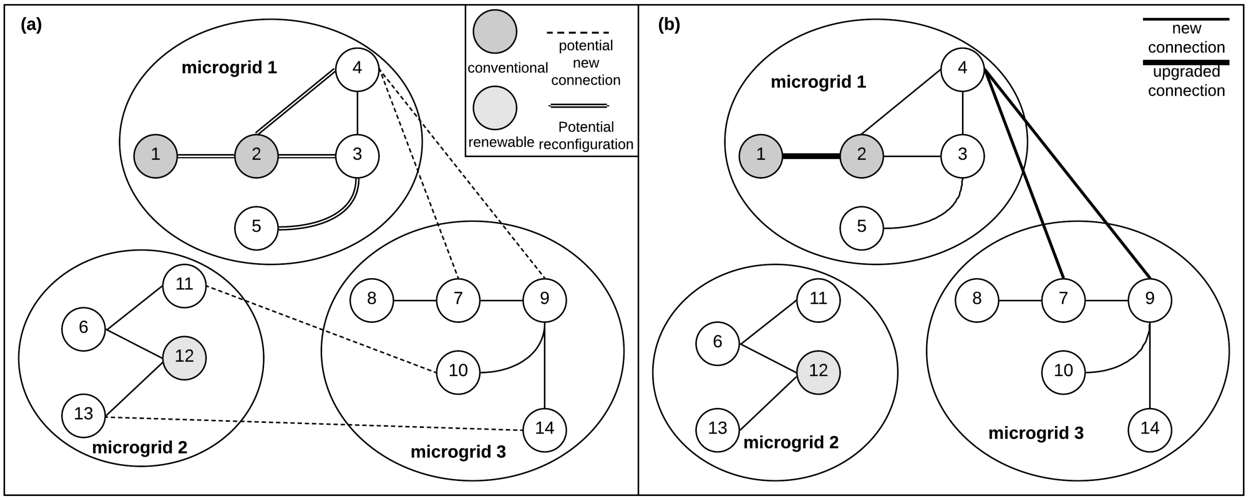

Fig. 1: The microgrid structures: (a) expansion (b) expansion with reconfiguration

V. Computational experiments

Computational experiments have been performed on IEEE 14 bus system represented in fig. 1, using the data-set contained in table II. It is assumed that the arcs $4-9, 4-7, 5-6, 11-10, 13-14$ are non-existing and potential connections should be evaluated. Therefore the system is now split into three microgrids as highlighted in fig. 1. Microgrids 1 and 2 are equipped with conventional and renewable sources respectively, while microgrid 3 is without any resource and can be considered as an emerging district that has been created and that needs to be connected to a neighbourhood area. The microgrid 1 considers restructuring of the existing network to accommodate the emerging district. It is straightforward that restructuring is not considered for the emerging district, because it is assumed that a new microgrid will have new and up to date equipment. Hence the trade-off between the maintenance cost of existing network and the replacement costs to accommodate new emerging demand is analysed. Moreover reconfiguration is allowed on arc $1-2, 2-4, 4-3, 2-3, 2-5, 1-5, 4-5$ in order to verify how the establishment of new connections are affecting the reliability of the system.

As a result, new cables installations are created on arcs $4-7, 4-9$ and a cable $1-2$ is replaced with a new cable provided with higher sustenance. Note that microgrid 2 remains isolated because it already has enough power from the renewable plant.

VI. Conclusion

A methodology to analyse how connecting emerging districts to existing microgrids can affect the reliability of the whole system has been presented. The technical aspects of AC-OPF have been thoroughly taken into account and the reliability oriented Network Restructuring RNR framework has been developed and implemented. The results showed that reliability aspects are crucial when evaluating new investments in grid expansion: new connections should always be coupled with a more holistic evaluation of the conditions of the existing networks as they may require further investments in upgrades to fulfill the new requirements. When the system operator considers investments for power network expansion, it should also consider restructuring of the existing network at the same time. The presented model RNR is able to address both decisions holistically and therefore more investigation is required in this area.

Nomenclature

Indexes

- t time step
- i, j nodes of the grid
- c available new cables
- g conventional generators
- w wind plants
- b batteries

Parameters

- C^{op} Operational costs
- C^{inv} Investment costs
- C_g Operational cost of conventional generator g
- $\overline{P}_{g,t}$ Upper limit on active power from conventional generator g at time t
- $\overline{Q}_{g,t}$ Upper limit on reactive power from conventional generator g at time t
- $\overline{P}_{w,i,t}$ Upper limit on active power from wind plants w on node i at time t
- $\overline{Q}_{w,i,t}$ Upper limit on reactive power from wind plants w on node i at time t
- B_b^{cap} Capacity of battery b
- B_b^{eff} Efficiency of battery b
- B_b^{rate} Rating of battery b
- $T_{i,j}^{tr}$ Tap ratio of transformer placed between nodes i and j
- $K_{i,j}$ Conductance of existing cables placed between nodes i and j
- $S_{i,j}$ susceptance of existing cables placed between nodes i and j
- $S_{i,j}^{sh}$ shunt susceptance of existing cables placed between nodes i and j
- $S_{i,j}$ Susceptance of existing cables placed between nodes i and j
- $S_{i,j}^{sh}$ Shunt suceptance of existing cables placed between nodes i and j
- $C_{i,j}$ Representative cost of existing cables due to their history of maintenance operations
- $A_{i,j}$ Binary parameter defining if a new potential cable can be installed between nodes i and j
- $X_{i,j}$ Binary parameter defining if an existing cable between nodes i and j should be checked for possible replacement
- K_c Conductance of new cables of type c
- S_c Susceptance of new cables of type c
- S_c^{sh} Shunt susceptance of new cables of type c
- CRF_c Capital recovery factor of new cables of type c
- C_c Investment cost of new cables of type c
- V^{SVC} Possible incremental voltage due to installation of a SVC device

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$\underline{V}, \overline{V}$ Minimum and maximum limits for voltage
$\underline{\delta}, \overline{\delta}$ Minimum and maximum limits for phase angle
$\underline{Z}, \overline{Z}$ Minimum and maximum limits for current
C^{SVC} Investment cost of an SVC device
$P^L_{i,t}$ Active load in node i at time t
$Q^L_{i,t}$ Reactive load in node i at time t

Variables

$P_{g,i,t}$ Active power from conventional generator g in node i at time t
$Q_{g,i,t}$ Reactive power from conventional generator g in node i at time t
$W_{g,i,t}$ Binary variable equal to 1 if the conventional generator g in node i is working at time t
$P_{w,i,t}$ Active power from wind plants w in node i at time t
$Q_{w,i,t}$ Reactive power from wind plants w in node i at time t
$B^{SOC}_{b,i,t}$ State of charge of battery b in node i at time t
$P^{out}_{b,i,t}$ Active power from battery b in node i at time t
$P^{in}_{b,i,t}$ Active power into battery b in node i at time t
$Q^{out}_{b,i,t}$ Reactive power from battery b in node i at time t
$Q^{in}_{b,i,t}$ Reactive power into battery b in node i at time t
$V_{i,t}$ Voltage value in node i at time t
$\delta_{i,t}$ Phase angle value in node i at time t
$Z_{i,j,t}$ Current value between nodes i and j at time t
$dir_{i,j,t}$ Binary variable equal to 1 if the power flow is from node i to node j, 0 otherwise
$Y_{i,j,c}$ Binary variable equal to 1 if a potential new cable of type c is installed between nodes i and j, 0 otherwise
$R_{i,j,c}$ Binary variable equal to 1 if an existing cable between nodes i and j is replaced by a new cable of type c, 0 otherwise
D_i Binary variable equal to 1 if an SVC device is installed on node i, 0 otherwise

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