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Modelling of corrective actions in power system reliability analysis

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***Abstract*—Consequence analysis, including the modelling of corrective actions, is an important component when performing power system reliability analyses. Using an integrated methodology for power system reliability analysis, we investigate the impact of different modelling choices for the consequence analysis on estimates for the energy not supplied. These investigations corroborate the large impact modelling assumptions for corrective actions have on the resulting reliability indices. We have also identified other features of the consequence analysis, such as islanding and distributed slack, that can be important to take into account. The findings and the underlying structured approach contribute to improving the accuracy of power system reliability analyses.**

***Index Terms*—Power system reliability, power system control, consequence analysis, contingency analysis, corrective actions, remedial actions, corrective measures.**

I. INTRODUCTION

Power system consequence analysis is an important part of reliability assessments of electric power systems. For every contingency that is to be considered in a reliability analysis, one needs to somehow evaluate the consequences for the power system. Typically, a consequence analysis involves power flow calculations to estimate the power supplied to each delivery point. This output is then used as input to the reliability analysis to estimate reliability indices for the system, such as the total annual expected energy not supplied. For an accurate assessment of the reliability of a real power system, the models used in the reliability assessment need to capture the features of the real system that has the most substantial impacts on the results. How the power system is operated, including the corrective actions taken by the operator, is essential in determining the consequences in a real power system. This has motivated recent research work and projects on power system reliability where the modelling of power system operation is an important component [1], [2].

In this work, a *corrective action* will be understood as any action taken in the power system (manually or automatically) in response to a contingency. Other terms that could be used partly synonymously are, e.g., remedial actions, control actions, operator actions, or corrective measures. Somewhat simplified, one can say that there are two extremes in the modelling of corrective actions and power system consequences: Cascading-failure-type models and optimal power flow models. A *cascading failure model* may assume no operator actions aside from tripping of overloaded lines, leading to cascading failures and potentially complete blackout of the power system. This typically gives an overly pessimistic estimate for the reliability of the system. On the other hand, a model based on *optimal power flow* (OPF), i.e., optimization algorithms with parameters characterizing system operation and corrective actions as decision variables, may result in overly optimistic estimates for the reliability of the system. After all, real system operation is rarely “optimal”, and the choices actually made by the operator are often based on rules, heuristics or experience rather than mathematical optimization.

The large difference between models for corrective actions leads to a large gap between different results for the reliability indices for the same system, as demonstrated, e.g., in [3]. It is likely that the actual reliability for a power system is to be found somewhere inside this gap between the two extremes described above. However, little work have been done on exactly how to model corrective actions to approach a reliability assessment more representative for real power system operation. Despite the extensive body of work on reliability assessment, with a variety of methods for consequence analysis [4], we are not aware of work comparing in detail how different assumptions and modelling choices affect the end results for the reliability. One possible exception is the comparison of two power adequacy assessment programs in [5]. This comparison shows that the modelling of corrective actions indeed impacts the results, but it is not able to pinpoint any particular aspects as more important than others. Other research work is done from the perspective of operational decision support for choosing the optimal corrective actions [6], but the objective of such research work is then not necessarily to increase the accuracy of the reliability analysis. Reference [7] deserves mention for analysing the impact of different corrective actions on reliability estimates in the context of operational planning.

The objective of the present work is to investigate how different modelling choices for corrective actions and other

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features of the consequence analysis affect the results of the reliability analysis. The objective is emphatically not to model or identify the optimal corrective actions generally or for the specific cases we consider. Hypothesizing that models more representative of real system operation would give results between those of cascading failure models and OPF models, we see how different modelling choices may contribute to more accurate reliability assessments. This is done by defining a set of options for operator actions, implementing these in a consequence analysis, and running power system simulations to estimate consequences and resulting reliability indices. The methodology is presented in more detail in Sec. II, where we also introduce the test systems we consider. Results from the reliability analysis of these test cases are presented in Sec. III and discussed in Sec. IV, after which we summarize our findings and conclude in Sec. V.

II. METHODS

A. Approach to study the effect of corrective actions

Our main goal is to arrive at general conclusions about the effect of different modelling choices. To achieve this goal, we have tried to restrict ourselves to corrective actions that are in some sense generic. This poses a challenge because power system operation, in particular when in an emergency state, follows very few general rules [8]. Precisely what actions are taken depends on the system, the operator, the *operating state* (combination of generation and load), the disturbance in question, the localization of the disturbance in the system, and so forth.

Furthermore, to avoid conclusions that are particular to a particular test system, we have considered two test systems for our case study. To increase the robustness of our results further, we have also run our simulations for a number of different, representative operating states.

B. Corrective actions and other features of the consequence analysis

To investigate the impact of different corrective actions and modelling choices in a structured manner, we have defined a number of *corrective action options*. A case in our investigation is thus defined by whether each of these corrective action options is enabled or disabled for the case. This is illustrated in the table in Fig. 1, which defines some of the cases we have considered in the case study.

The options we focused on in this work are defined in the following list:

1) reschedule_gen: Whether generation rescheduling is included as a corrective action. Which algorithm that is used to determine the generation rescheduling is determined by the option *reschedule_gen_opf*.

2) reschedule_gen_opf: If enabled, OPF is used for generation rescheduling, with active and reactive power being decision parameters and operational security limits being constraints in the optimization. If disabled, one reschedules generation by using a heuristic algorithm that tries to remove line overloads by decreasing generation on generators feeding into the overloaded line and increasing the generation correspondingly for generators at or close to the other end of the line.

		Corrective action options								
		reschedule_gen	reschedule_gen_opf	load_shedding	partial_shedding	shedding_also_gen	shed_closest	opf	allow_islanding	distr_slack
Cases	Cascading failure								x	x
	Controlled load shedding: non-partial			x		x			x	x
	Controlled load shedding: partial			x	x	x			x	x
	Generation rescheduling using heuristics	x		x	x	x			x	x
	Generation rescheduling using OPF	x	x	x	x	x			x	x
	Gen. resch. and load shedding using OPF			x	x			x	x	x

Fig. 1. Cases for modelling choices in the consequence analysis defined in terms of corrective actions options.

3) load_shedding: Whether controlled load shedding is included as a corrective action in case of line overload or generators exceeding their generation limits. If enabled, a heuristic algorithm is used to identify delivery points into which the overloaded lines or generators are feeding and where load shedding could thus be expected to be an effective corrective action. If enabled, corrective actions for rescheduling of generation will be attempted before load shedding.

4) partial_shedding: Partial load shedding. If disabled, all load at a delivery point is shed when shedding load. If enabled, one iteratively sheds parts of the load at a delivery point during load shedding. The amount to be shed is determined from estimates of what is required to remove violations of operational security limits.

5) shedding_also_gen: If enabled, a heuristic algorithm will try to reduce generation on generators feeding an overloaded line after shedding load being supplied by this line. If not enabled, the load reduction will be absorbed by the swing bus or by distributed slack. Only relevant if *load_shedding* is enabled.

6) shed_closest: If enabled, buses that are candidates for load shedding are chosen somewhat arbitrarily as the buses closest (in terms of geodesic distance in the network) among the buses that are supplied by the overloaded line or generator. If disabled, a heuristic algorithm is used to choose the delivery point or combination of delivery points that minimises the load to shed given that the entire load on each delivery point has to be shed. Only relevant if *load_shedding* is enabled.

7) opf: OPF is used to find the corrective actions, with load at delivery points and active and reactive generation being decision parameters and operational security limits being constraints in the optimization.

8) allow_islanding: Whether one should allow island operation of a subsystem not including the (original) swing bus of the system. If disabled, all load on such isolated subsystems will automatically be lost.

9) distr_slack: Distributed slack. If enabled, any over- or underproduction (slack) due to contingencies is distributed on all generators proportionally to their capacity. If disabled, all slack is assigned to the swing bus. If there are several generators connected to the swing bus, slack is distributed on these generators also if *distr_slack* is disabled.

C. *Method of integrated reliability analysis*

The method for reliability assessment used in this paper is based upon the approach described in [9], where the main idea is to establish a strong conceptual connection between a power market simulation, a consequence analysis, and a reliability analysis.

Both the consequence analysis and the reliability analysis used in this work is described in [10]. The reliability analysis is based on a contingency enumeration approach, and the consequence analysis was implemented using MATPOWER 4.1 [11]. A number of user options in the implementation of the consequence analysis, including those defined in Section II-B, contribute to making the modelling assumptions explicit and traceable. For the analyses presented in this work, we have chosen to study contingencies consisting of branch outages up to 2nd order. For each contingency an AC power flow is run with the branch(es) removed. Then a check is carried out to see whether or not any operational security limits are violated, in which case corrective actions are attempted. The operational security limits that are considered are active and reactive generation limits for generators, thermal limits for lines, and voltage limits for buses. None of the heuristic corrective action algorithms described in Section II-B are designed to explicitly handle voltage limit violations. OPF, on the other hand, takes all of the operational security limits into account.

D. *Test networks for case studies*

For our case studies, we have considered two test networks: A four-area test network and the Roy Billinton Test System (RBTS) [12]. The reliability index we consider is the total energy not supplied (ENS) for the system, averaged over all operating states.

1) The four-area test network: The four area-test network in depicted in Fig. 2 is a test network used by SINTEF Energy Research for reliability studies. Its original configuration, including line data, generator and load data is described in [13]. In this article we use the modified version introduced in [14], where an extra line has been added to increase the reliability. In addition, we have augmented the system to increase the reliability further by neglecting outages of lines supplying delivery points with one-sided supply. This is done to make the system $N-1$ secure and remove contributions to the reliability indices from first-order contingencies, thus emulating a system much more reliable than the RBTS, to be presented below. The operating states assumed for this test network are generated by the power market model mentioned in Sec. II-C according to the description in [13]. The generation was initialized using an OPF. Out of the 10 400 generated operating states, representing 50 years, we have chosen the 208 operating states for the median year in terms of the total load.

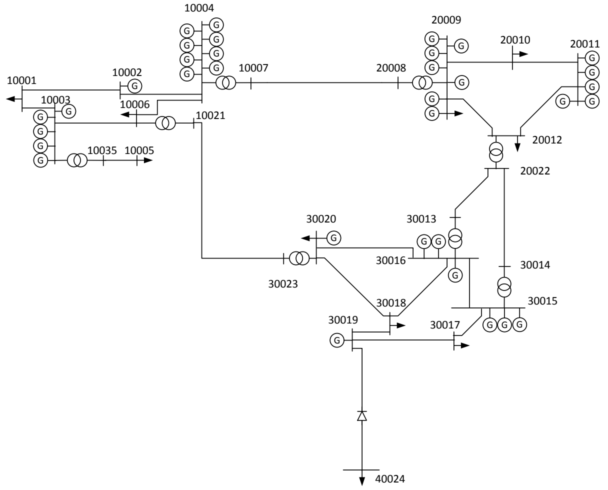

Fig. 2. Schematic of the four-area test network.

2) The RBTS: The RBTS [12] is depicted in Fig. 3 and is a well-known test system used in academia and education. In this paper we have used the same configuration as described in [12], except for extending the peak operating state described in [12] to 12 distinct operating states. In [12] a load duration curve is defined, which could be used for defining multiple operating states. However, only one load duration curve is provided for all loads. In other words, using this load duration one will end up with operating states where the proportion of each load to the total system load remains constant. This also means that the most overloaded line in all operating states will be the same. For the purpose of ensuring representative results and robust conclusions this is not desirable, as specific contingencies are likely to result in the same issues for each operating state.

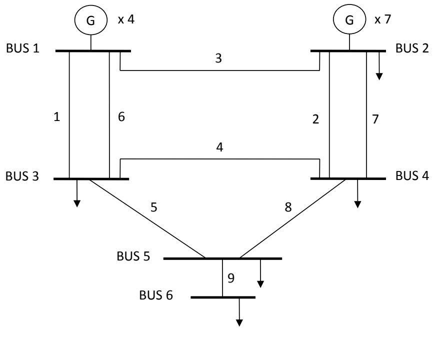

Fig. 3. Schematic of the Roy Billinton Test System [12].

Furthermore, since each delivery point is defined to be one particular customer type, they would in a realistic case not follow the same load duration curve. In this paper we chose to use the relative load factors found in [15] to generate the operating states. These factors define how the load varies relative to a reference time for months, days and hours for particular customer types. This allows for obtaining up to 2016 operating states. The loads in the RBTS are not classified using the same classification as the one in [15]. Due to this, the loads had to be reclassified as presented in Tab. I. Using this approach, we obtained the load curves in Fig. 4 that were used in this work. The generation was then initialized using an OPF, with generation costs in the same order of magnitude as in [12].

TABLE I
CUSTOMER TYPES USED FOR THE RBTS.

Bus	Type
2	Industry
3	Energy-intensive industry
4	Residential
5	Public service
6	Agriculture

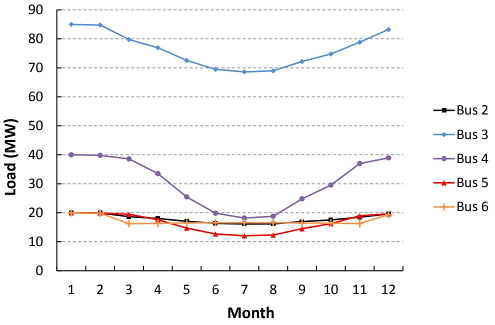

Fig. 4. Load profiles for the RBTS.

III. RESULTS

A. Comparing the estimated reliability for different corrective action models

We first consider the different cases for the modelling of corrective actions defined in Fig. 1. Using the methods outlined in Sec. II-D, we obtain estimates for energy not supplied for the different cases as shown in Fig. 5 for the four-area test network and in Fig. 6 for the RBTS. For the results for both networks, we have scaled the values by the value for the case with the highest ENS result. The results demonstrate the gap between the most simplistic and pessimistic modelling of corrective actions ("Cascading failure") and the most optimistic ("Generation rescheduling and load shedding using OPF"): For both systems the estimated ENS is more than 10 times larger for the former than for the latter.

B. Sensitivities to different modelling choices

Next, we investigate the sensitivity of the estimated ENS to the different corrective actions options defined in II-B. As our base case, we choose the case "Generation rescheduling using heuristics", which assumes partial load shedding as well as generation rescheduling not relying on mathematical optimization. Based on a survey of TSO experts [8], we believe this case is relatively representative of actual power system operation. This case also resulted in an intermediate value of the ENS estimate in Fig. 5.

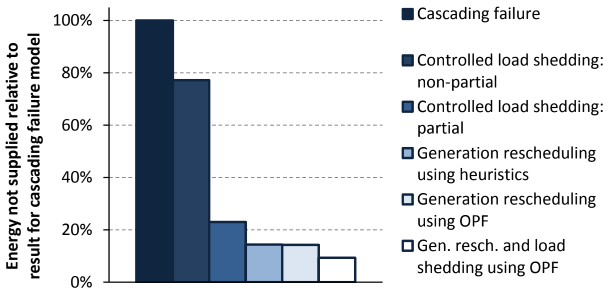

Fig. 5. Comparison of energy not supplied for different corrective action cases for the four-area test network.

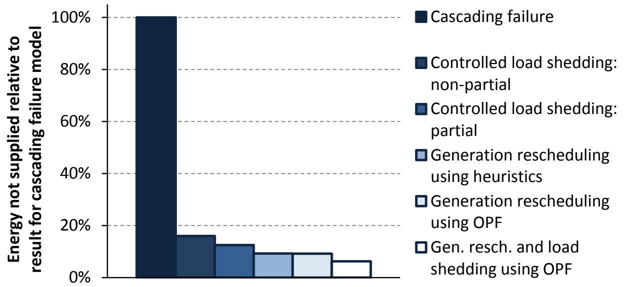

Fig. 6. Comparison of energy not supplied for different corrective action cases for the RBTS.

The sensitivities are shown in Fig. 7 for the four-area test network and in Fig. 8 for the RBTS. It is evident that which options are enabled or disabled in the consequence analysis has a major impact on the results from the reliability analysis.

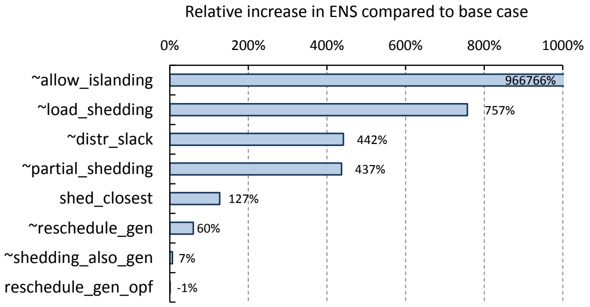

Fig. 7. Sensitivity of the energy not supplied to disabling (indicated by the ~ symbol) and enabling different corrective action options for the four-area test network.

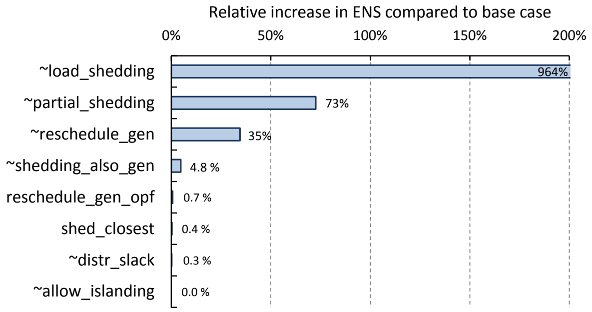

Fig. 8. Sensitivity of the energy not supplied to disabling (indicated by the ~ symbol) and enabling different corrective action options for the RBTS.

IV. DISCUSSION

Although many of the same trends are visible for both test systems considered in our case studies, there are also differences. We will explain these differences before discussing findings which seem to be more general across different systems.

A. Comparison between the four-area test network and the RBTS

More striking for the four-area test network is the strong sensitivity to allowing subsystems to operate in island mode. For the four-area network, there are huge contributions to ENS from delivery points in some of the areas when islanding is not enabled as an option in the consequence analysis. All contingencies that lead to the disconnection of all lines between the central area (having bus numbers starting with the digit 3) and another area then result in blackout of all delivery points in the other area. When islanding is not enabled, only the subnetwork containing the swing bus (30019) is able to continue operation. Islanding is particularly important for the four-area network precisely because it consists of several well-defined areas that realistically should be able to operate isolated from the rest of the network. For the RBTS, on the other hand, the ability of islanding is not found to be significant for the consequence analysis. The reason is that the RBTS, in contrast to the four-area test network, does not have natural subnetworks for islanding. The two generator buses are in a different part of the network from most of the delivery points.

Whether all slack is absorbed by the swing bus or is distributed on other generator buses as well could also be an important feature of the consequence analysis. For the four-area network, contingencies causing islanding of some of the areas lead to large amounts of slack that needs to be absorbed in each area. If this slack is not distributed, this easily leads to generation exceeding generator limits or thermal overloading of lines connected to the swing bus. That distributed slack is an utterly unimportant consequence analysis option for the RBTS is explained by this system having only two generator buses both being in the same part of the network. Whether excess generation in case of loss of load is distributed on bus 1 or bus 2 to does not make much of a difference. Disconnection of generation from the rest of the network only occurs very rarely, and then it is sufficient to be able to distribute slack on the different generators on the swing bus.

What seems to be a general result across different test systems is that controlled load shedding is essential in reducing the estimated energy not supplied to more realistic levels. In contrast, modelling *uncontrolled* load shedding would be to allow cascading line tripping until complete system blackout or until some subsystem is able to restore operation. Furthermore, how load shedding is modelled also impacts the estimates substantially. Most important is deciding whether partial load shedding for delivery points should be allowed. Modelling of generation rescheduling (*reschedule_gen*) as a first operator action to take in case of contingencies is also generally significant. For the cases we have studied, generation rescheduling is an effective corrective action also if modelled by heuristics and not using optimal power flow algorithms (*reschedule_gen_opf*).

B. The importance of the number of operating states

We have also compared our results, which were averaged over multiple operating states, with the results using only a single operating state. First we chose a worst-case operating state for the four-area test network, namely the one operating state among the 208 considered having the highest total load. For this high-load operating state, it appears that controlled load shedding is ineffective in reducing the energy not supplied, and generation rescheduling becomes important in reducing the consequences of contingencies. One possible reason for getting different conclusions when studying only a single operating state is that all contributions to the energy not supplied comes from only a few contingencies.

We then chose a more typical operating state, or more precisely, the operating state among the 208 having the median total load. For this operating state, the overall trend in energy not supplied for different corrective action options is relatively similar to that found using 208 operating states. However, it then appears that the energy not supplied is completely insensitive to most of the corrective action options. In other words, although one captures the effect of the corrective actions with the largest impact, the more subtle sensitivities are lost. The same conclusion can be found from doing an analogous analysis of the RBTS. This highlights the advantage of using multiple representative operating states in the analysis in order to get more representative and accurate results.

C. Simplifications and limitations

Even for our base case modelling of corrective actions, the consequence and reliability analyses involve a number of simplifications that could conceivable impact our conclusions. The sensitivities of the results to different corrective action options depend quite strongly on the network in question, at least for relatively small test networks. The RBTS is a very simple network, and some effects observed for RBTS

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are probably particular to this test network. The four-area test network is a larger system, but still it would be interesting to do a comparative analysis of even larger and more realistic networks. Still, studies of the four-area test network have made us able to identify effects that we expect would also be relevant also for large, realistic systems. Since the results presented in Fig. 7 and Fig. 8 were obtained through a local sensitivity analysis, the magnitude of the sensitivities will also depend on what combination of corrective action options is chosen as the base case.

Another approximation is that the dependency of failures is not modelled explicitly, and we have only considered independent branch outages. For the four-area test network, designed to be very reliable, only second-order branch outages contribute to the reliability indices. Contributions from first-order contingencies would possibly dominate the results and typically make them less sensitive to the modelling of corrective actions. For an $N-1$-insecure system where some first-order contingencies immediately isolate delivery points from the rest of the network, contributions to the ENS from these contingencies for these delivery points will remain the same irrespective of how corrective actions are modelled. The results show that the ENS estimates are less sensitive to modelling choices for the RBTS than for the four-area test network.

Furthermore, protection systems are not modelled explicitly in the case studies we present. Protection systems could both be regarded as an important part of corrective actions, as defined in this study, and is also an important source of dependent outages for higher-order contingencies. To investigate the possible effect of protection systems, we have also performed the same analyses including protection system failures as described in [16]. The conclusion is that although the inclusion of protection systems definitely reduces the estimated reliability of the systems, the relative effects of different corrective action options are largely unchanged.

V. CONCLUSIONS

The main contribution of this paper is to present a structured approach to investigate the effect of different modelling choices for the consequence analysis on the reliability analysis. We have defined and implemented a number of corrective action options and investigated them by means of sensitivity analysis. The analysis demonstrates how modelling of controlled islanding and controlled load shedding is essential to avoid underestimating the reliability of the power network because of unrealistically large contributions from large blackouts. We have also shown that modelling of distributed slack can be important to be able to obtain more accurate results for the reliability indices. It should, however, be pointed out that the sensitivity of the reliability estimates to different modelling choices can depend strongly on the specifics of the system one is analysing. It could therefore be interesting to extend the analyses presented here to a number of larger and even more realistic test systems. The large impact of the modelling of corrective actions implies that large differences can be expected between different tools and models for reliability assessments, depending on how the consequence analysis is implemented. In general, a more careful selection of modelling assumptions is important for more accurate estimates of the reliability of the system.

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