Quantifying Influence of Strategies and Network Properties in Repairing Simultaneous Failures in Smart Grid

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Abstract

The behavior of networks under simultaneous failures has been subject to various studies in the field of network science. However, the measures used do usually not take into account the peculiarities of the studied network. In this paper, we introduce a new measure for power grids based on the balancing of power and on the accumulated cost of energy not supplied (CENS) during an outage. With the help of this measure we quantify the performance of seven repair strategies. We find that both the choice of the right strategy and the topology of the power grid has a major influence on the outage cost and the survivability of the power grid. Additionally, we appraise the potential of smart grid services and conclude that both distributed energy resources (DER) and demand response (DR) has a large potential to reduce the cost of an outage.

1 Introduction

Studies in information and communication technology (ICT) systems show the vulnerability of complex systems to human and software errors [1, 2] which may be caused, among others, by the complexity of large networks [3]. These errors affect potentially many devices as they run the same software, same configuration and are operated by the same humans. Studies indicate indeed that failures in ICT networks are not independent but rather correlated [4–6].

As the power grid relies more and more on the use of ICT [7], the dependency increases [8]. Failures in the power grid caused by failed ICT services are not new [9, 10] but they may become more frequent and exhibit a different pattern.

Correlated or simultaneous failures have been studied in various networks including power grids [11, 12].These studies model the simultaneous failure based on percolation theory which describes the behavior of the network when removing

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a fraction of $1 - p$ nodes in a network. The most common measure to quantify the outcome of a simultaneous failure is to count the nodes in the largest connected component of the network, however, it is not clear how to use this results for a classic dependability analysis as this measure is agnostic to characteristics of the underlying network. Therefore, some measures were put forward considering connections between consumers and power sources [11, 13].

In this work, we analyze and compare several repair strategies to recover from simultaneous failures and quantify their performance during the repair time. In order to evaluate the different repair strategies we introduce a quantification method based on the accumulated cost of energy not delivered (CENS) during the repair. We consider the scenario in which the failure only affects the power grid and leaves the ICT system completely unaffected, i.e. the control center has the full information about the state of the whole network. We study how changes in the network, namely increasing the average node degree or increasing the number of power sources affect the repair costs. Further, we interpret our results in the advent of the smart grid services *Demand Response* and *Distributed Energy Resources.* And finally, we show how the results can be used for a survivability analysis.

Our analysis covers the repair of the physical structure of the power grid. We do not consider the restoration of the service, i.e. power delivery. The results give valuable information about the upper limit of what can be achieved if all power engineering challenges are successfully met.

2 Modeling

Our analysis takes place in regional grids with typical voltage levels of 66 kV and 132 kV. A regional grid consists of power plants, interconnection points to other regional grids, transformer stations connecting to both the distribution grid and the transmission grid, and lines and cables connecting all these entities. The network is modeled as an undirected graph in which all the mentioned entities are modeled as nodes and the lines and cables are modeled as links between the nodes. The lower voltage levels with the consumers are not included in the model. However, the nodes have a load and power production corresponding to the sum of all the loads or power production connected to them. All nodes have a load, some nodes have additionally an attached power production, these nodes are called power producing nodes or power sources. We do not differentiate whether the power production is the sum of several smaller power sources in the distribution grid or one large power plant. Neither differentiate we between power plants, connections to the transmission grid and interconnections to regional grid. Important is only the sum of the power production. It is assumed that there exist no other connections between the nodes than those in this voltage level, i.e. in the network.

Cost of Energy Not Supplied (CENS)

In regulated networks, the regulator gives incentives for efficient and reliable operation of the grid. In the following we use the Norwegian regulation framework based on a yardstick regulation where the performance of a utility is measured in comparison with the others. Cost of Energy Not Supplied (CENS) is one parameter used for the efficiency and cost calculations for the revenue cap [14]. CENS is calculated by a function taking as input the *power not supplied* to a customer and the *time of the outage*. There exists a function for each customer group as listed

Table 1: Cost functions and groups used for the CENS calculation (Unit: Norwegian Krone /kW).

Customer group	original cost function depending on outage time r		avgerage cost function used in sim.	share of customer
	$r \leq 4h$	$r > 4h$		
Agriculture	$10.6r + 4$		62.3	4%
Residential	$8.8r + 1$		49.4	75%
Industry	$55.6r + 17$	$18.4r + 166$	244.8	1%
Commercial	$97.5r + 20$	$33.1r + 280$	422.45	10%
Public	$14.6r + 1$	$4.1r + 44$	59.85	10%

in Table 1. In the simulation we do not consider outage times, therefore, we use a time independent cost function, which depends only on the *customer group* and on the *power not supplied*. The value used in our cost function is the expected value of the time-depending cost function under the assumption that the outage times are uniformly distributed and take integer values between 1 and 10 hours. More details about CENS can be found in [14].

The nodes in the network have no CENS values themselves because they are substations and not customers. However, the sum of the CENS values of all customers connected to a node is taken as the CENS value for that node. It is assumed that all nodes have the same load and each node has only customers of the same group attached. To calculate the cumulative CENS for a network node we can use its cumulative load and use the cost function with the CENS parameter for the corresponding group.

Failure and Repair

The nodes are modeled with a binary state, either the whole node is alive or it has failed. Link failures are not included in our model. The ratio *(link failures)/(substation failures)* varies strongly between different nations [15].

The considered failure is a simultaneous failure of a fraction of f nodes. The set of failed nodes is denoted as V_{failed}, A failure can lead to a supply shortage or disconnection of additional nodes leaving the network with a total of s% of nodes non-alive. The set of non-alive nodes is in the following denoted $V_{non\text{-}alive}$. The sets have the properties: $|V_{failed}| = fn$, $|V_{non\text{-}alive}| = sn$ and $V_{failed} \subseteq V_{non\text{-}alive}$ where n is the total number of nodes in the network.

The considered repair mode is a one-by-one repair, i.e. only one failed node at a time can get repaired. In each repair step one node is chosen according to a strategy and repaired. It is assumed that the repair is successful and that no additional failures happen during the repair. All repair strategies start with $|V_{non\text{-}alive}|$ non-alive nodes and end after $|V_{failed}|$ repair steps because only the failed nodes need to be repaired. However, the order of repairing the nodes has an impact on how many nodes of the network are alive as repairing the right node may bring back the power supply to many other nodes as well.

3 Simulation Setup

The simulation covers only the repair process. A snapshot of the system is considered in which the load is maximal and close to the maximal production of the power plants. All consuming nodes have the same power consumption and the consumption is assumed to be static. All the producing nodes have the same production capacity. The total production capacity is 10% higher than the total load at this peak moment in the year. These assumptions are strong, but justifiable as the focus of this discussion lies on the strategies. Moreover, these assumptions can easily be changed for a more realistic analysis of a given power grid.

This *Monte Carlo* simulation has as stochastic variables the location of power sources, the location of failed nodes and the assignment of CENS customer groups to the nodes. The first two use a uniform distribution, the last a distribution with the expected values from Table 1. All stochastic variables change in each repetition.

During the analysis two different networks are used. First, a network based on a typical medium-sized regional grid from Norway with voltage levels 66 kV and 132 kV. It consists of 104 nodes and 124 links. Second, a network randomly generated with a node degree distribution that follows an exponential distribution. It has been shown in a study that the European transmission networks possess this property [12].

To cover grids based on larger centralized and smaller decentralized power plants, the simulation is run for two parameters: for a power grid with 10 and for a power grid with 40 power sources.

The ICT network is completely independent from the power grid and it is assumed to work flawlessly also after the failure in the power grid happened. The control center has therefore a full and correct overview over the system and knows which nodes belong to the set of non-alive nodes $V_{non\text{-}alive}$ and also which nodes belong to the set of nodes with a failure V_{failed}. The former gives information about the extent of the outage, the latter the valuable information about which nodes need to be repaired. As all the information is available only the order of repairing the nodes has to be determined by a chosen strategy. We consider the following strategies to choose the next node to repair:

1. *Baseline for comparison:*
   (a) *Random Repair:* Choose a random node from V_{failed}.
2. *Strategies based on properties of single nodes:*
   (a) *Highest Node Degree:* Choose the node with the highest node degree, i.e. the most links, in V_{failed}.
   (b) *Highest CENS:* Choose the node with highest CENS value in V_{failed}.
3. *Strategies optimizing outcome of next step:*
   (a) *Maximize Node Count:* Choose the node from V_{failed} which maximizes the number of alive nodes. The algorithm simulates all possibilities for the next step and takes the one giving the highest result.
   (b) *Minimize CENS:* Choose the node from V_{failed} which minimizes the CENS costs for the next step. The algorithm simulates all possibilities for the next step and takes the one giving the lowest result.
4. *Strategies based on properties of connected component:*

(a) *Biggest Failed Component:* Consider the graph formed by the nodes in $V_{non\text{-}alive}$ and choose the biggest connected network component. Consider all nodes from that component which are in V_{failed} and take the one with the highest node degree.

(b) *Failed Component with Highest CENS sum:* Consider the graph formed by the nodes in $V_{non\text{-}alive}$ and choose the one with the highest sum of the CENS values of its nodes. Consider all nodes from that component which are in V_{failed} and take the one with the highest node degree.

The strategies are chosen in a way to study the influence of considering *single nodes* versus *connected components*, and *node or degree count* versus *CENS values*. After the random strategy, which is used for comparison, there are three pairs of strategies. The strategies from the first pair consider only properties of single nodes for their decision, the strategies from the second pair consider the outcome of all possible repair steps and take the optimal solution and the strategies of the last pair base their decision on connected components of nodes in $V_{non\text{-}alive}$, i.e. they consider also the non-alive nodes that have no failure. In each pair there is one strategy considering only topological aspects like node degree or node count and one strategy considering CENS.

Measures

In the following, we use the two measures proposed in our previous work [13] to quantify $V_{non\text{-}alive}$: *Connectivity* counts the number of nodes still connected to any power source, *Balancing* requires in addition that the sum of loads in a surviving connected network component is at maximum equal to the sum of power production in that component. If the load is too high, loads are shut down.

When considering the financial impact of an outage for the responsible utility it becomes important *which* nodes are non-alive and not only *how many*. Therefore, we extend the measures to include the financial impact of the whole outage.

Definition 1 (CENS outage cost)**.** *The* CENS outage cost *is the sum of the CENS values of all the non-alive nodes, summed up over all repair steps. The non-alive nodes are determined with either the* Connectivity *or* Balancing *measure.*

4 Simulations and Results

Performance of Strategies

We first investigate the performance of the previously introduced strategies. The simulation is run with the network based on the described Norwegian regional grid. The results of 100 simulation runs are given in the lower row of Fig. 1. The best performing strategy, i.e. the strategy that leads to the lowest *CENS outage costs* is the *Minimize CENS* strategy. This is not surprising, as it optimizes the outcome for the next step. The *Maximize Node Count* strategy performs reasonably well considering that it is agnostic of the CENS values of the nodes. Although, for a higher number of power sources (40) the difference becomes bigger. The other five strategies are more than 50% more expensive than the best one. For a low number of power sources the difference is even slightly higher.

The strategies *Highest Node Degree* and *Biggest Failed Component* consider only topological aspects. They both have a similar performance. Taking into

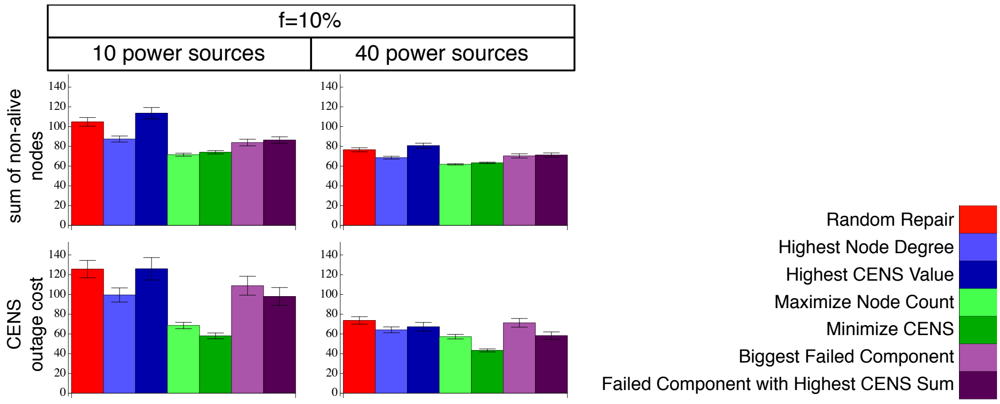


Figure 1: CENS outage costs in the regional grid model when 10% of the nodes fail. In the left column 10 nodes have attached power sources, in the right column 40 nodes have attached power sources. The upper row shows the sum of non-alive nodes over the whole repair process and the lower row shows the sum of CENS values of all non-alive nodes over the whole repair process (*CENS outage cost*) for the different strategies. The non-alive nodes are determined with the *Balancing* measure. The results are mean values of 100 repetitions of a Monte Carlo simulation with randomly positioned power sources and random failures. Whiskers indicate the standard error of mean.

account groups of nodes from $V_{non-alive}$ like in *Biggest Failed Component* brings no advantage against considering only single nodes from V_{failed} like in *Highest Node Degree*, it yields even a slightly worse performance. The opposite is true for the two strategies considering only the CENS values. Here the strategy taking into account components of nodes from $V_{non-alive}$, i.e. trying to reconnect the component with the highest CENS sum (*Failed Component with Highest CENS Sum*) performs better than the strategy *Highest CENS Value* which considers only single nodes from V_{failed}.

Comparing CENS outage cost with Node count

A simple measure to quantify a repair strategy could be to count the number of non-alive nodes per repair step and then sum it up. The proposed measure *CENS outage cost* takes the additional information about the CENS values into account, which is not directly topology related. Using this new measure we try to find a strategy that minimizes this *CENS outage cost*. It may seem wrong to use a financial parameter to measure the performance of repair strategies, but the CENS values can also be understood as a criticality indication of the nodes. In order to check the implications on the availability of the nodes, we run the same simulations with all strategies and measure it with the purely topological measure *sum of non-alive nodes* and also with the measure *CENS outage cost*. The results are presented in Fig. 1. The strategy *Maximize Node Count* optimizes the first measure, the strategy *Minimize CENS* optimizes the second measure. The results show, that those two strategies perform very similar when using the first, topological measure, i.e. optimizing for CENS values optimizes also the sum of non-alive nodes. However, this is not the case for the second measure. The difference between the two strategies becomes bigger with a higher number of power sources. The same is true for the two last strategies focusing on components on either the topological level or the CENS level. The statistical relevant differences are smaller here. Interestingly this is not true

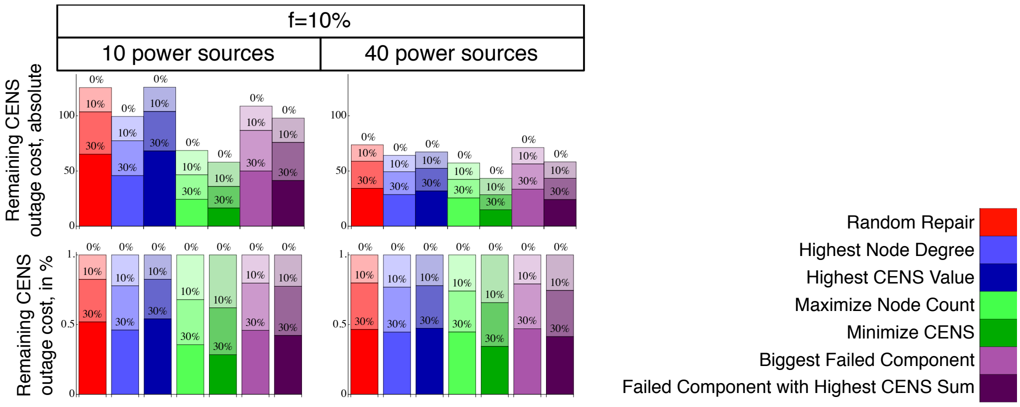


Figure 2: Remaining costs *before* repairing, after having repaired 10% of the failed nodes, after having repaired 30% of the failed nodes in the regional grid model. The upper row gives the absolute value for CENS, the lower row gives the remaining outage costs after in percentage of the total costs. The non-alive nodes are determined with the *Balancing* measure. The results are mean values of 100 repetitions of a Monte Carlo simulation with randomly positioned power sources and random failures.

for the first pair of strategies after the random strategy. Using the *Highest Node Degree* strategy is for both measures better than using the *Highest CENS Value*. The difference to the other two strategies using CENS is, that the two latter consider the CENS-sum of a group of nodes which includes also a topological aspect, therefore, they also perform well compared to their topological counterparts using the sum of non-alive nodes measure.

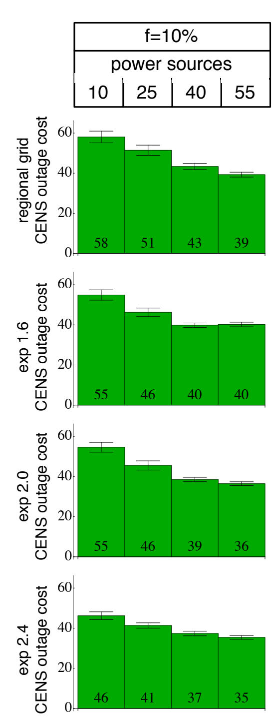
As conclusion we can state that using the best strategy *Minimize CENS* reduces the costs without increasing the number of non-alive nodes compared to the strategy *Maximize Node Count*. This can be done because optimizing for a minimal CENS implicitly also favors a small number of non-alive nodes. The utility can here reduce costs without sacrificing the availability of its nodes.

Cost Development of Strategies

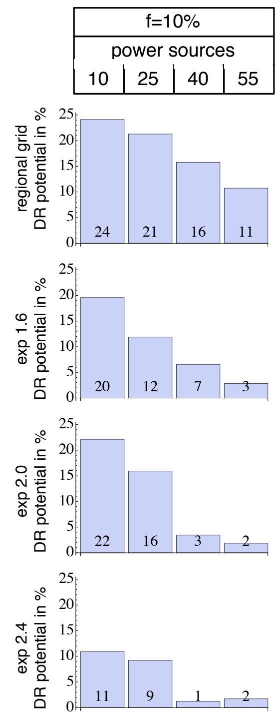
In our model the repair takes always the same amount of steps, each strategy needs to repair $|V_{failed}|$ nodes. But depending on the strategy the degree to which the service is back will be different. In Fig. 2 we have plotted the remaining *CENS outage cost* after having repaired $0\%, 10\%$ and 30% of the failed nodes. The strategy with the lowest absolute *CENS outage cost* also has the property of reducing the cost faster. In the scenario with 10 power sources, the best strategy *Minimize CENS* reduces the *CENS outage cost* by 30% by repairing 10% of the failed nodes, i.e. by repairing one single node. After repairing 2 additional nodes (in total 30% of the nodes) only 1/3 of the total *CENS outage cost* remain. The results illustrate that repairing with the right strategy can reduce the costs drastically.

Influence of Node Degree and Number of Power Sources

In the following we study the effect of increasing the number of power sources. As before the regional grid is used with randomly positioned power sources and a random node failure of 10% of the nodes. The number of power sources takes the values $10, 25, 40$ and 55. Only the best strategy *Minimize CENS* is considered.



(a) *CENS outage cost* in the regional grid and in random networks whose node degrees follow an exponential distribution *exp*(λ) with $\lambda \in \{1.6, 2.0, 2.4\}$. The repair strategy *Minimize CENS* is used after 10% of the nodes failed. The non-alive nodes are determined with the *Balancing* measure. Whiskers indicate the standard error of mean.



(b) DR potential to reduce *CENS outage cost* in the regional grid and in random networks whose node degrees follow an exponential distribution *exp*(λ) with $\lambda \in \{1.6, 2.0, 2.4\}$. The repair strategy *Minimize CENS* is used after 10% of the nodes failed.

Figure 3: The results are mean values of 100 repetitions of a Monte Carlo simulation.

Additionally we use random networks whose node degrees follow an exponential distribution *exp*(λ) with $\lambda \in \{1.6, 2.0, 2.4\}$. The simulation results are shown in Fig. 3a. For all four networks the *CENS outage cost* goes down when the number of power sources increases. Increasing λ, which increases the average node degree, reduces the *CENS outage cost* as well. However, this effect is stronger for a small number of power sources in the network. If the number of power sources increases even more the difference disappears completely as can be seen when considering the case when all nodes have a power source. Then, the node degree of the nodes has no influence anymore as each node is self-contained.

Utilities have two ways of reducing *CENS outage cost*: First, by increasing the average node degree. Second, by increasing the number of power sources. The former is very expensive, usually not practical because of restrictions for building new links and as shown in the results less effective than the latter.

5 Discussion

The results show that choosing the right strategy can reduce the costs of an outage drastically. The best strategy is the one finding the optimal solution for the next step, i.e. it simulates all possibilities for the next step and chooses the one with the best outcome. The computational complexity is higher than with the other strategies, but this is not an issue as the number of possibilities is only as large as the number of failed nodes. In our examples, the simulation runs could be executed very quickly, the simulation finished in a matter of milliseconds on a normal desktop computer and is several orders of magnitude smaller than the actual repair time. The network type, the average node degree and the number of power sources has an influence on the total *CENS outage cost*. Usually those parameters cannot be changed in a power grid. However, with the advent of smart grid with its new services two things may change:

1. The number of power sources may change drastically as small and distributed power sources (DER) are promoted.

2. A *Demand Response* (DR) scheme may reduce the load.

The results can be used to appraise the potential to reduce the cost of outages by using these two smart grid concepts.

Impact of Distributed Energy Resources on Outage Costs

Distributed energy resources (DER) are medium and small scale power sources located in any level of the power grid. The coordinated operation of DERs requires either a centrally located controller or a more local micro grid controller. The latter having the advantage of being able to run this part of the power grid in an island mode, i.e. a decoupled micro grid [16, 17]. Micro grids are a mean to make parts of the grid independent from the functioning of the rest of the grid. Assuming a high density of DER in the underlying distribution grid which are controlled by local micro grid controllers yields a scenario where the number of nodes with power sources is high. As seen in Fig. 3a increasing the number of power sources reduces the *CENS outage cost*. We can, therefore, conclude that DER reduces the *CENS outage cost* and it can even be quantified by using the introduced measure.

Impact of Demand Response on Outage Costs

Changing topological parameters or the number of power plants is in reality either unrealistic or connected with potentially high costs. Instead, the existing infrastructure may be used more efficiently; one solution is to use *Demand Response* (DR). DR is a mechanism by which consumers change their consumption based on the price, the load or another signal [7]. In contrast to load shedding, i.e. disconnecting loads to achieve the power balance, DR reduces the loads without disconnecting nodes. In a scenario with a high density of distributed power production and energy storage, DR may also control the distributed production or feeding of power from the storages to the grid. However, we do not consider the control of production by DR in this paper. A DR scheme has the advantage of using the existing infrastructure in a more efficient way by regulating the load. This is also linked with costs to install the DR infrastructure like devices and a communication platform. But as the new infrastructure is also used by other smart grid services like monitoring and controlling the costs can be split.

To study the potential of DR for reducing outage costs it is important to consider the reason for a power loss in a node. According to the *Balancing* measure, a node can be non-functional because a) it was affected directly by the failure, b) it is part of a component without power source, or c) it is part of a component with too little power. The first two cases require repair. In the latter case, assuming a network-wide instantaneous and failure-free DR scheme, the load of the alive nodes can be reduced to supply non-functional nodes and turn them into alive nodes.

The measures *Balancing* and *Connectivity* may be considered as the two extreme cases of using DR, i.e. *Balancing* corresponds to *no DR* and *Connectivity* corresponds to 100% *DR* with no restriction on a minimal load per node. The difference between the measures is then the potential of DR. In Fig. 3b this potential is plotted, i.e. the reduction of *CENS outage cost* when the whole DR potential could be used compared to no DR.

The results show that the DR potential is highest for a low number of power sources in the network. Increasing the node degree leads to a decrease in DR potential as the probability that a network component is without a power source becomes smaller. In the extreme case of a complete graph the potential disappears completely as the nodes are not dependent on the load of other nodes anymore. The same holds for the case when the number of powered nodes goes to 100%.

The results depend on the ratio *(total production capacity)*/(*total consumption*). If this ratio is close to 1 or even smaller than 1, the potential for DR is large. If the ratio increases, the results of the two measures will get closer and the potential for DR will decrease.

Survivability Contribution of Strategies

Dependability is defined as "*ability to avoid service failures that are more frequent and more severe than is acceptable*" and it contains metrics like availability and reliability [18]. A related measure is *survivability* which is defined as *"system's ability to continuously deliver services (...) in the presence of failures"* [19]. It can also be understood as how fast and to what degree the service is still delivered or restored after a failure. The CENS value has been introduced with the objective "*to achieve the most optimal level of continuity of supply for the society as a whole*" [14]. Therefore, it can be understood as a criticality indicator of the node. The *CENS outage cost* is then a measure for how well the continuity of supply has been provided during the repair, or in other words it measures the survivability. The lower the value, the higher its survivability. To get more details for the survivability analysis it is necessary to investigate the development of service restoration; a highly survivable system should restore the most critical parts first. These information can be found in Fig. 2, which shows the development of the *CENS outage cost* for the different strategies. The results can be directly applied to survivability analysis, i.e. using the right strategy increases the survivability drastically.

Assuming we include time as a factor, we can also state that it is most crucial to have short repair times for the first nodes. For the second half or even for the second 2/3 of nodes time is not so crucial anymore, as the most critical nodes are already repaired.

6 Conclusion

Simultaneous failures have been studied in various networks in the field of network science. These abstract results can be used for power grids, however, it is crucial to tailor them to the specific peculiarities of the system. In this paper, we introduced a measure based on CENS values of power grid nodes and on the *Balancing* measure. The new measure allowed us to quantify and compare the performance of different repair strategies and networks. As CENS has a direct impact on the regulated tariffs of a utility it is an important parameter to consider in the event of an outage but especially also for determining the order of repairing the nodes. CENS was introduced specifically as a sort of criticality value for each node and to give incentives to prioritize certain customer groups.

The results show that using the strategy minimizing the CENS costs for the next step has various advantages. First, it performs comparably to the strategy *Maximize Node Count* when using the node count measure. Second, it reduces the *CENS outage cost* considerably compared to the CENS-agnostic strategies. Third, it improves the survivability by restoring critical nodes faster.

We could also show that increasing the average node degree of a network reduces the *CENS outage cost*. However, increasing the number of power sources leads to an even stronger improvement and reduces the difference between networks of different average node degrees. Thus, increasing the number of power sources is the less expensive way of reducing the *CENS outage cost*. In smart grid terminology this indicates that DER reduces the *CENS outage cost*. And finally, we showed that a DR scheme has the potential of reducing the *CENS outage cost* by up to 24%.

The structural analysis conducted in this study concentrates on the structure of the power grid and its repair. We do not consider the service, i.e. power delivery and, therefore, dynamics in the system are not included. The results give valuable information to power engineers about the upper limit of what can be achieved if all power engineering challenges are successfully met.

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