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Analyse probabiliste de la résilience des réseaux intelligents

Probabilistic resilience assessment of smart power systems

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Résumé

Les réseaux électriques ont été traditionnellement organisés d'une manière centralisée : la production était concentrée en de grandes centrales, les systèmes de transport s'occupant de transférer l'énergie de ces centrales vers les centres de consommation, et les systèmes de distribution fournissaient des consommateurs purement passifs. Cette organisation a commencé à changer avec l'introduction d'unités de production distribuées (renouvelables), et avec l'apparition de consommateurs actifs s'inscrivant dans des programmes d'adaptation de la demande. Dans le but de mesurer et contrôler ces sources de production distribuée, d'équilibrer production et demande et de stabiliser le système électrique, les Technologies d'Information et de Communication (TIC) se voient attribuer un rôle grandissant. Un des avantages significatifs possible de cette nouvelle structure pourrait être l'amélioration de sa résilience vis-à-vis de désastres tels que les tornades, les tremblements de terre, … En effet, les lignes de transport et de distribution sont très vulnérables à ce type de désastre. Le recours généralisé à des sources distribuées ouvre la voie à une reconstruction rapide et potentiellement partielle des consommateurs qui sont proches de ces sources. Cependant, il n'y a pour l'instant pas de méthode satisfaisante permettant de quantifier la résilience des systèmes électriques. Le but général de cet article est le développement d'une méthodologie pour quantifier de manière probabiliste la résilience d'un système électrique de transport vis-à-vis d'événements ayant un impact élevé mais une faible probabilité. Cette méthode passe par une caractérisation de la menace et de la vulnérabilité des composants physiques à cette menace, de la réaction électrique à cette menace et de la restauration du système ; elle est appliquée au réseau IEEE 39 nœuds puis utilisée pour implémenter et comparer différentes méthodes de restauration. Différentes conclusions et recommandations sont tirées sur l'efficacité des différentes méthodes.

Summary

Power systems were traditionally organized in a centralized way: generation was concentrated in large power plants, transmission systems were in charge of transferring the energy from power plants to load centers, and distribution systems supplied purely passive consumers. This organization has started to change dramatically with the massive introduction of distributed (renewable) generating units and the emergence of active consumers through demand response programs. In order to monitor and control those distributed energy resources, to balance the generation and the load and keep the stability of the system, the importance of Information and Communication Technologies (ICT) is also rising in the grid. A possibly significant advantage of this new structure might be the increase of its resilience to disasters such as tornadoes, earthquakes, ... Indeed, transmission and distribution lines are very vulnerable to these kinds of disasters. Resorting more largely to distributed generators opens the way to a quick, potentially partial, resupply of power to consumers that are near those energy sources. However, there is currently no satisfying methodology to quantify the resilience of power systems. The general goal of this research is the development of a methodology to quantify, in a probabilistic way, the resilience of a power system against High-Impact, Low-Probability (HILP) events. This probabilistic method involves threat characterization, physical vulnerability assessment against this threat, electrical reaction assessment and restoration, and it is applied to the IEEE 39 bus and then used to implement and compare different restoration strategies. Conclusions and advices regarding the effectiveness of these restoration strategies are finally drawn.

1. Introduction

1.1. Context

Power systems are currently undergoing a deep change in topology, following society needs and pushed by technology breakthroughs. On one hand, the need for decarbonized power generation drives the decentralization of generation towards smaller units (wind or PV), distributed all over the transmission and sometimes distribution grids. This evolution in generation dispatch also implies changes in the grid topology itself, allowing for new control strategies such as working in standalone microgrids, active load control, distributed generation (DG) for grid restoration, ... On the other hand, weather- or earth-related events such as earthquakes and hurricanes become critical both technically and economically: between 2003 and 2012, 80% of the major electricity outages (impacting more than 50,000 customers) in the US were caused by natural events (Kenward et al., 2014). As a result, countries subject to high-impact, low-probability (HILP) weather events see the emergence of new possible ways to mitigate these events but also the need for better understanding of these events and how to model them and their impact on the grid. This increased controllability and flexibility over power systems coupled with the important share of power asset failures attributed to rare natural events motivates the need for a better understanding of (1) these events and their impact on the grid and (2) of the reaction of the grid facing them in order to be better prepared.

1.2. Motivation – limitations of traditional reliability studies

Traditional reliability studies on the power systems are generally split between security and adequacy assessments.

Security is defined by (ENTSO-E, 2018) as *the ability of the system to withstand disturbances arising from faults and* *unscheduled removal of equipment without further loss of facilities or cascading failures.*

Adequacy is defined by (NERC, 2018) as *the ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.*

Based on these two definitions, power system operation and planning teams assess and enhance power system reliability so as (1) the grid is able to withstand different disturbances and (2) the aggregated demand is supplied. Also based on these two definitions, it can be understood that reliability studies generally refer to probable events but with low (or even null) impact on the grid. The traditional N-1 criterion used to assess the operability of the grid with respect to a list of standalone failures of different assets, where the grid be operated within acceptable value bounds and remain stable, gives a good example of the type of events reliability studies often consider. As a result, HILP events are completely out of the scope of reliability.

As a second shortcoming, reliability studies often focus on "how to avoid failure" rather than on "how to restore when it failed". The implicit assumption made during reliability studies is that the event will have only little impact on the grid. As a result, the restoration phase is slightly put aside. Resilience studies however, as they will be introduced in the following section, cannot neglect the restoration phase. One of the underlying assumptions in resilience studies is that the system will undergo severe degradation which could lead to partial or full failure of the systems. The objective is to reduce the impact of these failures. The two limitations motivate the introduction of the paradigm associated with resilience and the need for a clear definition.

1.3. Definition state-of-the-art and choice

There is no clear consensus in the literature regarding a commonly accepted definition for power system resilience. The first definition was first introduced in 1973 as *the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.* (Holling, 1973). Since then, multiple definitions were given in the field of power systems. (NIAC, 2009) insists on *the ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.* (Park et al., 2013) defines resilience principle as the ability to *adapt to changing conditions without losing function permanently.* He also emphasizes the fact that intentional failure can be allowed in order to mitigate possible heavier failure later on. Finally, (McCarthy, 2007) gives the following definition: *Resilience is the ability of a system to recover from adversity, either back to its original state or an adjusted state based on new requirements*. This non exhaustive list of definitions is enough to show divergences, but also to emphasize the fact, common to all, that resilience concerns high impact events, with important consequences on the system. Importance is also given to the restoration phase. The definition chosen for this research in the frame of power systems is adapted from the previous considerations, and from (Panteli et al., 2015): *Resilience is the ability of a power system to withstand extraordinary and high impact-low probability events such as due to extreme weather, rapidly recover from such disruptive events and absorb lessons for adapting its operation and structure to prevent or mitigate the impact of similar events in the future.* Resilience assessment can hence be seen as an integrated reliability assessment focusing on HILP events, which consequently changes the assessment method to be applied due to the rareness and severity of the events considered. Finally, probabilistic methods will have to be applied to capture the full complexity of HILP events.

1.4. Objectives

This paper presents a 4-steps resilience assessment method (4SRAM). The two first steps characterize the event and their physical impact on the grid. Hazards considered in this paper are hurricanes. The third step concern the electrical reaction of the system after the event struck. The fourth step on which this paper focuses mainly, tests possible restoration strategies. Feasibility of these strategies, both human- and economic-wise is assessed. Following the 4SRAM, a feedback phase is envisaged for adaptation measures to be implemented in order to improve resilience through possible remodelling of the grid topology or management. The remaining of the paper is organized as follows: a complete description step by step of the method and its adaptations will be done in chapter 2. Then a description of the probabilistic assessment method through Monte Carlo Sampling (MCS) is done in chapter 3. Numerical application of the method is done in chapter 4 together with plausible restoration/adaptation methods description and application. Chapter 5 discusses the results and comments about the best restoration strategy, its requirements and application fields. The final objective of the paper is to prove the added value of a resilience assessment over a reliability assessment method, and to rank different restoration/adaptation methods in terms of effectiveness, feasibility and costs.

2. Resilience assessment method

The 4SRAM has been used in the literature in (Shinozuka et al., 2003), (Panteli, 2015), and (Espinoza et al., 2017) among others. It has the advantage to be the most coherent method with the time sequence of a HILP event on power systems, as it can be seen in figure 1. Steps 1 and 2 correspond to a healthy pre-hazard system. After the event has struck, the priority is to assess "how bad" the failure is or "how low does the system function F(t) goes", and it corresponds to step 3. Step 4 characterizes the speed of recovery, or "how fast will F(t) reach back acceptable levels".

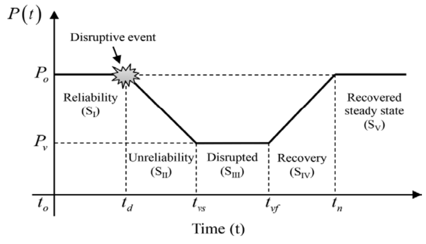

Figure 1. Resilience curve: Any system function F (e.g. supplied power, or electrical frequency) as a function of time (Yodo et al., 2016)

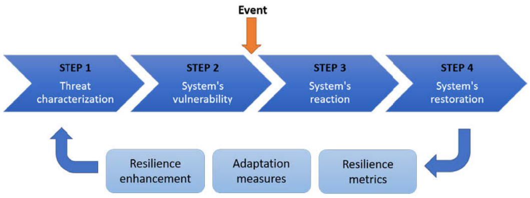

Figure 2. The 4-step resilience assessment method

At the end of the 4-steps process, a feedback is mandatory to improve the system continuously. The 4SRAM is summarized in figure 2 and the following sections will give details about it.

2.1. Step 1 – threat characterization

The purpose of this step is to quantify how probable a given event is, for a given location. Depending on the type of event considered, a metric characterizing the severity of the event should be chosen and associated to a corresponding probability of occurring. The chosen metrics for hurricanes and earthquakes are respectively wind speed (m/s or miles/h) and peak ground acceleration (PGA) (g). The output of this step should be a probability density function (pdf) of the wind speed or PGA. Such functions require different mathematical and physical models which are out of the scope of this paper. Different models available embed built-in database for pdf generation. Focusing on hurricanes, the American Society for Civil Engineering provides codes, norms and standards for civil engineering building resistance to different hazards. Using historic meteorological dataset and different recurrence models, the ASCE 7-10 norm (ASCE, 2010) basic wind speed map specifies wind speeds associated to 5 return intervals for the United States. Assuming a nonlinear interpolation fitting a Weibull distribution, it is possible to retrieve pdf wind speed distributions for the United states. Figure 3 shows one pdf extrapolated from the ASCE 7-10 database for Miami.

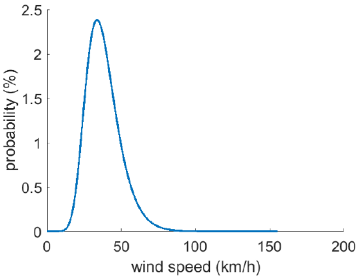

Figure 3. Wind speed probability distribution function for Miami

2.2. Step 2 – system's vulnerability

A power system is by nature a system of systems. As a result, the grid vulnerability to aforementioned HILP events is determined by the vulnerability of its constitutive items to the same events. In other words, power system fragility to hurricanes and earthquakes is characterized by the fragility of power plants, substations and high-voltage lines to these hurricanes and earthquakes. Consequently, the objective of this step is to associate, for each asset type, the severity of the event (characterized by one sample of the previously generated pdf, namely one wind speed in m/s for hurricanes) to a failure probability. These relations between event severity and failure probability of assets are called fragility curves and require civil engineering models and expert judgements, which will not be detailed.

Focusing on hurricanes, fragility curves are needed for all power system assets sensitive to strong wind gusts, namely transmission towers supporting transmission lines, and substations.

For substations, the HAZUS tool, developed by the US department of homeland security (FEMA, 2018), involves risk assessment and fragility description for hurricanes among others. The tool embeds fragility curves for the two assets mentioned before, whose development has been based on statistical data and expert judgement. Distinction is made between 5 terrain types (open, light suburban, suburban, light urban, urban), as the technology and hardware for a substation in open environment (outdoor building) is not the same as the one for an urban substation (often underground). It also considers 4 different damage states (slight, moderate, severe or complete).

Transmission lines failure is supposed to be due to tower collapse. Transmission tower stability assessment has been done for many different tower configurations and locations and the corresponding fragility curves vary a lot from one reference to another. The curve chosen arbitrarily in this paper is the one developed by (Qanta, 2008) whose failure probability is given by

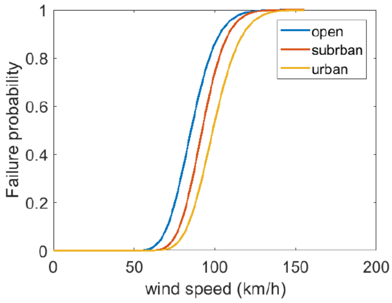

Figure 4. Fragility curves for substations in open, suburban and urban environment

$$F(v) = \min((2.10^{-7})e^{0.0834v}, 1) \quad \{1\}$$

Where v gives the wind speed. The number of towers of a line depends on its length. As a results, a longer line will be more vulnerable to hurricanes than a shorter one. Assuming that all towers are the same and that all these towers face the same wind speed, the failure probability of a complete transmission line with N towers whose individual failure probability F is given in equation 1 is

$$1-(1-F)^N \quad \{2\}$$

It is important to notice after steps 1 and 2 that important variability in these two steps depending on the reference chosen and assumptions made are logically observed due to different choices of hypothesis. These two steps should give plausible scenarios for a resilience assessment but moreover for testing restoration and adaptation procedures, but might lead to important variability in the results as well. As soon as the initial hypothesis are coherent for all simulations though, relative comparison between results are relevant. In other words, numerical results should not be taken in absolute values but rather relatively to compare different methods.

2.3. Step 3 – system's reaction

Steps 1 and 2 lead to a failure probability distribution, asset by asset. Assuming a sampling of these distributions, the output of steps 1 and 2 is a list of failed items on the grid. This gives a starting point to the electrical simulation of the grid. The objective is to assess the behavior of the system facing these failures. The question to be answered at this point is "what will be the impact of the asset failures (due to the HILP event) on the power systems"? This question is answered by performing a AC Optimal Power Flow (OPF) and by assessing whether the remaining generation and transfer capacity can supply the load.

An OPF is a mathematical tool for obtaining the steady state of a transmission grid minimizing the loss of supplied power, while satisfying the system's operational constraints (e.g. thermal ratings of transmission elements, voltage ranges, ...), is looked for. This tool allows to understand the power fluxes through each line, and the voltage levels at each bus. The program used is DigSilent PowerFactory.

2.4. Step 4 – system's restoration

Step 4 requires the generation of a restoration strategy for the grid to reach back acceptable service levels. Impact of different restoration strategies may be studied, in order to determine an optimal strategy to reduce down time as much as possible. It is important to keep in mind the reality of the field and to be able to comply to human and physical limits of restoration times whilst proposing restoration strategies. The different strategies envisaged in this concern an optimization of the time-to-repair (TTR) of the different failed assets of the system, in order to (1) reduce the down time of the whole system and (2) make sure the TTR generated are physically and humanly reachable for the repair teams. Adaptation measures concern grid reinforcement at strategic locations.

3. Monte Carlo simulation (MCS)

3.1. Method

As already mentioned, the rareness of the HILP events requires probabilistic methods to be applied. Studying a standalone iteration of one hurricane that might happen would not capture the total risk associate to all probable hurricanes of a given location.

In order to sample randomly all possible hurricanes generated by step 1's pdf, to simulate the reaction and the possible restoration strategies for all of these samples, a Monte Carlo method has to be applied. A described in (Zio, 2013), a MCS can be seen as a methodology for obtaining estimates of the solution of mathematical problems by means of random numbers. The starting point of the method is the pdf generated at step 1.

1. The pdf is integrated into a cumulative distribution function (cdf), which is by definition always between 0 and 1. This cdf is truncated in order to keep only HILP events: only the last quartile is chosen.
2. N_s random numbers between 0 and 1 are generated to sample the wind cdf. Hence, N_s wind speeds are generated. The stopping criterion associated to N_s will be discussed later on.
3. The wind speeds are fed to the fragility curves of every substation and line of the test system. The output of steps 1 and 2 is therefore a $N_s \ x \ N_a \ F$ matrix filled with failure probability. The F_{ij} item of the matrix gives the failure probability of the j^{th} asset to fail during sample i.
4. For each of the N_s lines of the matrix, the N_a failure probabilities have to be turned into binary failures. To do so, N_a random numbers are generated and compared to F_{ij}. Depending on the result, either the "failed" or "not failed" state is assigned to F_{ij}.
5. The binary vector associated to line i is used as a starting point for step 3. The electrical reaction is assessed for each of the N_s samples and different restoration strategies are implemented.

3.2. Convergence criterion

The random number concept has already been explained before, and the fact that "a great number" N_s of samples need to be drawn. However, a stopping criterion needs to be set in order to know how great should *Ns* be, in order to avoid lack of convergence and hence precision on one hand, and to avoid useless computation after sufficient convergence is achieved on the other hand. The stopping criterion chosen, retrieved from (Zio, 2013) but common in the literature, is to stop the simulation when *Ns* is sufficiently high so that the relative standard deviation is smaller than a threshold:

$$\frac{\sqrt{var(I)/N_s}}{avg(I)} < threshold \qquad \{3\}$$

Where I is a metric characterizing resilience and *threshold* is to be chosen wisely (as close as possible to 1 that the computation allows it) to avoid too high uncertainty in the outputs. The relative standard deviation threshold has been set to 5%. As a result, N_s will be adapted so as to meet this criterion.

4. Simulation considerations and numerical results

4.1. Test grid

The test grid, chosen among the IEEE test grids, is the IEEE 39-bus. First described in 1979 (Athay et al., 1979), the grid consists of a 10 generators, 34 lines high voltage (345 kV) transmission grid, supposed to be simulating a part of an actual grid located in the area of New-England, USA. A representation of this grid is shown in figure 5. This choice is motivated by the need to have a sufficiently complex and flexible grid that could adapt and reroute power when a line outage happens. The size should be kept reasonable though for future dynamic simulations. Finally, the grid should have geographical dimensions to take into account the number of towers as mentioned in equation (2). The IEEE 39-bus was meeting all the aforementioned requirements.

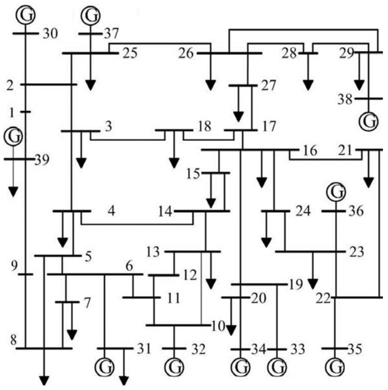

Figure 5. Fragility curves for substations in open, suburban and urban environment

4.2. Restoration strategy

Steps 1 and 2 detailed implementations have been already described together with their coupling to a MCS. The starting point of each simulation (namely which assets are unavailable) is known. Steps 3 and 4 have to be conducted together as an electrical reaction assessment (step 3) is mandatory after each asset repair (step 4). The sequence of events is as follows for each of the N_s samples:

1. Assign initial conditions to each asset
2. Generate TTR
3. Assess electrical reaction
4. Repair first failed asset
5. Repeat 3 and 4 until all assets have been repaired
6. Retrieve and exploit relevant results.

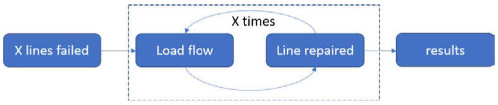

Figure 6. Restoration strategy

Three different TTR generation methods have been applied. The first method, called "**base case**", consists in simply assuming that the TTR are uniformly distributed between 2 values, namely between 36 and 72 h for the failed towers, and between 84 and 168 h for the failed substations. The second method, called “**linspace**”, consists in assigning constant times between repairs (TBR) during the restoration process. The TTR are spread equally between the two values given before. The order of repair is however determined randomly, without prioritization. The third method, called “**prioritization”,** is an improvement of “linspace”. TTR generation is the same but priorities are given to lines with bigger nominal rating. The order of repair is hence determined according to the ranking of nominal powers of lines. An example of TTR generation for a same scenario is given in table 1. 6 lines (lines 1, 8, 15, 22, 28, 33) failed.

Line	**1**	**8**	**15**	**22**	**28**	**33**
Rating (MW)	122	273	70	489	57	358
1	54.5	36.8	67.8	53.8	56.7	70.0
2	36	43.2	50.4	57.6	64.8	72
3	57.6	43.2	64.8	36	72	50.4

Table 1. Example of TTR generation for methods base case (1), linspace (2) and prioritize (3), in hours.

Scenario “base case” has the drawback to be completely random. As a result, TBR can be very short (3 hours between repairs of line 22 and 28 in this case). Depending on the number of repair teams involved in the restoration process, this could lead to unreachable repair objectives. Scenario “linspace” has the advantage to adapt the TBR to the number of failed items. As a result, work load is adapted to the severity of the event, which can be physically translated into involving more teams for more severe events. Scenario “prioritize” gives more importance to lines with higher power rating: in this case, line 22 is repaired first because it has the higher rating. Effectiveness of these different methods will be detailed later on.

4.3. Adaptation strategies

The adaptations measures envisaged consist in reinforcing the grid in strategic zones, namely where the grid is heavily loaded before the hazard strikes. 3 scenarios, which will have to be compared to the 3 previous restoration scenarios, have been implemented. Scenario **“double2**” duplicates the two most heavily loaded lines. Scenario “**double1**” duplicates the most loaded line. Scenario “**double0**” duplicates one lightly loaded line to confirm the usefulness of the two previous scenarios. Results associated are given in the next chapter. The last adaptation strategy will be the reinforcement of the substations (physical strengthening of the building) so that their fragility can be neglected with respect to the towers. In other words, only lines will be sensitive to hurricanes. This strategy will be called **“only lines”**.

4.4. Resilience metrics

In order to compare the previously explained restoration and adaptation strategies, metrics need to be chosen. Resilience metrics is an active field of research and is one of the topics of the recently started CIGRE C4.47 [1]working group: *What metrics should be used to quantify the resilience performance of a power grid in face of a disaster?* (Watson et al., 2015) gives however a clear framework for selecting relevant metrics: they should be quantitative (1), reflect uncertainty (2), support risk-based approach (3) and consider recovery time (4). According to these points, two metrics have been chosen to quantify resilience:

1. The Expected Energy Not Served (EENS) is a performance-based metric, giving the expected amount of energy that will not be supplied due to the event, the failures and load shedding associated. EENS can be also seen as the area below the performance curve of figure 1 when taking power supplied as the performance function P(t). The EENS has been in this case divided by the total energy demand and multiply by 100 to render an EENS in percent, independent of the simulation time. As a result, simply reducing the TTR will not affect the EENS due to its relative assessment.
2. The Loss Of Load Expectation (in h) is the average duration during which a supply default occurs. It assesses the speed of restoration of the system.

4.5. Numerical results

	EENS (%)	**LOLE (h)**	N_s
Base case	25.71	66.37	1155
Linspace	24.38	67.96	1123
Prioritization	18.75	65.4	1510
Double2	12.4	67.78	2500
Double1	18.07	67.23	1357
Double0	24.02	67.77	1276
Only lines	21.58	55.99	1198

Table 2. Simulation results.

N_s is given only for information, and can be understood as the required iterations or sample count before a sufficient convergence level is reached. Simulations run during approximately 15 minutes on an intel i7-77003.6 GHz processor.

5. Discussions

Different observations may be drawn from the comparison of the restoration and adaptation strategies. Base case scenario is used as benchmark for all observations.

1. Linspace strategy does not bring any added value to the base case. The linspace method can be seen as a uniform TTR distribution (same as base case), with only discrete possible values. As a result, these two methods give similar results.
2. Prioritization improves EENS by almost 7 %. The improvement is significant and the investment are limited. Indeed, prioritization can be implemented on the field simply by a better dispatching of the team before the event and a better restoration management after the event: no hardware investment is required. The LOLE remains unchanged. This can be explained by the fact that the LOLE is mainly impacted by the TTR which remain between the two same values for both scenarios.
3. Double2 and double1 scenarios improve EENS respectively by 13 % and 7 %. The method are effective, but the investment required are extensive. The investment decision is to be compared with less effective but also less cost-extensive methods such as Prioritization. Double0 leaves EENS and LOLE unchanged, which confirms that the lines involved in double2 and double1 were chosen wisely.
4. Only lines scenario decreases EENS by 4% and reduces LOLE by 10h. This can be understood as follows: among the 25% base case EENS, 21.5 % are to be attributed to line failures and 4 % to substations. Lines are indeed much more sensitive to strong winds than substations which are condensed over a small area and sometimes surrounded by a building. The decrease in LOLE can be explained by the fact that TTR are higher for substations.

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[1] 1 http://c4.cigre.org/WG-Area/WG-C4.47-Power-System-Resilience-PSR-WG

6. Conclusion

The ongoing decentralization of power generation, coupled with the inherent change in power transmission topology and usage changes the whole paradigm of power system operation and planning and introduces new observability and controllability possibilities. Power system operators have at their disposals new tools for a better management of all hazards occurring on the grid. Moreover, traditional reliability studies have been proven insufficient to deal with High-Impact, Low-Probability events such as weather-related events. Resilience completes reliability to tackle effectively HILP issues, and to focus also on the post-event recover phase which can be of the paramount importance when high degradation levels are involved.
In this context, this paper has presented a 4 steps resilience assessment method to assess resilience: threat characterization, system's vulnerability assessment, system's reaction assessment and system's restoration implementation. Focusing on hurricanes, all 4 phases have been discussed in detail, and different restoration methods or adaptation strategies have been implemented, namely optimal TTR generation and repair teams dispatch strategies, and grid reinforcement strategies.
The 4SRAM has been shown capable of comparing different restoration methods and assessing a ranking in the improvement brought by these methods. Simple methods such as better repair team management pre and post events have been shown to have an important positive impact on resilience, with limited cost. Adaptation strategies such as grid reinforcement in strategic locations were the most effective regarding resilience improvement, but also the most cost-extensive.
Future work on the topic should involve implementation of the strategy to other hazards such as earthquakes, dynamic electrical simulation instead of AC optimal power flow, and possibly adaptation of the metrics chosen.

7. Acknowledgements

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