Two-level blackout probabilistic risk analysis: application to a test system

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ABSTRACT: Blackouts in power systems are due to cascading outages. Based on the analysis of past events, the typical development of such a cascading failure can be split in two phases. In an initial *slow cascade* phase, an initiating contingency triggers a thermal transient which increases significantly the likelihood of additional contingencies. The loss of additional elements can then trigger an electrical instability. This is at the origin of the subsequent *fast cascade*, where a rapid succession of events can possibly lead the system to blackout. Once a blackout occurred, the recovery period can be viewed as an additional (and last) phase. The blackout PRA can be decomposed in three levels, according to these three phases. Levels I and II were previously developed and applied, but separately. The aim of this paper is to apply a two-level blackout PRA to a small test system in order to study in a coupled way the two phases of a cascading failure.

1 INTRODUCTION

In our society, private and industrial activities increasingly rest on the implicit assumption that electricity is available at any time and at an affordable price. Even if operational data and feedback from the electrical sector is very positive, generation, transmission and distribution of electricity can in no way be considered as totally reliable activities. A residual risk of blackout or undesired load shedding in critical zones remains. The occurrence of such a situation is likely to entail major direct and indirect economical consequences, as observed in recent blackouts. For example, the economic losses of the blackout that happened in the Northeastern area of the United States and in Canada on August 14, 2003 were about $4-10$ billion (approximately 50 million people affected) (U.S.-Canada Power System Outage Task Force 2004). Assessing this residual risk and identifying scenarios likely to lead to these feared situations is crucial to control and optimally reduce this risk of blackout or major system disturbance. The reliability of the grid has been studied from several years on, mainly through quasi-static reliability methods: the different states (or configurations) of the system are analyzed in a static way with an Optimal Power Flow (OPF) to evaluate possible load shedding (complete enumeration of the states, selective enumeration, non-sequential Monte Carlo (MC) simulation or sequential MC simulation) (Billinton and Allan 1996). However, these methods cannot deal with the specific problems of cascading outages leading to blackouts, as they do not account for the constraints imposed to the grid elements in the course of a transient after an initiating event. An adequate method able to consider dependencies between events must be used. We proposed in (Henneaux et al. 2012) such a method, based on the analysis of past blackout developments. Two different approaches are to be used for the two phases of a typical cascade leading to a blackout, by accounting for the different time and process characteristics. These two levels have been applied previously to test systems, but separately. Therefore, the aim of this paper is to apply a two-level blackout Probabilistic Risk Assessment (PRA) to a small test system in order to study in a coupled way the two phases of a cascading failure. As the level I is needed to have an estimation of the frequency of dangerous scenarios and the level II for their magnitudes in terms of loss of supplied power (due to load shedding or blackout), the coupling between these two levels can lead to an estimation of the triplets *{scenario,frequency,magnitude}* for the scenarios leading to an undesirable situation. We will also study the challenges that can appear in such an approach. In particular, we will focus on a clustering technique to group scenarios at the end of the level-I analysis.

The paper is organized as follows. First, Section 2 recalls the main mechanisms likely to lead to a blackout. Section 3 presents the 3-level blackout PRA and the clustering technique. We will then apply the first two levels of this methodology to a test case in Section 4. Finally, Section 5 provides conclusions.

2 BLACKOUTS

A blackout is a total collapse of the electrical grid on a large area leading to a power cutoff. It is due to a cascading failure, following the occurrence of an initiating event (e.g. line fault or loss of a power plant). However, the $N-1$ security rule is applied by Transmission System Operators (TSOs). This rule guarantees that the network state after the loss of one single element must be compatible with the operational security limits and must not lead to the triggering of an uncontrollable cascading outage, taking into account available remedial actions. Therefore, only one contingency should not entail a fast collapse of the electrical grid and at least one more contingency is necessary. Obviously, a second event, independent of the first one can occur before any corrective action. But, as the mean time between two independent failures is high (from some hours to several weeks) compared to the operators characteristic times (tens of minutes to some hours), the probability of such a succession of independent events is usually very low. Therefore, dependencies between events are more likely to explain blackouts.

Some blackouts can be due to multiple initiating events, the occurrence of which directly makes the $N-1$ security rule no longer valid. For example, earthquakes, storms, tower failures can be the cause of the simultaneous (or quasi-simultaneous) loss of several elements, as for the blackout which occurred in November 2009 in Brazil and Paraguay (heavy rains and strong winds caused short-circuits in power transformers, leading to the loss of the Itaipu hydroelectric power plant). Strongly dependent additional contingencies can be due to thermal effects, as for the 2003 blackout in the Northeastern area of the United States and in the Southeastern area of Canada (about 20 high-voltage overhead lines sagged low enough to enter in contact with something below the line between 3 PM and 4 PM (U.S.-Canada Power System Outage Task Force 2004)). Following the occurrence of a first event, the reconfiguration of the power flows in the grid can increase the temperatures of overhead lines, underground cables and transformers (with thermal time constants ranging from tens of minutes to some hours). When the temperature of an overhead line increases, its sag also increases, possibly leading to a short circuit between the line and the vegetation. When the temperature of an underground cable or of a transformer increases, the dielectric strength decreases, possibly leading to a dielectric breakdown. If another element undergoes a thermal failure, the thermal effect on other elements will be reinforced, possibly leading to a cascade. An operator action can also trigger a collapse, as it was the case in the major system perturbation in November 2006 in Europe: based on an incorrect state estimation, a busbar coupling caused a line tripping.

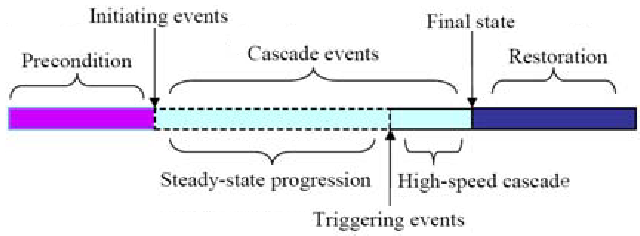

Figure 1: Phases of a blackout. From (Lu et al. 2006).

As explained in (Lu et al. 2006) and in (Henneaux et al. 2012), the typical development of a cascading failure leading to a blackout can then be split in two phases, as illustrated in Figures 1 and 2. Following the occurrence of an initial perturbation (*initiating(s) event(s)*: the loss of one or several elements), two possibilities arise. If this perturbation causes the simultaneous loss of several elements, the $N-1$ rule directly ends up and the system can become electrically unstable (the initiating events are also the triggering events). A fast collapse of the electrical grid can then start. But, in most cases, thanks to the $N-1$ rule, the grid stays electrically stable after the initiating event. A competition then starts between operators corrective actions and possible additional failures, either due to thermal effects or independent. This phase is called *slow cascade* (or *steady-state progression*), because it displays characteristic times between successive events ranging from tens of seconds to hours. The occurrence of additional events during this phase can trigger (after the *triggering event*) an electrical instability (violation of protections set points, angular instability, etc.). Then a second phase called *fast cascade* (or *high-speed cascade*) occurs, ruled by electrical transients, displaying characteristic times between successive events ranging from milliseconds to tens of seconds. This phase is too fast to allow operators to take corrective actions and is characterized by a rapid succession of electrical events (additional failures, protection actions, etc.) whose occurrence order and timing are driven by the power system's dynamic evolution in the course of this transient. After this fast cascade, the electrical grid reaches a stable state: a possible collapse of the power system in some zones, or a major load shedding. Once a blackout or a major load shedding occurred, the recovery period can be viewed as an additional (and last) phase.

3 BLACKOUT PRA IN 3 LEVELS

According to the analysis of previous blackouts and the typical blackout development, we proposed in

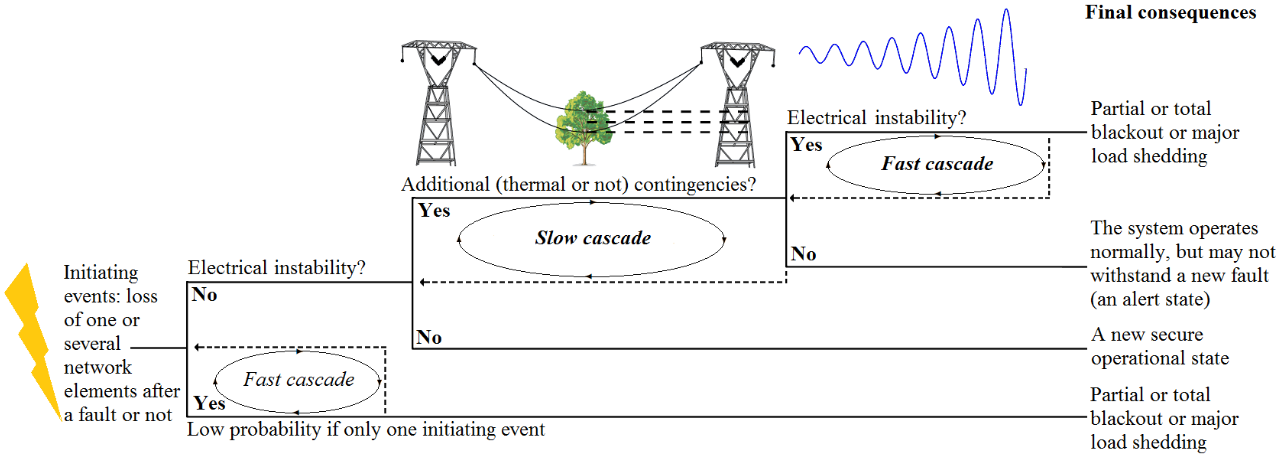

Figure 2: Event tree after an initiating event. Adapted from (Henneaux et al. 2012).

(Henneaux et al. 2012) a methodology for blackout PRA based on dynamic PRA. The main idea of dynamic PRA is to describe the electrical grid not only by discrete states, but also by a set of process variables (like temperatures, currents, voltages, etc.). This allows to consider the mutual interaction between discrete system states and continuous process variables: in each system state, process variables follow a deterministic evolution and transitions between system states depend on process variables. Dynamic PRA then allows to consider dependencies between events through process variables: the failure or the trip of an element can trigger the failure or the trip of another one through process variables. Different methods are to be used for the two phases of a typical cascade leading to a blackout, by accounting for the different time and process characteristics. Thus, the probabilistic risk assessment is decomposed in three levels.

Level-I analysis is the assessment of the slow cascade: it starts with an initiating event and ends either when the electrical dynamics of the system becomes dominant[1] or when the system is put back into a secure state. In this level, we have to take into account the competition between additional failures, due to thermal effect (depending on the thermal transient) or independent and corrective actions: operators will try to eliminate overloads and to come back to a secure state. Electrical time constants are very small compared to thermal time constants and operator actions' characteristic times. This means that, after each transition in the system state during the slow cascade, electrical variables reach their stationary values in a negligible time compared to thermal transients and operators' actions. However, if variations in the values of the electrical variables become important, the power system could become electrically unstable and the fast cascade simulation could then be starting. In conclusion, after any event occurring during the slow cascade (level I), we suppose that electrical variables instantaneously reach their stationary values (if the system remains electrically stable).

Level-II analysis is the assessment of the fast cascade. It starts when the electrical dynamics of the system becomes dominant (the system can then be subject to electrical instability and the steady-state simulation does not capture anymore the grid behavior) and finishes when the system reaches an electrically stable state (blackout state or operational state with load shedding). Interactions between electrical variables and protections and load-shedding relays have to be taken into account, but since the mean time between events is then much smaller than thermal characteristic times, the variation of the temperatures of the grid elements during this phase can be neglected. This time, dynamic PRA must be adapted in order to include the effect of electrical variables (currents, voltages, frequencies ...) on transition rates. Consequently, we suppose that the temperatures are constant, that the variation of electrical variables does not depend on thermal variables and that transition rates depend only on electrical variables. On the contrary, an algorithm for the level-II PRA has to simulate the evolution of electrical variables, and simulate the tripping of elements when the setpoints of their protections are reached by of electrical variables. Misoperation of distance protection systems, involved in the propagation of disturbances, has to be integrated into the approach to provide more trustworthy results. There are globally four kinds of misoperations of distance protections: a relay can fail to trip, the setpoint of a relay can differ from its nominal value, measurement errors can occurs, and a distance protection seeing a faulted line in its backup zone can trip instantaneously instead of doing it after a delay. These misoperations make the evolution of the power system stochastic.

If an operational state with load shedding is reached at the end of the level II, the level I should be restarted. Indeed, any operational state could continue to endure additional failures even if the system was electrically stabilized thanks to load shedding. When the system reaches a both electrically and thermally sta-

[1] i.e. if the system is locally or globally subject to voltage instability, frequency instability or angle instability (transient or small-signal) or if electrical variables violate one or several protections' set points.

ble state, the level-III PRA, which is the assessment of the restoration, starts. The restoration is mainly ruled by operators' actions, through procedures, and electrical transients.

Therefore, level-I PRA reveals vulnerabilities paths (including critical initial conditions and critical initiating events) of an electrical grid, level-II PRA gives the magnitude of possible blackouts (in terms of loss of supplied power) and level-III PRA the consequences (in terms of energy not served). These three levels are shown in Figure 3.

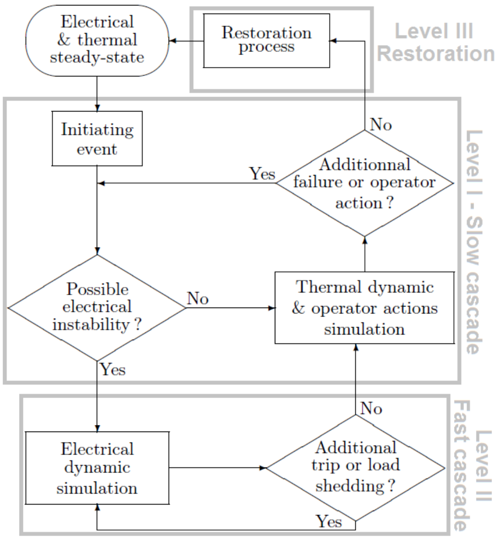

Figure 3: Decomposition of the power system PRA in 3 levels.

3.1 *Level-I PRA*

A Monte Carlo (MC) simulation algorithm for the slow cascade is given in Figure 4. The initial conditions and the initiating event(s) are sampled. The electrical stability is assessed and the steady state computed (if it exists). If the electrical dynamics of the system becomes dominant (local or global possibility of electrical instability), the scenario is called "dangerous" (blackout or major load shedding possible), the slow cascade simulation is stopped and the fast cascade simulation could be started. Otherwise, the thermal transient is simulated. Lines, cables and transformers failure times (either thermal or independent) are sampled as well as operator corrective actions. If a new event occurs before the system is put back into a secure state, the simulation continues with this new contingency: the electrical stability is assessed and the electrical steady state is computed, etc. In the opposite case, the slow cascade simulation is stopped and the scenario is labeled as safe (non-dangerous). In order to run this algorithm, we need to model the evolution of failure rates (or failure probabilities) with temperature, hence the temperature evolution. The effect of a temperature increase is different for overhead lines, for underground cables and for power transformers. For lines, the problem is the sag increase, possibly leading to a short circuit with the ground. For cables and transformers, the issue is the dielectric strength decrease, possibly leading to a dielectric breakdown. The thermal models and thermal failure models used are described in (Henneaux et al. 2012).

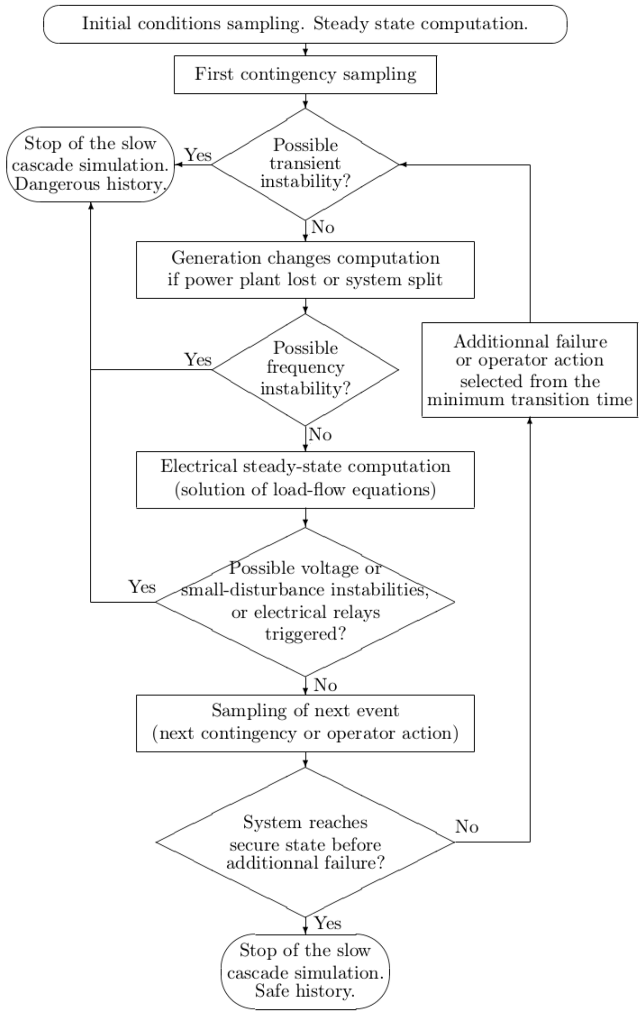

Figure 4: Simulation flowchart of dynamic PRA model - level-I.

3.2 *Level-II PRA*

Discrete Dynamic Event Trees (DDET) were proposed in (Faghihi et al. 2012) to be the core of the scheme used for the fast cascade. After the occurrence of the triggering event (i.e. the last event of the slow cascade), the process variables follow evolution laws associated to the resulting configuration on the so-called mother branch. The process variables' evolution is traced by simulation and new branches are generated at user-specified discrete time intervals due to branching rules (on setpoints, on probabilistic thresholds,...). The development of a scenario is stopped according to specific criteria. Two main stopping criteria are used. First, a maximum time between two successive events is considered to end up the simulation if nothing new occurs during a certain period of time. Secondly, a cut-off probability is defined so that the branches carrying a probability lower than it are truncated. Finally, the frequency of the user-specified absorbing state can be calculated and related scenarios are identified. The method used for the risk analysis of the fast cascade was split in two steps. The first step consists in building a so-called skeleton (i.e. a purely setpoint-based DDET), while the second step consists in integrating the stochastic behavior of distance relays into this skeleton. Finally scenarios leading to blackout are identified and their frequencies are calculated, considering both setpoint-based performance of relays and distance protections' misoperations.

3.3 *Clustering between level-I and level-II PRA*

Applying the level-II analysis on each scenario given by the level-I PRA (which could be viewed as the equivalent of an integrated level 1 - level 2 approach in the nuclear sector) can lead to analyze separately two quasi-identical (or identical) scenarios. As electric dynamic simulations need important computing times (especially for large power systems), it is important to limit the level-II analysis to a minimum set of scenarios while keeping a satisfying accuracy on results. Therefore, we proposed not to analyze each scenario given by the level-I PRA, but to group scenarios into clusters and to analyze only the "equivalent scenario" to each cluster (equivalent to the grouping of level 1 scenarios in "plant damage states" in nuclear PRA).

Only electrical properties are important for the fast cascade (not the ambient temperature, the wind speed, ...). Scenarios can be grouped into clusters on the basis of two considerations. First, the sequence of events during the slow cascade must be the same for all scenarios of a cluster. The clustering can then be applied separately to each sequence of events. Secondly, the electric stationary states before the triggering event must be "similar" for all scenarios of a cluster, which is equivalent to require that load/generation patterns must be "near". This notion of proximity must indeed be defined precisely. The load/generation pattern depends on the active/reactive power generation P_g/Q_g and active/reactive power consumption P_l/Q_l at each bus. The load/generation pattern can then be represented in a $4 \times N_b$-dimension space, where N_b is the number of buses with non-null load and/or generation. The proximity can then be quantified on the basis of distance between points in this space.

Clustering techniques were developed in order to group into clusters points in any multi-dimensional space, on the basis on distance between points. They are used in the nuclear sector in a similar context to "make the dynamic analysis manageable from both a computational and phenomenological viewpoint" (Metzroth et al. 2012) when a dynamic PRA methodology is used. In particular, it is impractical both in the nuclear and the electric sectors to perform a dynamic level-II analysis for all generated level-I sequences. Different clustering techniques are analyzed in (Mandelli 2011) and the Mean-Shift is proven to be well suited for the scenario analysis.

4 RESULTS

4.1 *Test system*

The test system used is shown in Figure 5. It is an adaptation of the *Kundur's Two-Area System* (Kundur 1994). There are 8 power plants with a maximal power of 400 MW for each of them. The peak load connected is 971 MW (and 100 MVAr) into bus 11 and 1787 MW (and 200 MVAr) into bus 13. At peak load, the generated power is 350 MW in each power plant. The load is modulated along the day and the hour (according to load factors[2] given in the IEEE-RTS (Grigg et al. 1999)). The same load factor is applied to each load and each power plant. Overhead lines are protected with overcurrent and distance relays. There are under-frequency and undervoltage load shedding as system protection scheme. Generators are modeled by synchronous machines equipped with IEEE-AC4A excitation systems, power system stabilizers and a gas turbine-governor system. Power plants are protected with over-excitation, under-voltage, under-frequency, over-frequency and loss-of-synchronism relays.

4.2 *Level-I PRA*

4.2.1 *Modeling assumptions*

Some simplifications are adopted to reduce the complexity of the analysis. We choose a unique vegetation height for all lines and all MC runs. For the electrical instability of the system, we do not consider small-signal angular instability. Voltage instability is detected through the non-convergence of load-flow equations, frequency instability through the steady-state frequency deviation, and transient angular instability through the simulation of a simplified dynamic model[3] during several seconds and static violation of overcurrent protections[4]. We consider the system thermally stable if there is no new contingency during 60 minutes. Average failure rates are taken as their nominal values in nominal conditions. Initial conditions (load pattern and climatic conditions, sampled at the beginning of each history) are kept constant during each MC run.

4.2.2 *Results*

The "most dangerous scenarios", which means scenarios leading to electrical instability with the higher frequency are given in Table 1. These scenarios are very simple: they are all two-event scenarios, which

[2] We call here *load factor* the total actual load divided by the total peak load.

[3] A one-axis model for the synchronous machine, with the modeling of the excitation system, and constant-impedance loads.

[4] In case of voltage instability, this "overcurrent instability" is not checked since it is not relevant if load flow iterations did not converge.

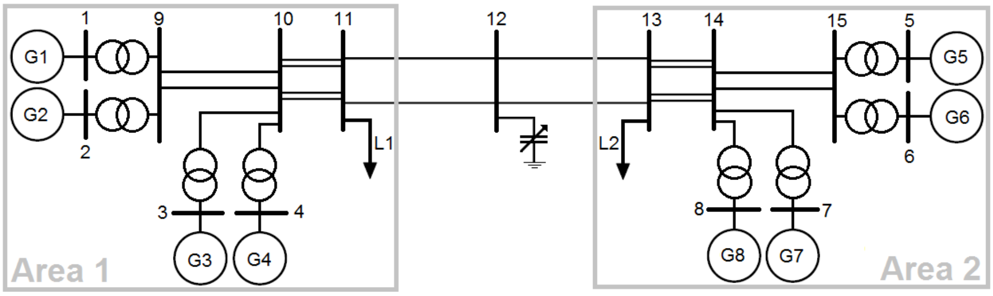

Figure 5: Test system for a two-level blackout risk analysis.

means that the second event is the "triggering event", and they lead to a system splitting. We must note that scenarios are grouped in this Table according to the sequence of occurring events, but several different scenarios (different timings, different load patterns) correspond to each sequence of events. The electrical instabilities triggered by the last event are shown in Figure 6 for each type of level-I scenario. We should note that these electrical instabilities are different from one type to another, but at each time, frequency instability occurs.

Table 1: Most frequent dangerous scenarios revealed by level-I blackout PRA. Each event is a trip of a line after a permanent line fault. Each line is referred by the two buses it connects.

Scenario type	Initiating event	Triggering event	Frequency (/year)
1	14-15	14-15'	1.29E-03
2	9-10	9-10'	1.24E-03
3	12-13	12-13'	2.33E-04
4	11-12	11-12'	2.30E-04

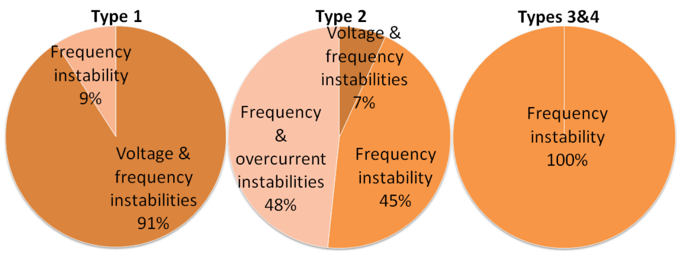

Figure 6: Electrical instabilities per type of level-I dangerous scenarios.

4.3 *Clusters*

In the present case, the complexity of the clustering problem is greatly reduced, since all loads and generations are proportional to the load factor. We can then group level-I into clusters according to only one variable, this load factor or the total load. We propose to use 10 intervals of equal size between the minimum and the maximum loads for each type to serve as clusters. The probability distribution of these 10 clusters per type of level-I dangerous scenarios is shown in Figure 7.

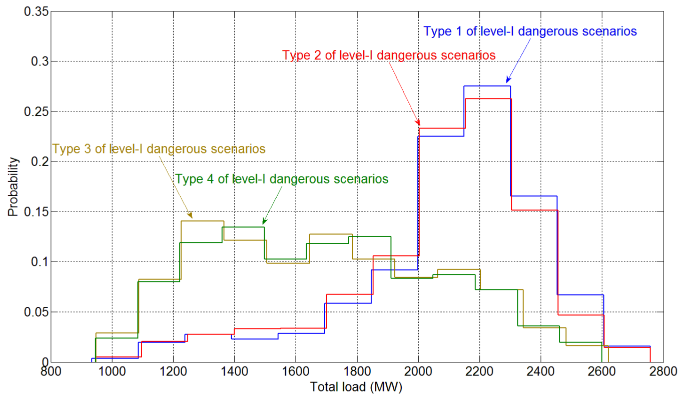

Figure 7: Probability distribution of total load per type of level-I dangerous scenarios.

4.4 *Level-II PRA*

4.4.1 *Modeling assumptions*

Some simplifications are also adopted here to reduce the complexity of the analysis. We consider that the setpoint of a relay is equal to its nominal value (i.e. setpoints are not distributed according to a probabilistic law) and we neglect measurement errors. Power plants' protections are considered perfectly reliable. The on-demand failure probability of lines' protections and load shedding relays are taken respectively to 10^{-2} and 10^{-1}. The maximum time between events (transition or relay failure) is limited to 8 seconds, which means that the system is considered to be electrically stable if nothing new occurs during 8 seconds. The simulation of a branch is stopped when its probability goes under a threshold equal to 10^{-7} (cut-off probability).

The dynamic modeling of the loads[5] can be crucial to give realistic results in case of voltage and/or frequency instabilities. The dynamic behavior depends on the equipments behind the load (motors, discharge lighting, electronics, ...). Then, it varies according to the consumer type (industrial areas, residential areas, commercial areas, ...) and according to the season, the day and the hour. We consider here a simplified model with 30% constant impedance and 70% constant power for both loads at any time. However, in order to solve convergence problems, this constant power is simulated through the re-computation of admittances at each time step according to the voltage at

[5] How the power consumption varies with the frequency and the voltage.

the previous time step.

4.4.2 *Results*

The level-II results for each type of level-I scenarios according to the clusters in Figure 7 are given in Tables 2, 3, 4 and 5. The column "Loss of power (MW)" gives the mean loss of power supplied (either due to load shedding or a blackout) in MW, the columns "Area 1 BO probability" and "Area 2 BO probability" the probability to have a blackout respectively in area 1 and in area 2 (including a total blackout) and the column "Area 1+2 BO probability" the probability to have a total blackout. For low loads, blackout is always avoided, even in case of failure of one or several load shedding relays. On the contrary, for high loads, a total blackout cannot be avoided, even if all load shedding relays work perfectly. Between these two extreme cases, there are transition loads for which a partial and/or a total blackout can occur with a probability lower than 1. These probabilities seem globally to be an increasing function of load, but not monotonously. The transition between low loads and high loads is different for each level-I type of scenarios: for types 1 and 3, it occurs between clusters 3 and 7, but for types 2 and 4, it occurs between clusters 6 and 9.

Table 2: Level-II results by clusters for level-I type 1 (as denoted in Table 1) scenarios.

Cluster #	Loss of power (MW)	Area 1 BO probability	Area 2 BO probability	Area 1+2 BO probability
1	144	0.0000	0.0000	0.0000
2	205	0.0000	0.0000	0.0000
3	289	0.0163	0.1175	0.0163
4	1155	0.0000	0.9997	0.0000
5	1330	0.0059	0.9997	0.0059
6	1659	0.2789	1.0000	0.2789
7	2120	0.9999	1.0000	0.9999
8	2302	1.0000	1.0000	1.0000
9	2485	1.0000	1.0000	1.0000
10	2667	1.0000	1.0000	1.0000

Table 3: Level-II results by clusters for level-I type 2 (as denoted in Table 1) scenarios.

Cluster #	Loss of power (MW)	Area 1 BO probability	Area 2 BO probability	Area 1+2 BO probability
1	142	0.0000	0.0000	0.0000
2	182	0.0000	0.0000	0.0000
3	236	0.0000	0.0000	0.0000
4	296	0.0000	0.0000	0.0000
5	340	0.0000	0.0000	0.0000
6	391	0.0000	0.0000	0.0000
7	465	0.0007	0.0009	0.0007
8	586	0.0199	0.0361	0.0195
9	2475	1.0000	0.9880	0.9880
10	2667	1.0000	1.0000	1.0000

The five branches with the highest risk (product of the probability by the loss of supplied power) of the DET for the cluster 3 of level-I type 1 scenarios are depicted in Figure 8. The voltages at buses 9-15 for the top scenario and for the bottom scenario are given respectively in Figures 9 and 10. In both cases, power

Table 4: Level-II results by clusters for level-I type 3 (as denoted in Table 1) scenarios.

Cluster #	Loss of power (MW)	Area 1 BO probability	Area 2 BO probability	Area 1+2 BO probability
1	121	0.0000	0.0000	0.0000
2	256	0.0000	0.0000	0.0000
3	324	0.0000	0.0279	0.0000
4	583	0.0004	0.2704	0.0001
5	1307	0.0026	0.9997	0.0026
6	1505	0.0644	0.9997	0.0644
7	1927	0.7268	1.0000	0.7268
8	2203	1.0000	1.0000	1.0000
9	2371	1.0000	1.0000	1.0000
10	2538	1.0000	1.0000	1.0000

Table 5: Level-II results by clusters for level-I type 4 (as denoted in Table 1) scenarios.

Cluster #	Loss of power (MW)	Area 1 BO probability	Area 2 BO probability	Area 1+2 BO probability
1	90	0.0000	0.0000	0.0000
2	220	0.0000	0.0000	0.0000
3	244	0.0000	0.0000	0.0000
4	294	0.0000	0.0000	0.0000
5	374	0.0000	0.0000	0.0000
6	436	0.0027	0.0000	0.0000
7	834	0.6721	0.0000	0.0000
8	1033	0.9776	0.0000	0.0000
9	1123	1.0000	0.0000	0.0000
10	2517	1.0000	1.0000	1.0000

plants 5 and 6 are isolated and trip after some seconds (loss of synchronism and over-excitation) at the beginning of the fast cascade. The example 1 corresponds to the scenario where all relays work perfectly. Thanks to several load shedding steps, a partial or a total blackout can be avoided. On the contrary, a load shedding relay failure at the beginning of the example 2 entails a partial blackout in area 2.

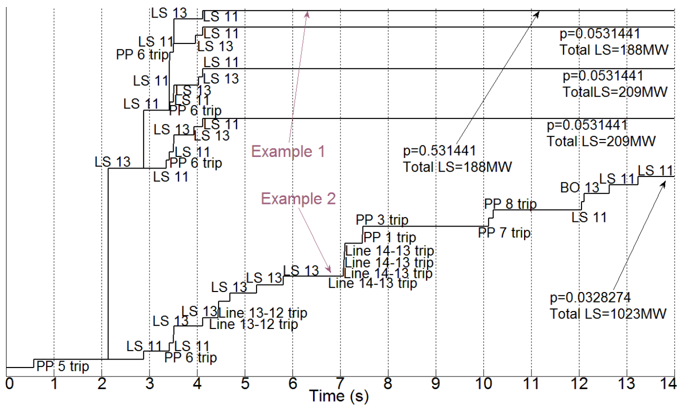

Figure 8: DET main branches for type 1 scenarios, cluster 3. A relay action is represented by a vertical transition. If the relay fails, the branch continues horizontally. The flags "Line $x-y$ trip", "PP x trip", "LS x" and "BO x" indicate respectively that the transition is due to the trip of the line between buses x and y, the trip of the power plant x, a load shedding at bus x or the notification of a blackout state at bus x.

4.5 *First two levels*

From the combination of the first two levels, we can compute the total risk of the loss of power supplied per year and the frequency of a blackout or major load shedding. Table 6 gives the overall risk and the contribution of each level-I type of scenarios. Two main ob-

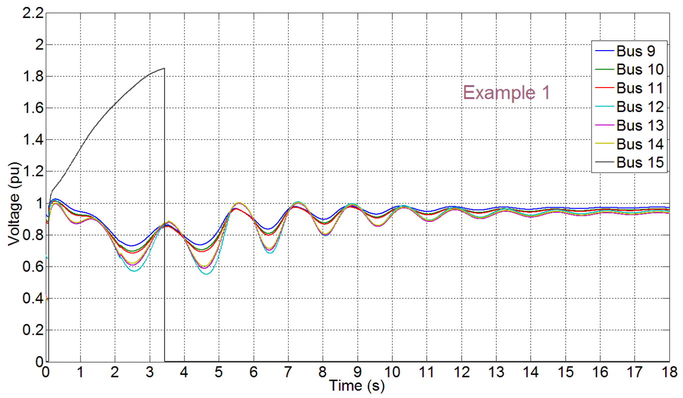

Figure 9: Voltage evolution for type 1 scenarios, cluster 3, example 1. No relay fails and no element (except power plants 5 and 6) is lost. Even if oscillations occur, the voltages are stabilized quickly between 0.9 and 1.0 pu thanks to several load shedding steps. A blackout is avoided.

servations emerge from the comparison between this Table and Table 1. First, two level-I types of scenarios with a similar frequency can induce very different risk and blackout frequencies. Secondly, even if the level-I type 3 scenarios have a frequency one order of magnitude below level-I type 2 scenarios, the blackout frequencies in area 1 are nearly the same for these two types. Therefore, it seems not relevant to rank scenarios only according to the frequency given by level-I PRA, since consequences can be very different from one type to another.

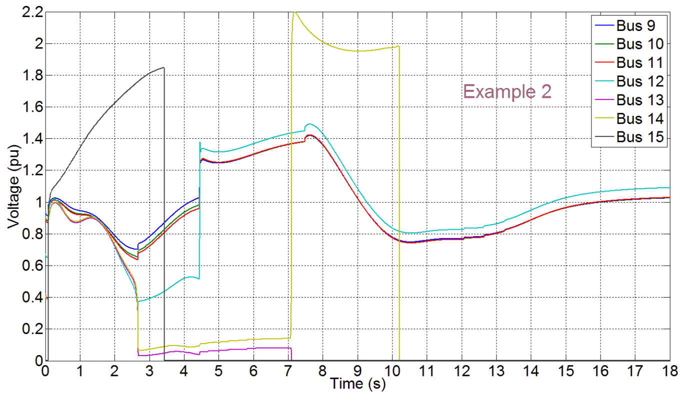

Figure 10: Voltage evolution for type 1 scenarios, cluster 3, example 2. A load shedding relay failure entails very low voltage and high currents, such that distance relays operating in zone 2 disconnect the lines between buses 12 and 13. Over-current relays then trip lines between buses 13 and 14, leading to a BO in area 2.

Table 6: Risk and frequency of blackout.

Type	Risk (MW/year)	Area 1 BO frequency (/yr)	Area 2 BO frequency (/yr)	Area 1+2 BO frequency (/yr)
1	2.537	9.74×10^{-4}	1.21×10^{-3}	9.74×10^{-4}
2	0.832	1.40×10^{-4}	1.44×10^{-4}	1.39×10^{-4}
3	0.264	5.95×10^{-5}	1.36×10^{-4}	5.94×10^{-5}
4	0.121	5.60×10^{-5}	5.19×10^{-6}	5.19×10^{-6}
Total	3.754	1.23×10^{-3}	1.50×10^{-3}	1.18×10^{-3}

5 CONCLUSIONS

This paper applied a two-level blackout PRA to a small test system in order to study in a coupled way the two phases of a cascading failure. As the level I is needed to have an estimation of the frequency of dangerous scenarios and the level II for their magnitudes in terms of loss of supplied power (due to load shedding or blackout), the coupling between these two levels can lead to an estimation of the triplets *{scenario,frequency,magnitude}* for the scenarios leading to an undesirable situation. We showed that the level-II analysis after that level I is necessary to have an estimation of the loss of supplied power that a scenario can lead. The level-III analysis should be developed to estimate the energy not supplied. A clustering technique was also proposed to group scenarios at the end of level I.

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