Reliability Engineering and System Safety 102 (2012) 41–52

Contents lists available at SciVerse ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

A level-1 probabilistic risk assessment to blackout hazard in transmission power systems

Pierre Henneaux *[,1], Pierre-Etienne Labeau, Jean-Claude Maun

École polytechnique de Bruxelles, Université libre de Bruxelles, 50, av FD Roosevelt CP165/84, 1050 Brussels, Belgium

ARTICLE INFO

Article history:
Received 14 September 2011
Received in revised form
10 February 2012
Accepted 24 February 2012
Available online 3 March 2012

Keywords:
Power system reliability
Power system security
Power system stability
Probabilistic risk analysis
Blackout
Monte Carlo methods

ABSTRACT

The blackout risk in power systems is difficult to estimate by actual probabilistic methods because they usually neglect, or do not properly consider, the dependencies between failures and the dynamic evolution of the grid in the course of a transient. Our purpose is therefore to develop an integrated probabilistic approach to blackout analysis, capable of handling the coupling between events in cascading failure, and the dynamic response of the grid to stochastic initiating perturbations. This approach is adapted from dynamic reliability methodologies. This paper focuses on the modeling adopted for the first phase of a blackout, ruled by thermal transients. The goal is to identify dangerous cascading scenarios and better calculate their frequency. A Monte Carlo code specifically developed for this purpose is validated on a test grid. Some dangerous scenarios are presented and their frequency calculated by this method is compared with a more classical estimation neglecting thermal effects, showing significant differences. In particular, our method can reveal dangerous scenarios neglected or underestimated by the more classical method because they do not take into account the increase of failure rates in stress conditions.

1. Introduction

In our modern society, electricity has become a fundamental ingredient of private and industrial activities. But, as regularly observed, a risk of blackout in power systems, or of undesired major load shedding in critical zones, remains, and can entail major economical consequences. Therefore, it is crucial to identify most probable scenarios leading to a blackout in order to avoid them. A blackout is a collapse of the electrical grid on a large area, leading to a power cutoff, and is due to cascading failure. In such a cascade, there is a strong coupling between events. Indeed, the loss of an element increases the stress on other elements and, hence, the probability of additional failure. Current probabilistic methods do not correctly consider these dependencies between failures. Non-sequential methods sample contingencies simultaneously at the beginning of each history. This sampling is based on the basis of average availabilities (average failure rates and average repair rates). Consequences are then evaluated through an optimal power flow (with load shedding) in terms of energy not supplied, average interruption duration, etc. These methods are not adequate to analyze blackouts because they do not take into account dependencies between failures. On the opposite, sequential methods try to consider these dependencies. But, as explained in [1,2], the influence of primary contingencies on the availability of other elements is in general studied in a statistical way. Branching models in the course of the scenario have parameters that estimate an average tendency for the failure to propagate (constant average failure rates in each system state [3], probability to have an overloaded line short-circuited with ground before corrective actions [4,5], etc.). These approaches present some limitations: because they ignore some details of cascading, specific phenomena cannot be accounted for correctly in the course of the incident. Moreover, the parameters used are difficult to estimate because they try to aggregate different competing processes (loss of additional elements, corrective actions), their values can change significantly depending on the context and they require validation by more complex models.

The objective of this paper is to propose a probabilistic methodology able to reveal underestimated dangerous cascading failure and to estimate their frequencies with a satisfying accuracy. This method allows accounting for the peculiarities of the present transmission power system, i.e. the intermittence of decentralized production, the variability in cross-border power transfers, load fluctuations and the geographical distribution of the meshed network including the possible propagation of events on large geographical zones, etc. The methodology will be developed for a specific phase of cascades leading to a blackout, but the

* Corresponding author.
E-mail address: pierre.henneaux@ulb.ac.be (P. Henneaux).
[1] F.R.S.-FNRS Research Fellow ("Aspirant").

0951-8320/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ress.2012.02.007

aim of the general methodology is to provide a Probabilistic Risk Analysis (PRA) convenient for all kind of electrical grids. Consequently, Section 2 analyzes previous blackouts in order to deduce a typical blackout development, Section 3 is devoted to reviewing previous relevant works on power system reliability methods and blackout Probabilistic Risk Analysis (PRA) methods, and Section 4 introduces dynamic PRA which will be used to consider dependencies between events. Section 5 proposes to decompose the power system PRA in three levels and Section 6 presents the methodology adopted for the level I (first phase of blackouts). As an example, the model developed for the level I is applied to a test system in Section 7. Therefore, the methodology developed in Section 6 and applied in Section 7 will reveal scenarios where the heating of lines after a line trip and independent failures when the system is electrically stable are critical issues. The development of the model for the level II should reveal scenarios where dependencies between events are not connected to the thermal transient (e.g. electrical stability problems). Finally, conclusions are presented in Section 8.

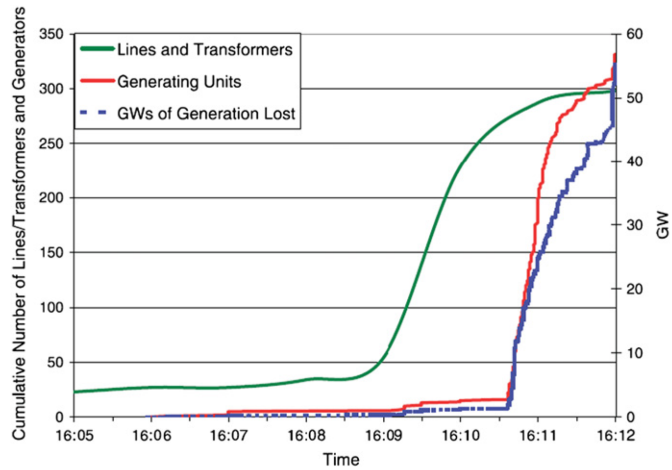

Fig. 1. Rate of line and generator trips during the cascade. From [7].

2. Blackouts

This section will analyze some recent previous blackouts and major system perturbations in order to deduce a typical blackout development. Additional information about these blackouts and other recent blackouts can also be found in [6].

2.1. Previous blackouts and major system perturbations

On August 14, 2003, a few minutes after 4:00 pm Eastern Daylight Time (16:00 EDT), a blackout occurred in the Northeastern area of the United States and in the Southeastern area of Canada. Approximately 50 million people were affected and the economic losses in the United States were in a range between $4 billion and $10 billion [7]. The power was restored only after four days in some part of the United States. The blackout started in Ohio, in the FirstEnergy (FE) area, and rippled in the last part of the cascading failure from the Cleveland–Akron area across much of the Northeast United States and Canada. The initiating event was the tripping of Eastlake Unit 5 in Northern Ohio connected to FE's 345-kV transmission system at 13:31 EDT. Transmission line loadings were then notably higher but well within normal ratings. Three 345-kV lines tripped between 15:05 and 15:41 EDT, due to a contact between the line conductor and a tree. Two of them were not overloaded. Between 15:42:53 EDT and 16:05:55 EDT, several (about 13) 138-kV lines tripped, due to short circuits with ground. At 16:05:57 EDT a 345-kV line tripped on too low apparent impedance in protective zone 3. At 16:06 and 16:08 EDT, three more overloaded 138-kV lines tripped. With another loss of a 345-kV line at 16:08:59 EDT, the rate of trips increased (see Fig. 1) and the cascade spread beyond the Cleveland–Akron area. At 16:13 EDT, the cascading sequence was essentially complete. Many of the key lines which tripped during this phase operated on zone 3 impedance relays which responded to overloads rather than true faults on the grid. Power plants tripped mainly on low voltages or over-excitations, but also on underfrequency and overcurrent. During this cascade, the Midwest Independent System Operator (MISO) state estimator (a system monitoring tool) was unable to assess system conditions. Consequently, operators did not identify fast enough problems in the network in order to take adequate corrective actions.

On September 23, 2003, at 12:36 (local time), a blackout occurred in southern Sweden and eastern Denmark (total non-supplied demand: 1 GWh) [8]. The total demand in Sweden was quite moderate (15,000 MW) due to the unusually warm weather for the season, but several elements (power plants and lines) were in maintenance. The initiating event was the loss of a nuclear power plant (1250 MW) at 12:30 on the eastern coast. Five minutes later, a double busbar fault occurred in a 400-kV substation on the western coast of Sweden. The reason was a thermal damage to one disconnecter device: one of the mechanical joints had been disrupted as a result of overheating. The loading current of the isolator had increased from around 1000 A to some 1500 A following the initiating event (rating for maximum load: 3100 A). About 90 s after the busbar fault, the situation developed into a voltage collapse in a section of the grid and the grid split up in two parts. The southern part (southern Sweden and eastern Denmark) suffered from an important imbalance between power injection to the system and system load. Within seconds, the frequency and voltage had dropped to levels which caused the entire subsystem to collapse.

On September 28, 2003, at 03:28 (local time), a blackout occurred in Italy (about 57 million people affected) [9]. Power was restored only after 18 hours in some part of Italy. The initiating event was the tripping of a 380-kV line between Switzerland and Italy at 03:01:42, due to a tree flashover. This line was loaded at approximately 86% of its maximum capacity. Indeed, all tie-lines[2] between the Italian grid and the rest of the European grid were highly loaded just before the initiating event, because Italy was importing a big amount of power from the Northern border. The attempts of reclosing failed due to an overly high phase angle. After the loss of this line, the load on the neighboring lines increased. At 03:25:21, a second 380-kV line tripped, after flashover with a tree. This line was operating at around 110% of its nominal capacity just after the loss of the first line. From 03:02 to 03:25, operators tried to eliminate the overload: imports from the northern border were reduced. Unfortunately, the thermal transient was faster than operators. At 03:25:25, 03:25:26 and 03:25:28, three 220-kV lines tripped due to high overloads. The Italian grid then lost its synchronism with the UCTE (Union for the Coordination of Electricity Transmission—association of TSOs in Western Europe) main grid which entailed the disconnection of all remaining connecting lines between Italy and UCTE by regular function of the protection devices. The negative imbalance in Italy between power injection to the system and system load caused an abrupt frequency drop. The primary control operation of the generating units increased

[2] A tie-line is a circuit (e.g. a transmission line) connecting two or more control area or systems of an electric system.