Modeling Adequacy for Cascading Failure Analysis

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Abstract—**This paper describes the mechanisms of cascading failure as the cause of severe blackouts. The severe blackouts that occurred in 2003 affecting large metropolitan areas around the globe are first reviewed. Then the probable root cause of each blackout events is identified in order to seek effective corrective preventive solutions. Several of the well-known techniques for cascading failure analysis and correction are discussed and characterized based on their fundamental features. Thereupon a new model power system component is proposed for simulating cascading failure in actual networks.**

I. INTRODUCTION

The long-term development of power system technology resulted in the formation of large-scale interconnected grids in Europe during the last five decades. The integration of the national grids was motivated mainly by the growth in electricity demand alongside the desire to minimize operational costs of the power system yet safeguarding the high level supply of electricity. The Union for the Coordination of Transmission of Electricity (UCTE) synchronous system has experienced a chain of severe power system failures suggesting that the present day power systems are being operated quite close to their stability margins. Such would warrant a search for viable methods capable of preventing severe failures or at least decrease the risk of encountering them before blackouts become widespread.

Large blackouts become widespread by a complex sequence of cascading failures. Cascading failure refers to any components that fail as a result of overloading or activating relays as a result of loading transferred from one affected component to another according to the circuit laws. This kind of failure is typically rare given that the highly anticipated failure has already been accounted for in power system planning design and operational routines. In other words, it is customary in the operation of power systems to ensure that the $N-1$ criterion is fulfilled. Indeed an exhaustive and detailed analysis of these cascading events before the blackouts occur is difficult because of the huge number of possible combinations of unlikely events.

This study concentrates on the identification of modeling needed for adequate representation of cascading failure in power system simulations. In Section II, an overview of major power system cascading failures is first presented with a brief summary of causes of the four major blackouts in year 2003. The common techniques for cascading failure analysis are discussed in Section III followed by an outline of the modeling needs to improve the analysis in Section IV. In Section V, conclusions and recommendations for further research are then drawn out.

II. OVERVIEW OF MAJOR CONTINGENCIES IN YEAR 2003

Power systems are expected to become more heavily loaded to serve the increased demand of electricity consumption. However the upgraded transmission and generation capacity are finding it hard to keep up because of political, economical and environmental constraints. It is also known that liberalized systems lead to an increase of power exchanges among system areas. Such increasing power flows are likely to result in congestions of the transmission grids, as well as in the reduction of security margins [1]. This increase in the power flows has consequently raised the number of customer disconnection events in the past decades. For instance, a series of significant system outages during 2003 in North America and Europe has drawn political and public awareness to the importance of power system security. It is of interest to first have an overview of some of the major blackout events that happened in 2003 which had a dramatic effect not only on power engineering but also in public communities. The major causes and consequences of devastating blackouts in the year 2003 are summarized in the following sections.

A. August 14 - Blackout in North America [2], [3]

Based on the information available from the joint US-Canada task force final report [3], large portions in eight U.S. states and two Canadian provinces experienced an electric power blackout. The first major event started by loss of Eastlake unit 5 and several other generators in Northern Ohio which led to reactive power supply problems. Also, many 345 kV transmission lines were tripped due to tree contact in the area of Ohio and Michigan. Moreover prior to the first event, the system software was inoperative, subsequently preventing operators to have adequate situational awareness. This combination of events reversed power flow and finally heavily loaded the entire transmission system. The outage affected an area with estimated 50 million people and 61,800 MW of electric load was interrupted, which equates to approximately 11% of the total load served in the Eastern Interconnection of the North American system. During this event, over 400 transmission lines and 531 generating units at 261 power plants tripped. The following morning, 16 hours later, 48,800 MW were restored. Hence, some 16,000 MW experienced a longer than 16 hours outage and power was not restored for 4 days in some parts of the United States. Parts of Ontario suffered rolling blackouts for more than a week before full power was restored.

B. August 28 - Blackout in United Kingdom [4], [5]

The event commenced when alarm was raised from a power transformer or its associated shunt reactor that the first transformer had been taken out of service and the load was shifted to the second transformer. However due to an incorrectly installed protection relay specified during the design process, it led to the tripping of the second transformer. As a result 724 MW of the supplies amounting to around 20% sent to London were lost which affected approximately 476,000 customers including parts of underground and railway system. Birmingham experienced similar blackout in just over a week later with 250 MW of load lost and there were 220,000 customers affected including international airport and national exhibition. Although both blackouts lasted only less than an hour, it dramatically affected the mass transportation system.

C. September 23 - Blackout in Sweden and Denmark [6]

A number of inter-connectors and power lines in maintenance including four nuclear units were out of operation prior to event. A loss of a 1250 MW nuclear power plant unit occurred and it was regarded as a manageable contingency. However, with 5 minutes apart, a double busbar fault occurred in a substation that disconnected four out of five 400 kV transmission lines. Increasing flows on the other remaining lines in the system and low voltage in Southern Sweden was interpreted by protection relays as a remote short circuit, and Southern Sweden and Eastern Denmark were completely disconnected from the Central after 90 seconds. It is worth noting that the system is designed to have 15 minutes available to activate the standby reserve after the first critical component fails. A total load losses were approximately 4,700 MW in Sweden and 1,850 MW in Denmark. The restoration took about six hours to be completed.

D. September 28 - Blackout in Italy [1], [7]

The outages started with a 380 kV transmission line between Italy and Switzerland flashovered on to a tree. An automatic and a subsequent manual reclosure were refused to reconnect a line due to the large voltage phase angle across the breaker. Twenty minutes later, a second line tripped due to a tree contact. This initiated a cascade tripping of the remaining lines along Italy-Switzerland border. Italy tried to import more power from France to compensate the loss of the Swiss power corridors but lines became overloaded and tripped as well. The same happened to 220 kV and 380 kV line between Italy-Austria and Italy-Slovenia, respectively. After the separation from the European system (Italy with shortage of 6,400 MW that was the import level before the synchronous disconnection) the frequency decayed to a certain level that made generators trip due to under-frequency instability. As a result, Italy went into a total blackout. The restoration process lasted more than 18 hours before the supply with synchronization was complete effective.

The causes and consequences of mentioned blackout evens are summarized in Table I.

III. DEFINITION OF CASCADING FAILURE AND OVERVIEW OF CASCADING FAILURE ANALYSIS TECHNIQUES

The cascading failure mechanism was found to have originated after a critical component of the system has been removed from service. This removal creates load redistribution to other components which might become overloaded. The overall network is then weakened where further failures are created as a consequence. As such the former would lead to a blackout propagating to degrade the system performance. It can be deduced therefore that cascading failure is among the major causes of large blackouts due to its multiple processes and high number of possible interactions of undesirable events.

Moreover, the universal behavior of load that has high probability in generating cascading failure has been studied in [8]. The results indicate the efficiency drops significantly when buses with high number of connected links are tripped. This hypothesis has been confirmed that the cascading failures are likely to occur with the highest probability in heavy loaded regions with the smallest reserve margins [9].

A number of analysis techniques were developed to address the complexity of cascading failures involved to the power systems blackouts and facilitate their understanding. A plenty of deterministic approaches have been used to reproduce the features of the blackout. However, there are difficulties in predicting the exact location and timing of blackout occurrence hence calling for the result in probabilistic modeling. The analysis presented in this paper can be categorized into two groups which are (*i*) artificial system approach and (*ii*) conventional reliability approach. It is worth noting that all techniques are not reviewed in this paper in depth. Nevertheless, some features of the common and well-known techniques are briefly described in the following subsections.

A. Artificial system dynamics approach

OPA blackout model - One of the techniques to study complex dynamics of blackouts in power systems is ORNL-PSerc-Alaska (OPA) models. In OPA model, cascading algorithm is modeled in term of overload and outages of the lines determined in the context of linear programing, LP, dispatch of a DC load flow [10], [11]. To start the cascade, the random line outages are triggered with the generation and load is re-dispatched by using LP optimization. The load shedding should be avoided by weighting the cost function. Lines are outaged with fixed probability if these lines overloaded during the LP process. This process can be multi-iteration and is terminated when there are no more outages or load flow diverging. TThe model provides information for self-organization that improves the response of the systems which confront with the system that is being increased due to consumption growth as well as being decreased due to the network upgrade. The response can be decomposed into two intrinsic time scales which are slow time scale, of the order of days to years and a fast time scale, of the order

TABLE I
MAJOR CAUSES AND CONSEQUENCES OF BLACKOUT EVENTS

When	Where	Causes	Consequences	$N-2$	Volt. Instab.	Trans. Instab.
Aug 14th	North America	- Inadequate management and lack of situation awareness	Culminating in a blackout of several hundred lines and generation	–	✓	–
Aug 28th	UK	- Installation of an incorrect protective relay	Dramatic effect on local services and transportation system	✓	–	✓
Sep 23rd	Sweden & Denmark	- Protection maloperation - Not foreseen event in dimensioning criteria of the system	Loss of power generation sources and lost of transmission paths	✓	✓	–
Sep 28th	Italy	- Flashover due to tree trips - Unsuccessful re-closure - Miscommunication between system operators	Separation from the UCTE grids	✓	✓	–

of minutes to hours. The slow time scale evolve the upgrade of transmission network as an increment in maximum power flow which coincides with the increasing demand whereas the fast time scale interacts with overloading which might subsequently cascade and lead to a blackout. The model studies the behavior of blackouts that has the characteristic properties of a criticality as further elaborated in [12]. In simple terms, when the power demand is near the critical loading, the blackouts risk increases significantly. It also shows that the mitigation efforts such as increasing the generator capacity margin or improving transmission network, that is the opposing forces tend to curb the system towards criticality.

However, the efforts to mitigate blackout do not guarantee the number of blackout occurrence to be less than the case without any mitigation effort. This is due to a strong nonlinear coupling between the effect of mitigation and the frequency of the occurrence as shown in [13]. Furthermore this implies the difficulty of identifying the effective mitigation measures that successfully improve the performance of the power systems network.

CASCADE model - The study of CASCADE model begins with a system that consists of a number of identical components which are randomly loaded. The parameters such as the initial load, load increase at each component when failure, and initial disturbance are represented in range of upper and lower bounds of component loading [14]. To start the cascade, each component is loaded by its initial load. Then an initial disturbance is applied as a model. This initial disturbance might cause some components to fail by exceeding their threshold limits. When the component is outaged, its fixed amount of load is transferred and subsequent components are overloaded. With the system becoming overloaded thus the cascading process is likely to continue iteratively. It can be concluded that the extent of the cascade depends on their initial component loadings [15]. The cascading process ends when none of the combination between initial load and transferred load of the remaining components is greater than the maximum stability limit.

However, the CASCADE model is too simple to reflect the realistic aspects of power system. It provides only an understanding of a cascading failure mechanism. The main cause is that it disregards the system structure, neglects the times between adjacent failures and generation adaptation during failure, etc. In other words, analysis of this model merely suggests general qualitative behavior that may be present in power system cascading failures [16].

Hidden failure model - By definition, a hidden failure is defined to be a permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event [17]. In other words, if one line trips, all the lines that share the same bus with that line are exposed to the incorrect tripping. To start the cascade, the transmission lines are randomly tripped and DC load flow computed. Then, the line flow constraints are checked for the violation. Next, the probability of incorrect tripping for all lines that connected to the last tripped line is evaluated. The LP load shedding is adopted to keep the system stable. However, the importance sampling method has been used to increase the frequency of rare events of hidden failure with altered probability.

Hidden failure models can be categorized into two types [18] which are line protection hidden failure and voltage-based hidden failure. Line protection hidden failure occurs if any line sharing a bus with a transmission line trips then hidden failures at that line are exposed. If one line trips correctly, then all the lines connected to its ends are exposed to the incorrect tripping [17]. Meanwhile the voltage-based hidden failure is the failure where the generator tripped unnecessarily as an effect of the exciter misconducted by the fault low voltage conditions. In addition the model has also been improved from its previous state when a line is exposed multiple times such that it allows relays to malfunction with equal probabilities on all the line exposures. Yet it would be more likely that malfunction occurs in the first exposure than the subsequent one [19]. The information obtained from the model is a favor of determining locations in the system where protection is sensitive. Therefore, it develops tools that can assist planning system upgrade.

B. Conventional reliability approach

FTA model - A fault tree analysis is a logic diagram that displays the interrelationships between a potential critical event (accident) in a system and the causes for this event [20]. This event is an undesirable event which referred as *top event*. The fault tree analysis is a top-down method that aim to seek causes, *basic events*, or combinations of causes that lead to the contingency. To start analyzing, the problem and the boundary conditions are defined. These conditions include the physical state of the system, initial and external conditions (stresses) and the depth of resolution level of the potential failure causes. The causes are connected, level by level, via a logic gate until all fault events are resulted in the top event. Therefore, the probability of top event is the occurrence which is affected by a function of the probability of the basic events.

The major advantage of the widely used FTA model is its simplicity. Generally speaking, it can be easily comprehended by non-specialists provided that the system complexity can be decomposed into several parts. However the interaction between events cannot be modeled and the repair models, for example limited repair resources or logistic constraints, cannot be adequately represented [21].

Markov Analysis - Markov model describes a system using a set of mutually exclusive states and transitions between these states [22]. The system is represented by one state at a time and a transition from one state to another state is made according to a certain probability distribution. The model implies the assumption of a system event process with no memory. This means that the future states for the system are independent of all past states except the immediately preceding one [23]. The stochastic process of the system also needs to be stationary or time-homogeneous, meaning that the behavior of the system must be the same at all points of time. This leads to the basic characteristic of Markov modeling that the probability of making a transition between two specific states is constant at all times in the model. Markov modeling can be applied to the random behavior of a system that varies discretely or continuously with respect to time. When the time is discrete, the approach is called Markov chain; when the time is continuous the approach is generally known as a Markov process. The result of analysis can be evaluated by summing probabilities of all states that depicts the availability of the system.

Markov model may provide very detailed analysis which is the complete system description can be built in one model. However the analysis is complex and hard to be verified and constructed. The size of model can become very large.

As mentioned earlier, the major deficiency of analysis techniques are briefly described as shown in Table II whereas algorithms and their obtained information are summarized in Table III.

TABLE II
MAJOR DEFICIENCY OF ANALYSIS TECHNIQUES

Techniques	Deficiency
OPA	Small number of nodes in model compared with a real system and self-organization is not guaranteed in some cases.
CASCADE	Physical configuration of the network and the network internal interactions are neglected.
Hidden failure	Below the critical loading, the form of probability distribution of blackout size is not clear.
FTA	Requires different models to represent different events.
Markov Analysis	Analysis complexity increases as the size of the system increases.

IV. MODELING NEEDS FOR CASCADING FAILURE ANALYSIS

Power system blackouts become widespread by a complicated sequence of cascading failures. They are generally triggered by random events ranging from multiple equipment failures and protective relays play a central role in the course of cascading events as shown in Fig. 1. This section of the paper provides a comprehensive practical treatment of the modeling that will identify the modeling needs for adequate representation of cascading failure in power system simulations.

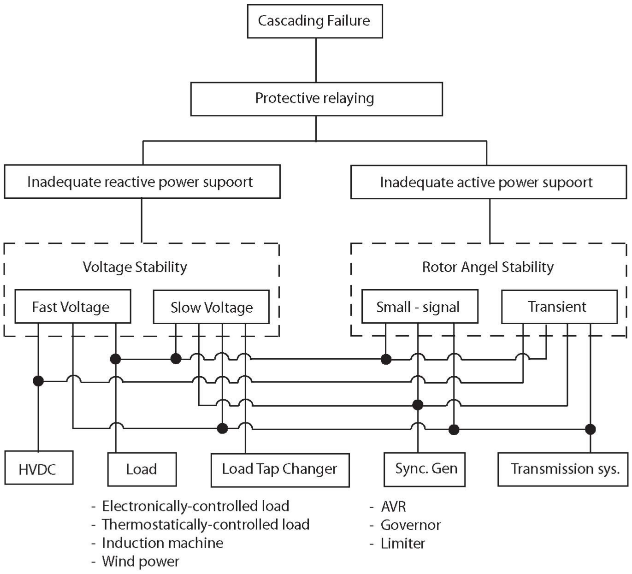

Fig. 1. Flow chart of components leading to cascading failure

The following items are the significant components required to be modeled before triggering series of cascading events:

- **Generator modeling** describes the behaviors of generator during different disturbances in a system. The order of model could be two to four orders which are classical models, one-axis or two-axis, respectively. The number of order is dominant the accuracy of outputs, however its

TABLE III
CASCADING FAILURE ANALYSIS TECHNIQUES AND OBTAINED INFORMATION

Approach	Technique	Algorithm & Purposes
Artificial System	OPA	Using standard DC power flow with solving power dispatch using LP method to satisfy restriction constrains. It is useful to determine the critical point of load demand [12] and to formulating the blackout mitigation effort. [13]
	CASCADE	Applying initial disturbance to identical components which randomly loaded. The failed-component transfers fix amount of load to other components with DC load flow checking an overloading to understand the propagation of failure. [15]
	Hidden Failure	Line is randomly tripped with DC load flow checking an overloading to determine locations where protection is likely to be malfunction.
Conventional Reliability	FTA	A top-down logic diagram displays and compute the probability of the interrelationships of potential events lead to the contingency.
	Markov Analysis	Stochastic process with the Markov properties which are memory less and time-homogenous. The result is the summing of probabilities for all system states represents the probability of dangerous failure.

trade off is computational time. More details of generator model can be found from [24].

- **Generator control systems** such as excitation system consists of an exciter and voltage regulator for example, an Automatic Voltage Regulator (AVR). Another various types of additional controls that can be applied are prime mover, governor, power system stabilizer (PSS), rotor and stator current limiters, under-excitation limiter, etc. The generator control systems must be modeled properly to portray the accuracy of dynamic behavior of the systems when subjected to disturbances. It is necessary to consider the control systems when placed in a system rather than considering them separately. The simulation results in [25] shows that consideration of separate machine may exhibit stable characteristic whereas introducing mechanical oscillations when places in a system.
- **Protective relays** are often classified according to the object that they protect. Normally, distance relays are suitable for meshed systems because they are designed with regard for their own unreliability. They provide good selectivity a number of steps (zones) with different time delays and sensitivities usually defined. For instance, three zones are simply defined, with the setting of 85%, 120%, and 150% in the impedance plane, respectively. When the apparent impedance, as seen from the line end towards the line, reaches the outer zone, the time delay starts. The clock of time delay is reset as soon as the impedance is outside that zone. For each of the zones a certain time limit is being defined. If the impedance value is within a zone and the time expires, the line breaker will immediately open. In addition, the time limit normally includes the breaker time.
- **Load modeling** may represent a mixture of various equipments. The load is affected by a number of factors such as voltage and frequency, dynamic properties, spontaneous variations due to consumer actions, etc. The difficulty to construct dynamic load is inadequacy of input data. Hence due to its simplicity, the common load modeling is average load.
- **Transformer modeling** is modeled by the impedance and the tap changer ratio. The transformer may be configured with a tap changer however the step of tap changer can be fixed to represent normal type of transformer. For simplicity, the steps between the taps are assumed to be equal. The control unit operates in either manual mode or automatic voltage control mode. Both in manual and automatic mode, the mechanical delay of the tap changer must be taken into account.
- **Sectioning of the busbars or Load shedding** can be modeled by considering frequency deviation. Load will be disconnected when the busbar frequency is below a certain value for a certain time. Although only one frequency level can be defined for each load, a large load shedding scheme may be modeled. It is achieved by defining several loads at each busbar. All of them can have individual load shedding models. However load shedding, sometimes, being considered as last defense due to economic policy.
- **Shunt capacitor and inductor** can be modeled as separate object. This separate object can be done by connecting the shunt elements to separate busbars. Shunt elements are modeled as shunt admittances and the control capability of elements should be able to select either automatically or manually.
- **Uncertainty in the systems** such as operator error, hidden failure (malfunction), or miscommunication can be curbed by setting a certain value of safety margin.
- **Special Protection Schemes (SPS)** is designed to detect abnormal system conditions and take predetermined, corrective action (other than the isolation of faulted elements) to preserve system integrity and provide acceptable system performance [26]. It reinforces system protection and emergency control to counteract power system instability. By providing guidance on how protective measures can be used, the power system instability can be avoided after unforeseen events. It can be modeled,

for example, activated relays trip generators to increase power transfer limit between interconnected area when severe faults occur during stressed operational conditions.

It is worth noting that the entire system must be modeled in such a way to satisfy $N-1$ criterion. The model will be unrealistic if cascading tripping of lines in case of stability disturbances is performed when one of the critical components of the system is removed from the service.

V. CONCLUSIONS

This paper presents an overview of major contingencies in the year 2003. The goal of this overview is to identify the dominating causes that generate catastrophes and to classify the instability type. The classification is helpful in seeking the lines of blackout prevention, as well as in seeking effective operating procedures and development of a corrective plan when needed. Cascading failures have involved in those mentioned blackouts. It is not involved only direct failure which is component failure but also indirect failure such as human errors, the unavailable of support tool, or inappropriate procedure, etc. Thereby, several of analysis techniques have been introduced to study key aspects of propagation mechanisms with the purpose of maximizing stability margin of the networks. Intensive contingency analysis of power systems is the first step towards a better understanding of the cascading failures mechanisms.

In the contingency analysis, a number of failed scenarios are defined and tested in simulations. However, simulating cascading failures is always a difficult task. Many system components, such as the protective relays which are suspected to be the main components involved in the mechanisms, the generation units which are involved in term of transient stability or the load modeling which related to the voltage stability, must be modeled in such a way that they are suitable for simulations. The proper component modeling is of paramount importance to making the simulations as close as possible to the realistic cases.

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