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A critical review of cascading failure analysis and modeling of power system

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ABSTRACT

Cascading failure analysis in power systems draws a wide attention from researchers due to frequent occurrence of blackouts all over the world during past decades. A variety of mathematical models and analysis tools have been proposed in order to better understand the complicated mechanisms during the cascading failure. This paper provides a brief overview on cascading failure analysis and categorizes the most relevant literatures and analysis models. Different features related to cascading failures have been demonstrated and discussed. Comparisons between different models have been presented. Advantages and disadvantages of these models are summarized. The paper also highlights the possible future trends.

1. Introduction

Power system, one of the most complex networks in modern society, plays a significant role in our daily life. The rapid evolution of its size and diversity, as well as the emergence of the smart grid, has brought many challenges including stability issues and the subsequent occurrence of blackouts [1]. Such blackouts are not so frequent, but substantially risky due to their catastrophic effects. For example, a large blackout happened on August 14, 2003 in areas of Midwest and Northeast United States, and Ontario in Canada with approximately 50 million people affected and total cost up to 10 billion U.S. dollars [2]. A vivid satellite photograph of the blackout is illustrated in Fig. 1, in which a total black zone can be found in the northeast [3]. On November 4, 2006, a similar blackout, which initiated from Germany, finally resulted in a large blackout across Europe [4]. A summary of major blackouts occurred in recent years is presented in Table 1 [1,2] [4–10],. These severe events draw wide attention from both academia and industry. Such large blackouts are more complicated than normal electric outages that are caused by small disturbances. Actually, these major blackouts are due to complex mechanisms rather than simple component failures.

Cascading failure is found to be the key factor leading to a large blackout from the reports of those blackouts [1,2], and [4]. According to North American Electric Reliability Corporation (NERC), a cascading failure is “the uncontrolled successive loss of system elements triggered by an incident at any location [11–14].” Actually, sometimes the cascading failure is initiated by more than one disturbance. Some cascading failures stop before they have a large effect on power system, while there are still many cases that disastrous events finally occur. In reality, most electric power grids are using N-1 secure criterion, which means the system could keep working under normal status with a single failure [15]. Nevertheless, other possible failures, such as hidden failures in relays or errors during operating procedures, may enlarge the failure and trigger more components, finally lead to a cascading failure. Generally speaking, the failure of components will cause the redistribution of the power flow in the power system, and then lead to the overload of other transmission lines or dynamic instability problems of generation units, thus forming the cascading failure and eventually affect a very large area.

The complex mechanisms during the cascading failure make it difficult to analyze through conventional power system analysis approaches and models. The consequence of this is the emergence of many researchers and research groups, as well as a variety of novel models and analysis tools, focusing on understanding, prediction, prevention, mitigation and restoration of cascading failures [12–14]. The research and analysis tools are plenty, while the summary and comparison among them are scarce. The aim of this paper is to briefly review these researches, disseminate the state-of-art cascading failure analysis tools and models, and highlight the future challenges.

The remainder of this paper is organized as follows. Section 2 introduces an overview from different perspectives on cascading failures. Section 3 presents various state of the art cascading failure analysis models. The comparison between them and their advantages and disadvantages are demonstrated as well. In Section 4, conclusions, discussions and future trends are summarized.

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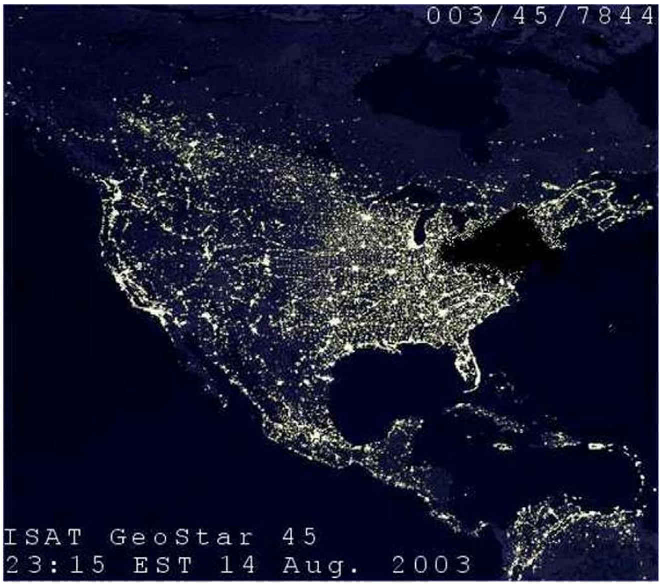

Fig. 1. The satellite photograph shows a totally black zone in the northeast of North America.

2. Overview on cascading failure

Cascading failure involves a large amount of complicated mechanisms, which makes the thorough understanding of the whole event a great challenge. This section demonstrates an overview from different perspectives on cascading failure and highlights the challenges on its analysis and modeling.

2.1. Causes

There are various causes for a cascading failure [12]. Exogenous disturbances that initiate the event, and endogenous events that trigger the components can be generally classified as four groups:

- Nature disasters: Lightening strike, strong winds (tornado, hurricane), earthquakes;
- Human activity: Errors caused by human misoperations, inappropriate setting for protection devices, intentional physical or cyber-attacks on power grids;
- Unexpected component failures: Hidden failures (exposed during changing operation status), transmission line that contact vegetation;
- System failures: Distance relays trigger the transmission line due to overcurrent or undervoltage, voltage collapse, abnormal excitation in generators, abnormal speed in generators, generators tripped by under-frequency, generators tripped by under-voltage, generators tripped by out-of-step, insufficient reactive power, small signal instability;

The first three groups are common failures that initiate the events, whereas the fourth group are failures that commonly exacerbate the cascading. The first and second group of failures are unlikely to be prevented with modern technology. The third and fourth groups are dependent failures that would be involved in most cascading failure blackouts.

The various and stochastic causes are challenging cascading failure analysis models on simulating all of these mechanisms. Quite a lot of approaches and models have been provided trying to take them into consideration [16–35] [91–161],. Some are using stochastic approaches to simulate uncertainties in a cascading failure. Some are modeling dynamics of system to involve voltage and machine problems. High-level statistical models have also been provided in order to estimate the average cascading propagation and blackout distribution sizes. Interdependent infrastructures are modeled to analyze the interactions between power networks and cyber networks during the cascading failure.

2.2. Procedure

During the cascading, the complex procedure and the complicated mechanisms are also great challenges. According to [16], cascading failure can be divided into two phases, namely slow cascade and fast cascade.

For the slow cascade phase, the failure cascades slowly and gives rise to little effect on power system stability. This phase ranges from several minutes up to several hours. Most failures during this phase are common problems that operators are hardly aware of their impact, thus missing the chance to prevent the cascading. Besides, some hidden failures may be exposed during this phase, which trigger some important devices or transmission lines. In [36], the author showed that the relays with hidden failures work normally under stable conditions. When a transmission line is tripped, all the transmission lines connected to its ends are exposed to incorrect tripping. Overload transmission lines that eventually touch trees or ground due to high temperature are also likely to occur during this phase.

Table 1
List of major blackouts since 2003.

Blackout Llocation	Date	People affected (Millions)	Loss of load (MW)	Estimated cost (Million Dollars)	Time duration	Improvements after blackout
Kenya	7 June 2016	44	N.A.	N.A.	< 3 h	N.A.
Sri Lanka	13 March 2016	21	800	N.A.	> 4 h	Adopting ‘must run units’
Turkey	31 March 2015	70	32.2	700	> 7 h	Improve overload monitoring and protection of transmission lines
India	30–31 July 2012	670	48	6000	2–8 h	New load shedding strategies
Brazil	4 February 2011	40	8.884	N.A.	> 3 h	Implement new islanding protection scheme
Brazil and Paraguay	10–11 November 2009	87	24,436	N.A.	4–6 h	Introduce House Load Operation (HLO) and new restoration strategies
Colombia	26 April 2007	41	6.644	130	> 4 h	Improvements of communication channels among the control centres
Europe	4 November 2006	45	14.5	N.A.	2 h	Amendments UCTE Operation Handbook
Pakistan	24 September 2006	160	11.16	N.A.	5–6 h	N.A.
Italy	28 September 2003	57	24	1200	5–9 h	Implement Day-Ahead Congestion Forecast (DACF)
London	28 August 2003	0.5	724	N.A.	> 30 mins	Enhance cooperation between utility companies
North America	14–15 August 2003	50	61.8	Over 10,000	5–72 h	Introduce higher reliability standards for North American electricity industry