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Modeling and impact analysis of interdependent characteristics on cascading failures in smart grids

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ABSTRACT

Smart grids are increasingly interactive with communication networks and have even become interdependent networks. The majority of previous research has assumed that a minor failure might evolve into cascading failures through interactive interdependency. However, in the interdependent power grids and communication networks, the point-to-point interdependency is embedded based on certain topological characteristics rather than at random. This paper aims to analyze the impacts of different interdependencies and structure characteristics of communication networks on cascading failures in power grids. An interactive cascading model for power grids and coupled communications systems is proposed based on the redistribution of DC power flow and the routing of the open shortest path first (OSPF) strategy with consideration of the abnormal transmission, and the interdependency is analyzed numerically. Quantification of the different types of interdependencies illustrates that greater interdependency leads to a lower probability of a large blackout. Furthermore, a threshold value for the transmission inefficiency of communication networks is shown in the cascading process. The most of the power system can be functional when the transmission inefficiency is under the threshold value. Comparison of the threshold values in the double-star and the mesh communication networks illustrates that the heterogeneous characteristics of the double-star structure provide better control to mitigate cascading failures.

1. Introduction

The smart grid is increasingly dependent on and interactive with the communication networks, and the two are becoming interdependent networks [1]. Cascading failures in interdependent networks have been observed several times during recent decades [2]. For example, for the blackout that occurred in Italy in 2003, some communication nodes were initially lost because of the shutdown of the corresponding power stations. As a result, some information was lost and more power stations went into blackout, eventually leading to catastrophic conditions [3]. A similar accident within Northeast America in 2003 was essentially caused by a software bug.

The research conducted to date has largely attempted to address the importance of the interdependency and modeled the interdependency using Petri nets, co-simulation and complex networks [2,4,5]. The interdependency was presented as the process in which any failure of physical nodes caused the failure of the interdependent cyber nodes, and vice versa [3,5]. Ref. [6] provided the physical understanding of the extreme events caused by the interdependency based on the betweenness and degree distribution. Many works tried to describe the mechanism of cascading process and to improve the robust against the cascading failure of power systems [7,8]. The approaches to assess the contingency with different topological properties and operational parameters were studied in the past few years, such as the small cluster [9], Q-learning-based analysis [10], K-reliability analysis [11]. The attack vulnerability was studied extensively through the novel metrics such as the risk graph [12], and the component interdependency graph [13]. Those pioneering work further demonstrated that the cascading process could be accelerated by the interdependency. Ref. [14] pointed out that the cascading failures should be modeled based on both inner-dependency and interdependency. However, for interdependent power systems, the isolation of communication nodes did not cause a blackout [15]. The interdependency should be a type of interactive relationship among power flow redistributions, cyber reliability and optimal control from the dispatch center [16].

The interdependent works with different structure characteristics, the coupling methods and attack strategy were studied to improve the robust against the cascading failures: Ref. [17] noted

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that the betweenness and degree were the essential structure parameters for designing robust interdependent networks. The strength of the interdependency, which was reflected by the degree heterogeneity or similarity, was essential impact on vulnerability [18,19]. The load-based attack and link-based attack made the multi-layer system more vulnerable than degree-based attack [12,20,21]. Ref. [22,23] addressed the fact that different types of interdependencies might lead to different collapses in a system. In practice, the critical nodes tend to couple with the critical node [24,25]. Thus, by classifying and then quantifying different types of interdependencies, an approach to analyze their impacts on cascading failures can be established.

We analytically investigate the interactions between power grids and communication systems to determine the impacts of the interdependencies and structural features on cascading failures. A three-layer topological model is proposed according to the actual structural properties of communication networks in China. By quantifying different types of interdependencies, the cascading failure model is then modeled based on the redistribution of DC power flow and data exchange considering abnormal transmission. The impacts of interdependency and structural features on the blackout are discussed in detail.

The remainder of the paper is organized as follows: in Section 2, we introduce the interactive mechanism and framework for interactive cascading failure simulation. The three-layered topological model of communication networks and the data exchanging model are described in Section 3. The mathematical approach to calculating different types of interdependencies is detailed in Section 4. Case studies are presented in Section 5. The conclusions are given in Section 6.

2. Cascading failure model in the interdependent power grid and communication networks

2.1. Interactive mechanism in cascading failures

The interactive mechanism is summarized in Fig. 1. At the beginning of cascading failures, a small failure in power grids not only leads to the hidden failures in protections but also has a small probability of bringing the faults to communication nodes and telecommunication links. The communication network appears to still be operable because of the uninterrupted power supply (UPS); however, some communication functions might be infected and disabled in some extreme cases, such as the transformer exploding due to an intentional attack and plant shutdown due to an earthquake.

During the cascading failure process, the emerging of few non-self-supply islands causes power flow redistributions, which stresses the capacity of the power supply and transmission. The disconnections of more overloaded transmission lines cause to the topology to become fractal and thus have a small probability of causing the communication topology to act as several smaller clusters. The functions disabled in some communication nodes or telecommunication links are harmful to the implementation of control for power grids.

The reaction time of an effective control from the dispatch center is essential to mitigate cascading failures. However, the emerging failures in power systems rapidly increase the amount of data in the communication networks. The changes in power grids and communication network topologies make the situation worse. Facing the problem of delayed and lost data, the efficiency of data transfer is changed [3]. In this paper, we define such deficient transferring behaviors as abnormal transmissions. All of these behaviors may lead to control failure and evolve into a catastrophe.

2.2. Interactive cascading failure model

First, we attempted to model the power flow redistribution and its influences on protective actions. The inverse-time overcurrent protection was used as an index to determine whether certain overloaded lines were tripped during the cascading failure. When some transmission lines are outage, the redistribution of power flow might result in some lines overloaded or running out of hot limited. We assume that the time t_{ij} allowed for the overloaded transmission lines to continue working is shorter if the power flows are larger as (1) [16]. The relationship between time step t_{ij} and the power flow is shown in Fig. 2. At any time t, if some transmission lines ij are overloaded, calculate the inverse-time t_{ij} as (1) and let $t = t + 1$; if $t_{ij} < t$, the overloaded line is tripped.

$$tij = \frac{K}{|Iij/Isetij|^{\alpha} - 1} \qquad (1)$$

where K and α are constants and I_{ij} and I_{setij} are the current and setting current, respectively. We used $K = 7$, $\alpha = 0.3$ in the simulation to minimize the influences from the difference of the protections on the cascading failures.

Second, we modeled the data exchange. At any time t, the abnormal message packets of the overloaded transmission line or thermally failed line are generated by its corresponding communication node B_i, which is defined as the source node. The message packet is sent to the dispatch center step by step. If the dispatch center is in its neighbor set, the message packets are sent to the dispatch center directly at the next time increment. Otherwise, at the next time step, $t = t + 1$, the message packet is sent from the source node B_i to one of its neighbor nodes B_j (node $B_j \varepsilon L_i$, L_i is the neighbor node sets of B_i) based on the chosen probability P_j as (2) [26]. Such a data exchanging model obeys the first-in,

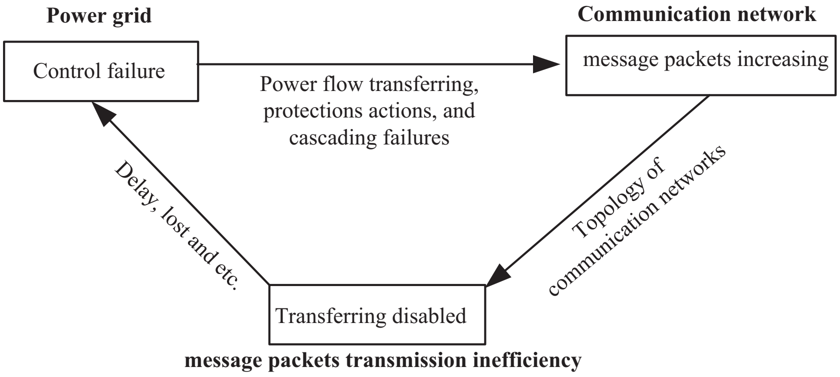

Fig. 1. Interactive mechanism in the cascading failures of interdependent power grids and communication networks.