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Long-term effect of different topology evolutions on blackouts in power grid

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ABSTRACT

The topology evolution is a significant characteristic of a network. However, its long-term effect on blackouts in the power grid is rarely analyzed in the simulation of cascading failures. Therefore, in this paper, a topology evolution model of the power grid is proposed to investigate the correlation between topology evolution and large blackout. The model is built by integrating topology evolution into the OPA model proposed by researchers at Oak Ridge National Laboratory (ORNL), Power System Engineering Research Center of Wisconsin University (PSERC) and Alaska University (Alaska). Three topological parameters are employed to quantify the topology characteristics in the evolution. Simulation results show that the probability of large blackouts in a power grid can be reduced by separately changing any one of these topological parameters. But in most cases, the variation of one topological parameter may cause simultaneous deviations on the other two, which might have opposite effects on the probability distribution of blackout. Also, in realistic power systems, the topology varies with the construction of transmission lines. Simulation results indicate that it is better to link a new bus, e.g. a substation or a power plant, with a low-degree bus than a high-degree bus, in order to mitigate the risk of large-scale blackout, but it is not to link the new bus to the one with the lowest degree.

Introduction

With the rapid development of global economy, the interconnected power grid has become one of the largest and most complex modern artificial networks in the world. Unfortunately, its capability of transferring electric power over hundreds of miles also leads to the evolution of local failures to be grid-wide events and even triggers serious consequences [1]. Some examples of such extreme events are the August 2003 blackout in Northeastern America [2] and the November 2006 European blackout, etc.

It is well recognized that cascading phenomena are complicated and thus establishing a very detailed model of all possible failures and their interactions is challenging. Therefore, network theory approaches, which are more simplified but effective, have been widely used to research the dynamics of failures. For example, Watts [3] showed that a typical electric power network is a small-world network and explored the bimodal-size distribution of cascades in this network. Chassin and Posse [4] examined the reliability of electric transmission systems using a scale-free model of network topology and failure propagation. A model called extended betweenness that combines network structure with electrical characteristics was proposed by Yan et al. to evaluate the vulnerability of the power system components [5], and then the structural vulnerability of real power grids, such as the North American power grid [6], the interconnected power grid of continental Europe [7] and the Nordic power grid [8], was studied by means of topological measures. It was found in [9] that there seems to exist a positive correlation between static topological robustness measures and real non-topological reliability measures, such as energy not supplied, total loss of power and equivalent time of interruption.

However, it is noted that the topology characteristics of a power grid are not constant in practice, but evolving all the time. And there is hardly any analysis of the long-term effect of the variation of topology characteristics on blackouts. In this paper, we will investigate the influence of the formation process of power grids' topology characteristics on the blackout distribution by building a power grid topology evolution model. Moreover, the strategy for mitigating large blackouts is suggested. The proposed model is mainly based on the OPA model because it considers a power grid as an evolving grid that is continually upgrading to satisfy

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Nomenclature

k	degree of a node
C	average clustering coefficient
L	average path length
τ	probability for a transmission line outage due to external physical cause
η	probability for dispatching center false operation due to breakdown of the EMS
P_f	probability of failing to operate relay protection
P_u	base probability of unwanted operation of relay protection
λ	average daily growth rate of load demand
ε	load rate of weak lines
μ	increment rate of transmission capacity
N_{sub}	number of newly-built substations per year
p_{new}	probability of building a new power plant
ρ	redundancy coefficient of transmission line capacity
θ	preferential exponent
m	number of edges of newly-added nodes
n	total number of nodes in a power grid

the increasing load demands and reliability requirements. But the present OPA model and its variants [10–13] only simulate cascading failures in fixed grids, which is not in accordance with the aim of this paper. Therefore, an enhanced OPA model is proposed by integrating the topology evolution of a power grid into it to examine the long-term impact of topology evolution on cascading failures and large blackouts. Meanwhile, DC power flow is employed in modeling cascading line overloads because it is an acceptable approximation of real power flows; moreover, the amount of DC power flow calculation is relatively small, and it has no convergence problem.

The rest of this paper is organized as follows: Firstly, the traditional OPA model is reviewed in Section ‘A review of OPA model’; Secondly, the topology evolution model of the power grid is presented in Section ‘Power grid topology evolution model’; Thirdly, characteristic topological measures are illustrated in Section ‘Topology characteristics of power grid’; Fourthly, the impact of topology evolutions on cascading failures and large blackouts is discussed in Section ‘Cascading failures in topology evolution model’; Finally, conclusions are drawn in Section ‘Conclusions’.

A review of OPA model

The OPA model is built upon the Self-Organized Criticality (SOC) theory and contains dynamics on two different time scales. One is a fast time scale of minutes to hours, over which cascading transmission line overloads or outages may lead to blackout. The other is a slow time scale of days to years, over which load power demand slowly increases and the network is upgraded in response to its increase. Several papers extend the OPA simulation in various ways. And it has been well improved in [13] by exploiting the hidden failure model in cascading overloads and load forecasting in transmission line updates. The two timescale dynamics is demonstrated as follows:

Fast timescales

Cascading blackouts are modeled by the overloads and outages of transmission lines determined in the context of a standard DC load flow model of the electric power network, in which power flow and generator power dispatch are optimized by linear programming (LP). Each simulated cascade, i.e. the cascade at day T, starts from an initial disturbance modeled by independently tripping each line with probability τ. And there is only one simulated cascade per day. If any line trips, a DC load flow will be calculated. If there are some lines whose power flows are beyond the limits, the standard linear programming of generation re-dispatch [16] is executed to make sure there is no line overloaded. Otherwise, the simulated cascade stops. The linear programming of the generation re-dispatch could shed load, so a large weighting factor in the cost function should be employed so that load shedding could be avoided. The LP re-dispatch might not be executed due to the communication interruption or the breakdown of the EMS, so it is assumed that the failure rate of the dispatching center is denoted by η. If the re-dispatch is not implemented, the relay protection acts. However, the relay protection is not 100% dependable either. It is assumed that the probability of failing to operate relay protection is P_f. And normal lines are also possible to be tripped in a real power system, though the probability of unwanted operations and failures of the relay protection is usually less than 0.01. As a result, we set the probability to $P_u \times (F/F^{\max})^{10}$, where P_u is the base probability of unwanted operation of relay protection and $|F/F^{\max}|$ is the load rate of the transmission line. If there is any outage line, the load flow and re-dispatch are solved again until no further lines outage. For each simulated cascade, the total amount of load shed is recorded. It is noted that not every simulated cascade produces significant cascading, and tripping lines or shedding loads may not occur in a simulated cascade.

Slow timescales

In the long run, loads are bound to rise. For simplicity, the gradual growth in load is modeled by multiplying all loads by a fixed parameter λ which denotes the average daily rate of the increase in electricity demand before every simulated cascade. The slow average load growth gradually stresses the power system so that some reliability criterion finally cannot be satisfied. Then the power grid evolves in time by slowly upgrading system capacity to satisfy the gradually growing load demand. And the generator capacity is increased at the same rate λ as that of the power demand. Moreover, the transmission lines have to be upgraded to make sure that it would not be overloaded due to the load growth. The effect of planning based on load forecasting has been considered in [13]. According to the power demand and the generator capacity above, DC optimal power flow (OPF) is calculated. If loads are shed, restore the shed loads. Each generator increases its output proportional to its original generation, so the power could be balanced. Calculate the DC power flow, and then rebuild the lines whose $|F/F^{\max}|$ is larger than ε, i.e. the load rate of weak lines. The transmission capacity of weak transmission line j is updated according to the OPA model:

$$F^{\max}_{j,T+1} = \mu F^{\max}_{j,T} \tag{1}$$

where μ is the increment rate of transmission capacity. Finally, calculate the DC OPF again and determine the operation state of the next day.