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Performance and reliability of electrical power grids under cascading failures

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ABSTRACT

The stability and reliability of electrical power grids are indispensable to the continuous operation of modern cities and critical for preparedness, response, recovery and mitigation in emergence management. Because present power grids in China are often running near their critical operation points, they are especially vulnerable and sensitive to external disturbances such as hurricanes, earthquakes and terrorist attacks, which may trigger cascading failures or blackouts. This paper describes a quantitative investigation of the stability and reliability of power grids with a focus on cascading failures under external disturbances. The 118-bus (substation) power network in Hainan, China is employed as a case study to investigate the risk of cascading failure of the regional power grids. System performance and reliability of the power grids are evaluated under two hypothetical scenarios (seismic impact and intentional disturbance) that could trigger cascading failures. By identifying the most vulnerable (critical) edges and nodes, the robustness of the power network is evaluated under the triggered cascading failures. It is found that the system reliabilities could decline as much as 95% during the triggered cascading failure. This paper also explores the use of concepts from modern complex network theories such as state transition graph and characteristic length to understand the complex mechanism of cascading failures. The findings could be useful for power industries and emergency managers to evaluate the vulnerability of power systems, understand the risk of blackout induced by cascading failures, and improve the resilience of power systems to external disturbances.

1. Introduction

Urban infrastructure systems such as power networks are critical backbones of modern societies. The stability and reliability of power networks are indispensible to the continuous operation of modern cities. Because the present power grids are often running near their critical points and these critical infrastructures are attractive target for deliberate attacks [1], power grids are especially sensitive and vulnerable to disturbances such as natural and man-made hazards which could potentially trigger cascading failures. Cascading failure, also known as avalanche of power systems, has drawn intensive research interests in recent years, especially after the large-scale August 14 cascading failure in North America in 2003 [2]. Under extreme events such as natural hazard impact or intentional disruption, failure of power system infrastructure not only disrupts residential and commercial activities, but also impairs post-disaster response and recovery, resulting in substantial socio-economic consequences [2–9].

Evaluation of the performance and reliability of infrastructure systems is complex in nature due to the large number of network components, complex network topology [10], and component/system interdependency [11]. Currently, the most successful study of power network cascading failures is based on the OPA and CASCADE models [12–14]. Although some results can be drawn based on these models, it is still difficult to explain whether and how an external disturbance can cause a cascading failure [15].

Complex system theories have been recently employed to understand cascading failures [5,16–18]. Watts showed that the topology of modern power grid is always a small-world graph and the propagation of failures within the network can be studied using complex system theories [16]. Focusing only on the topologies of power systems, these approaches, however, ignored the weights of nodes (generators and substations) and links (transformers and transmission lines), which could be of more importance in practice [5,15]. For instance, stakeholders and emergency managers are often concerned about the availability of electricity services, or the connectivity between power generator and service areas. Network reliability, or the probability of connectivity between node-pairs can be evaluated based on the network configuration with system reliability theories.

For lifeline networks, system reliability can be measured in three perspectives [19]: (1) reliability of structural components; (2) connectivity reliability between node-pairs; and (3) system performance reliability, i.e., keeping infrastructure equipments from overloading or maintaining minimum water head (pressure)

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for serviceability requirements. In this paper, the scope of reliability analysis presented is limited to system-level connectivity reliability and the reliability of overloaded equipment is not discussed.

The underlying idea of analytic network reliability method is to convert complex network to combination of simple networks such as parallel or series systems, and then system reliability could be computed by finding the union and intersection of these simple networks, e.g. a generic substation can be modeled with a series system of macro-components [20]. Kroft [21] first described a shortest path algorithm to compute system reliability. Panoussis [22] and Taleb-Agha [23,24] proposed that general network reliability can be computed by converting complex lifeline networks to SSP (series systems in parallel) networks. However, finding the shortest paths is not always an easy task, especially for large-scale networks. Aggarwal and Misra [25] proposed disjoint shortest path algorithm. Later, this algorithm was improved to give exact reliability for large-scale complex networks [26–29]. The full probability analytic algorithm [30] and ordered binary decision diagram (OBDD) algorithm [31] are also able to find exact network reliability but neither is able to handle large-scale networks.

On the other hand, since complete information is not always available, especially for complex systems, researchers chose to describe the system reliability approximately with reliability bounds [32]. But the theoretical bounds are often too wide for practical uses until much narrower reliability bounds of the reliability of power substation systems were obtained by linear programming [33,34]. Recently, a matrix-based system reliability (MSR) method was developed to estimate the system reliability of infrastructure systems [35]. MSR is easy to implement and flexible to handle dependence and incomplete information [36].

This paper studies the cascading failure of the power system with the specific emphasis on its stability and network reliability. First, the stability performance is evaluated with the state transition graph. Next, the system reliability of the power system under cascading failures is analyzed. A provincial power network in China is used as a numerical example to demonstrate the analysis. The results and observations from the case study are summarized, and the identified future research topics are also presented.

2. Performance and the state transition graph of power grids

The capability of power grids to deliver electric power depends on boundary conditions (e.g., power and voltage from supply nodes and to demand nodes), admittance of transmission lines, and working states (operating or failure) of substation components.

Boundary conditions are specified at the nodes in terms of active and reactive components at the load nodes, real power and voltage amplitude at the generation nodes, and voltage amplitude and phase angle at the swing node. In general, the steady state of a power system is described by power flow, which is the solution of a typical nonlinear equation sets:

$$\dot{\mathbf{V}}\overset{*}{\mathbf{Y}}\overset{*}{\mathbf{V}} = \dot{\mathbf{S}} = \mathbf{P} + j\mathbf{Q} \tag{1}$$

where $\dot{\mathbf{V}}$ is the voltage phasor vector as a complex value; $\mathbf{Y}$ is the admittance matrix corresponding to the power network; $\dot{\mathbf{S}}$ is the vector of complex power injected into each nodes; $\mathbf{P}$ is active power (real part); $\mathbf{Q}$ is reactive power (imaginary part); "$*$" is the conjugate operator.

Electrical power transferred through a given edge (i.e., transmission line or transformer) can be calculated once the power flow equation is solved. The power flow model is theoretically appropriate since the power system runs normally for most of time, and most blackouts always happen with a long-period dynamics, which can also be described by power flow [37].

Power grids can be treated as a weighted digraph from a macroscopic viewpoint: generators and load motors as the nodes to inject electric power and loads into power grids, and transmission lines and transformers as the edges to transfer electrical power. To quantify the security of power system, the capacity factor of each edge other than mere electrical power is taken as the edge weight. For example, the weight of a transformer is the ratio of apparent power transferred over its rated capacity, while the weight of a transmission line is usually the ratio of actual transmitted current over its rated current.

Though most electrical equipments are designed with overloading protection capacities, it is assumed that the overloaded equipments shall quit the network and the working state be "failure", and vice versa. Electrical power grid can be treated as a discrete dynamical network when all buses, transmission lines, and transformers have binary working states, that is, operating state denoted by "1" and failure state by "0". By describing the states of nodes and edges with binary vectors, state transition graphs [15,38] can capture dynamic behaviors of both nodes (i.e., power plants and substations) and edges (e.g., transmission lines) and can be used to illustrate the cascading failure of power networks. In nature, the state transition graph is an enumeration of all possible initial states of the system. Since it is often computationally expensive to employ state transition graphs directly especially for large networks, the characteristic lengths of state transition graphs provide us an alternative measure to understand cascading failures. The global behavior of state transition graph can be illustrated with the characteristic length of the graph:

$$l = \frac{1}{n(n+1)/2} \sum_{i \geqslant j} d_{ij} \tag{2}$$

where l is the characteristic length of the graph, measured by the *average distance* between arbitrary two nodes in the graph; d_{ij} is the length of the shortest path between node i and node j. The characteristic length of a graph can be used to evaluate the possibility of state transitions of power grids [15].

3. System reliability under cascading failures

This paper employs the MSR method to assess the system reliability of power networks. The MSR method subdivides the sample space of component events with s_i distinct states, $i = 1, \ldots, n$, into $m = \Pi_{i=1}^{n} s_i$ mutually exclusive and collectively exhaustive (MECE) events. The probability of any general system event is then described by the inner product of two vectors:

$$P(E_{sys}) = \mathbf{c}^{\mathrm{T}}\mathbf{p} \tag{3}$$

where $\mathbf{c}$ is the "event vector" whose element is 1 if its corresponding MECE event is included in the target system E_{sys} event, and 0 otherwise; and $\mathbf{p}$ is the "probability vector" that contains the probabilities of all the MECE events. Efficient matrix-based procedures [39] were proposed to efficiently obtain these vectors by use of matrix computing languages such as Matlab.

The MSR method has the following merits over existing system reliability methods. First, the probability of a system event is always calculated by a simple matrix multiplication as in Eq. (3) regardless of the complexity of the system event definition. Second, the MSR method separates the tasks of identification of system event ($\mathbf{c}$) and computation of probability calculations ($\mathbf{p}$), which allows for an easy integration with other computation modules, e.g. geographic information system (GIS) or network analysis algorithms. Moreover, the matrix-based procedures proposed along with the method help obtain $\mathbf{c}$ and $\mathbf{p}$ vectors efficiently. Third, even if one has incomplete information on the component failure probabilities and/or their statistical dependence, the