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Wide-area multiple line-outages detection in power complex networks ☆

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ABSTRACT

Multiple line outages (MLOs) are common in blackouts, the detection of MLOs are very important for the robusty and securety of power grid. Many insightful methods have been reported to handle with line outage detection, but few of them focus on the detection of MLOs that happen in a short period of time. To deal with this promblem, based on the complex network theory, some novel algorithms are developed by using phasor measurement units (PMUs) information. By invoking virtual adaptive observers, the presented algorithms monitor the connectivity status between buses, which make the algorithms tolerant to the interaction effects between the multiple line outages. Besides, the proposed algorithms also address the reconstruction of the real-time adjacency matrix of the power transmission networks. Simulation results demonstrate the effectiveness of the presented algorithms.

Introduction

Line outages detection (LOD) is crucial to real-time monitor power grids health and prevent the cascading failures. Line outages lead to loss of loads, islanding, and the change of transmission network topology [1,2,24]. Accurate and timely knowledge of transmission network topology is essential for real-time monitoring and operation of wide-area power grid [1,2,39]. The wide area line outages detection (WALOD) is important for the timely acquiring of transmission network topology, therefore, it needs to be done validly and accurately.

To meet the challenge of the timely WALOD problem, it is advisable to treat the whole power grid as a network constructed by interconnected power systems [22,23,25]. Thus, the connectivity status of transmission lines in wide area power grid can be represented by a topological graph [26,27]. Real-time data of internal system topology obtains by telemetering status of circuit breakers and switches, while wide area topology information (including external system topology information and inter area topology information) timely updating is a critical task for power grid [30,31]. Wide area topology information updated by the system data exchange (SDX) module hourly doesnt meet the requirement of real-time monitoring [39], also the local area topology information need to be checked using reliable information other than telemetering status of circuit breakers and switches. Therefore, real-time methods are needed for internal system topology verification and inter area line outages detection using PMUs data in real time [9,10,11,15,28].

In early literature [3–6], methods for outage detection based on analytical data using artificial intelligence (AI) have been developed. These data (such as status of the protective devices like switchs and circuit breakers) are from the human inspection or some special sensors at the substation, where supervisory control and data acquisition (SCADA) systems are available. These AI approaches include fuzzy set approaches [3], knowledge-based approaches [5], fuzzy systems and neural networks [4], expert systems, etc. However, lots of these approaches do not only rely on RT measurement [5] (for example some use customers calls or the protective devicesstatus), the update frequency of their analytical data limited their time-sensitive [32–34]. More over, for the fuzzy set approaches, the membership degree and rule sets of fuzzy logic are unique for each power network model, they should be determined again when the power network model changed, instead of providing exact fault elements, most of the expert systems were developed based on the protective relays and circuit breaker information to estimate the fault region in the distribution substation [29], the knowledge-based and neural networks based approaches need to be trained with a number of experiments. These approaches often do not provide the admittance matrix of the power network but the outages region of distribution

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substation or the probability of outage branches. Because PMU data are more widely available in near real-time than other power system measurement data, it can provide unique insights into the global operation of the grid.

More recently, many works focus on the detection methods based on PMU data which is currently the best source of system-wide line status information [12–14]. Among those [7,14], the detection was transformed into an optimization problem to identify the most likely bus pair and the corresponding injections based on the changes observed in the bus phase angles of the internal system. In [8,12] the power grid was decoupled into some spanning trees, then the outage detection became a hypothesis testing problem of where the outage most likely located.

Although, the above mentioned methods are useful, there are still some problems unsolved. Most of the existing outage detection methods are based on the dc power flow assumption. This assumption needs the power grid to be settled into a quasi-stable state following the line outage [7]. Then, the power flow solution after the outage will match the observed values of system. However, if the power grid states are near the critical state, this assumption is hard to satisfy [6,31]. As a result, we need to develop some new detection methods which has weaker assumptions in the system. Another unsolved problem is that outages may lead to cascading failures in the power grid [35,36], especially in black out, which means outages may happen sequentially or at the same time, in other words, line outages may happen before the power grid oscillations damped out [25]. Probabilistic independence of outages is not assured. So it is necessity to develop the detection method for multiple line-outages. This paper contributes a computationally efficient algorithm for near real-time identification of multiple external line outages (and generally changes) using only hourly basecase topology information and local voltage phasor angle data available by PMUs. It relies on the power complex network model and leverages the fact that the outaged lines represent a small fraction of the total number of lines. The novel approach views the topology-bearing basecase information as the weighted Laplacian matrix of the grid-induced graph, moreover, in these methods, communication time delay is considered.

The rest of this paper is organized as follows. Section "Model description and mathematic preliminaries", we present the dynamic model of the power grid and outages based on the same physical system as power flow model. Yet, distinct from the power flow model, this model includes the dynamic behavior of elements in it. The power grid is modeled as a complex network and the line outages are modeled as zero values of power flows between buses. When faults occur, dynamic behavior of the power grid can be expressed by the model precisely. Additionally, since the algorithm detects the line outage locally, it has no extra constraint of the power grid topology, i. e. it has no limitation on the structure of the network. In Section "Multiple lines outage detection algorithm", we proposed a method to detect outages with the help of adaptive observers on buses. Because the observer monitors the connection between nodes separately, the adaptive observers can detect more than one outage which happened at the same time. With this method, each outage detection is isolated from the other outages and has small amount of computation. Additionally, the method can be applied as an online monitor, which can update the topology information instantly. In Section "Numerical tests", The proposed method is tested to verify its validity in the IEEE 14-bus system. Finally, the paper concludes in Section "Conclusions".

Model description and mathematic preliminaries

Before we introduce the modeling of power grid, some mathematical notations used in this paper are presented. R denotes the set of real numbers, R^n denotes the n-dimensional Euclidean space. For $x \in R^n, x^T$ denotes its transpose. $\|x\| = \sqrt{x^T x}$ denotes the vector norm of x. $R^{n\times m}$ are the set of real matrices. $\mathbf{f}(\cdot)$ represents a function vector, and $f_i(\cdot)$ is the *ith* component of the function vector $\mathbf{f}(\cdot)$.

Power transmission network model

Considering the power transmission network as a complex network, its topology can be described by a graph $(\mathcal{N}, \varepsilon)$, where $\mathcal{N} = \{1, 2, \ldots, N\}$ denotes the set of nodes including generator buses and load buses. Generator buses are labeled from 1 to l (the set of generator buses is defined as $\mathcal{N}_g := \{1, \ldots, l\}$), load buses are labeled from $l+1$ to N (the set of load buses is defined as $\mathcal{N}_l := \{l+1, \ldots, n\}$). $\varepsilon := \{i, j\} \subseteq \mathcal{N} \times \mathcal{N}$ denotes the set of transmission lines. For a set $\mathcal{N}$, let $|\mathcal{N}|$ denote its cardinality.

The real power flow equation [18] from the ith node to jth node follows as

$$P_{ij} = \sum_{j=1}^{N} V_i V_j G_{ij} cos(\theta_i - \theta_j) + \sum_{j=1}^{N} V_i V_j B_{ij} sin(\theta_i - \theta_j) \quad i, j \in \mathcal{N}, \tag{1}$$

where the P_{ij} is the active power of the ith node and V_i is the voltage modulus of the ith node, the θ_i denotes voltage angle of ith buses. For the jth node, these symbols represent the same physical measurement. G_{ij}, B_{ij} denotes the real part and imaginary part of the admittance of the line connecting buses i and j respectively. The $\mathcal{N} \times \mathcal{N}$ zero-row-sum symmetrical matrices G and B can be composed by (i,j)th entry calculated as following equations

$$\begin{aligned} B_{ij} &= \begin{cases} b_{ii} + \sum_{i\neq j} b_{ij}, & \mathrm{i=j} \\ -b_{ij}, & \{i,j\} \in \varepsilon \\ 0, & otherwise \end{cases}, \\ G_{ij} &= \begin{cases} g_{ii} + \sum_{i\neq j} g_{ij}, & \mathrm{i=j} \\ -g_{ij}, & \{i,j\} \in \varepsilon \\ 0, & otherwise \end{cases}, \quad i,j \in \mathcal{N}, \end{aligned} \tag{2}$$

where g_{ii} and b_{ii} represents the real and imaginary part of admittance-to-ground at bus i is often neglected, g_{ij} and b_{ij} is admittance of the transmission line connecting buses i and j which are nonzero constants (if there is no connection between node i and j, then $g_{ij} = 0$ and $b_{ij} = 0$). G and B can be viewed as the weighted Laplacian matrix of the graph. In the following section, the dynamical models of the generators and the loads should be introduced.

For the generator buses, the ith $(i \in \mathcal{N}_g)$ node, its dynamic behavior is described by the swing equation [18]

$$M_i \ddot{\theta}_i = P_{m,i} - E_i^2 G_{ii} - D_i \dot{\theta}_i - P_{e,i}, \quad i \in \mathcal{N}_g. \tag{3}$$

In the swing Eq. (3), the θ_i denotes voltage angle of ith node and ω_i represents its time derivative. E_i stands for the electromotive force modulus of ith node, $P_{e,i} = P_{ij}$ is the active power, $P_{m,i}$ is the energy input of the generator in other forms of energy (such as hydraulic power, nuclear energy, mechanical energy). M_i and D_i are the inertia and damping constants, respectively.

From (3) and (1), let $\lambda_i = P_{m,i} - E_{ii}^2 G_{ii}$, the power system generator's model can be formulated compactly as

$$M\ddot{\theta}_i + D_i\dot{\theta}_i = \lambda_i - \sum_{j=1}^{N} V_i V_j G_{ij} cos(\theta_i - \theta_j) - \sum_{j=1}^{N} V_i V_j B_{ij} sin(\theta_i - \theta_j), \quad i \in \mathcal{N}_g,$$

and it can be rewritten as

$$\begin{cases} \dot{\theta}_i = \omega_i \\ \dot{\omega}_i = \frac{1}{M_i}\lambda_i - \frac{D_i}{M_i}\omega_i - \frac{1}{M_i}\sum_{j=1}^{N} V_i V_j G_{ij} cos(\theta_i - \theta_j) - \frac{1}{M_i}\sum_{j=1}^{N} V_i V_j B_{ij} sin(\theta_i - \theta_j), \quad i \in \mathcal{N}_g. \end{cases} \tag{4}$$