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Electrical LeaderRank method for node importance evaluation of power grids considering uncertainties of renewable energy

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ABSTRACT

Node importance evaluation of power grids plays an important role in the safe operation and planning of power systems. This paper proposes an electrical LeaderRank (ELR) method to identify the important nodes in complex power grids, considering the renewable energy uncertainties, system topological structure, transmission power flow and the loss of loads caused by cascading failures. The proposed method uses an ELR value function to represent the importance of a system node, which can be derived iteratively from the weighted distribution strategy of its in-linked nodes. Furthermore, the uncertainties of wind and solar energy generation are modelled as interval numbers, and the interval power flow calculation is employed to obtain the interval power in transmission lines, direct adjacent matrix, and finally the interval ELR values. The performance of ELR method has been fully tested and benchmarked on the IEEE 118-bus power system and the Western Liaoning Power Grid of China. Comparative results on four performance criteria have not only demonstrated the validity and superiority of the proposed method, but also confirmed its capability to cope with the node importance evaluation of practical power grids.

1. Introduction

The power grid is a complex network threatened by natural disasters, deliberate attacks and equipment failures, and a single disturbance or contingency may trigger a chain effect of unpredictable and disastrous consequences [1]. The failure of important nodes in power grids would cause large-scale power blackouts, and may impact the economy and national security. Therefore, the system important nodes should be identified for power system reinforcement, relay protection, as well as power grid resilience enhancement for the prevention of load interruptions and protection of life and property from the consequences of electricity outages [2,3]. As an important part in the vulnerability evaluation of power grids, the node importance evaluation can provide significant decision guidance for the safe operation and planning of power systems.

So far, the existing node importance evaluation methods, including degree and betweenness measure, closeness and PageRank (PR) method based on complex network theory and social network analysis, have been reported in [4–14]. In the graph theory, the degree of a node is defined as the number of transmission lines adjacent to this node, and a node with the larger value of degree tends to have higher influence in the power network [8]. The betweenness expresses the dominance level of a node from the viewpoint of the whole power network [9]. Vertex-betweenness of a given node is the ratio of the number of shortest paths passing through the node over the number of all the shortest paths between vertex pairs. An electrical betweenness (EBT) method combining the capacity and distribution of generators and loads was proposed in [10] to evaluate and rank the critical nodes in power grids. In the complex network, the node closeness centrality reveals the compactness level from one node to other nodes, and also indicates the center extent and indirect influence of the node to other nodes [8]. The larger value of node closeness denotes the centrality and significance of the node to other nodes. With a better definition of electrical distance to express the system vulnerability, the closeness method has been adopted in [11] to identify important nodes or branches in the power system. Besides, a multi-criterion measuring method with adjustable parameters is proposed in [12], considering the node degree, star degree and betweenness, to estimate the importance of network nodes.

Furthermore, the PR is proposed in [13] to work by counting the number and quality of links to a given node in order to determine an

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estimation of the node significance, and a node evaluation method based on PR was proposed in [14] considering the importance of nodal load, nodal load capacity and network topology. However, the PR based method in [14] only considers the load loss of a single node when suffering the node attacks, and the loss of loads resulted from the cascading failure process is not involved. In 2011, Lv et al. [15] proposed a variant of PR, called LeaderRank (LR), in which a ground node is introduced to connect with all other nodes by a bidirectional edge to the original network. It has been demonstrated in [16] that LR outperforms PR with faster convergence and ranking effectiveness, wider applicability to any type of network, as well as higher robustness against the noisy data and initial conditions. In the recent years, modern power grids become more and more vulnerable with the increasing grid-connected renewable energy generations (REGs) [17,18]. Because of the intermittent and volatile nature of wind and solar energy sources, the power flow distribution when integrating large amounts of intermittent REGs could differ considerably from the power system with traditional generation sources [19], and the uncertainties in the power flow through transmission lines would further contribute to extend the failure size-scale when the cascading failure occurs. Therefore, the problem of node importance evaluation of power grids becomes even more complicated with the intermittent and volatile REGs.

In this paper, an electrical LeaderRank (ELR) method is proposed to assess and identify the important nodes of power grids considering the uncertainties of renewable energy. Due to the influence of variable wind and solar energy sources on the power system vulnerability, the output uncertainties of REGs are modelled as interval numbers to investigate the interval uncertain transmission power, and a cascading failure simulation model is formulated based on the interval DC optimal power flow (DC-OPF) to measure the loss of loads after the power system suffering from attacks. Consequently, the interval power flow distribution and load loss caused by cascading failures are taken into consideration to propose an interval weighted strategy of value functions for the ELR method in order to enhance the identification accuracy of system important nodes. Comparative simulations of the proposed ELR with other node evaluation methods have been fully tested and benchmarked on a modified IEEE 118-bus power system and the Western Liaoning Power Grid of China, and comparative results on four performance measures, including average load loss, maximum amount of load, network transmission efficiency, and system connectivity index, have demonstrated the validity and superiority of the proposed approach.

2. Modelling of cascading failure with REGs

2.1. Interval DC-OPF with REGs

The volatility and intermittency always accompany the wind and solar energy sources due to weather variability. For example, wind power generation is generally influenced by the fluctuating speed and orientation of wind [20]. The uncertainties of these REGs would lead to uncertainties in the power flow distribution of power grids, and may cause reliability issues especially for the systems with high renewable energy penetration [19]. Here, the uncertainties in wind speed, illumination intensity and solar cell temperature can be formulated as the interval numbers to model the wind and solar generation outputs so as to formulate the interval DC-OPF problem [21]. With the implementation of interval DC-OPF, the interval uncertainties in the transmission power of each line can be obtained and indicated by interval numbers. Firstly, the definition of interval wind speed is denoted as,

$$w^{\mathrm{I}} = [w^{\mathrm{L}}, w^{\mathrm{U}}] = \{w | w^{\mathrm{L}} \leqslant w \leqslant w^{\mathrm{U}}\} \tag{1}$$

where w^{I} is an interval variable to represent the uncertainty of wind speed; w^{L} and w^{U} are the lower and upper bounds of wind speed interval. Based on the elementary operations of interval arithmetic [22], the linearized output power curves of wind turbine generation (WTG) in [18,20] can be transformed into the interval model [23],

$$P_{\mathrm{W}}^{\mathrm{I}} = \begin{cases} 0, & (w^{\mathrm{U}} \leqslant w_{\mathrm{C}} \text{ or } w^{\mathrm{L}} \geqslant w_{\mathrm{F}}) \\ \left[0,\ P_{\mathrm{WTG}}\dfrac{w^{\mathrm{U}} - w_{\mathrm{C}}}{w_0 - w_{\mathrm{C}}}\right], & (w^{\mathrm{L}} \leqslant w_{\mathrm{C}} \text{ and } w_{\mathrm{C}} \leqslant w^{\mathrm{U}} \leqslant w_0) \\ \left[P_{\mathrm{WTG}}\dfrac{w^{\mathrm{L}} - w_{\mathrm{C}}}{w_0 - w_{\mathrm{C}}},\ P_{\mathrm{WTG}}\dfrac{w^{\mathrm{U}} - w_{\mathrm{C}}}{w_0 - w_{\mathrm{C}}}\right], & (w^{\mathrm{L}} \geqslant w_{\mathrm{C}} \text{ and } w^{\mathrm{U}} \leqslant w_0) \\ \left[P_{\mathrm{WTG}}\dfrac{w^{\mathrm{L}} - w_{\mathrm{C}}}{w_0 - w_{\mathrm{C}}},\ P_{\mathrm{WTG}}\right], & (w_{\mathrm{C}} \leqslant w^{\mathrm{L}} \leqslant w_0 \text{ and } w_0 \leqslant w^{\mathrm{U}} \leqslant w_{\mathrm{F}}) \\ P_{\mathrm{WTG}}, & (w^{\mathrm{L}} \geqslant w_0 \text{ and } w^{\mathrm{U}} \leqslant w_{\mathrm{F}}) \end{cases} \tag{2}$$

where $P_{\mathrm{W}}^{\mathrm{I}}$ represents the interval WTG output; P_{WTG} is the rated power capacity of the WTG; w_0, w_{C}, and w_{F} are the rated wind speed, cut-in wind speed and cut-off wind speed of wind turbine, respectively. Also, the interval output power of a photovoltaic (PV) system can be expressed as follows [23],

$$\begin{aligned} &H_{\mathrm{ING}}^{\mathrm{I}} = [H_{\mathrm{ING}}^{\mathrm{L}}, H_{\mathrm{ING}}^{\mathrm{U}}],\ T_{\mathrm{C}}^{\mathrm{I}} = [T_{\mathrm{C}}^{\mathrm{L}}, T_{\mathrm{C}}^{\mathrm{U}}] \\ &P_{\mathrm{P}}^{\mathrm{I}} = \left[\frac{P_{\mathrm{PV}}}{H_{\mathrm{STC}}}(H_{\mathrm{ING}}^{\mathrm{L}} + \varepsilon_{\mathrm{T}} H_{\mathrm{ING}}^{\mathrm{L}} T_{\mathrm{C}}^{\mathrm{L}} - \varepsilon_{\mathrm{T}} H_{\mathrm{ING}}^{\mathrm{U}} T_0),\ \frac{P_{\mathrm{PV}}}{H_{\mathrm{STC}}}(H_{\mathrm{ING}}^{\mathrm{U}} + \varepsilon_{\mathrm{T}} H_{\mathrm{ING}}^{\mathrm{U}} T_{\mathrm{C}}^{\mathrm{U}} \right. \\ &\left. -\varepsilon_{\mathrm{T}} H_{\mathrm{ING}}^{\mathrm{L}} T_0)\right] \end{aligned} \tag{3}$$

where $P_{\mathrm{P}}^{\mathrm{I}}$ is the interval generation output of PV array; P_{PV} denotes the rated power capacity of PV array; $H_{\mathrm{ING}}^{\mathrm{I}}$ and H_{STC} denote the interval of incident irradiance and the irradiance at standard test condition $1000\ \mathrm{W/m^2}$, respectively; α_{T} is the temperature coefficient of power; T_0 is the reference rated temperature; $T_{\mathrm{C}}^{\mathrm{I}}$ is the interval of PV temperature; $H_{\mathrm{ING}}^{\mathrm{L}}$ and $H_{\mathrm{ING}}^{\mathrm{U}}$, $T_{\mathrm{C}}^{\mathrm{L}}$ and $T_{\mathrm{C}}^{\mathrm{U}}$ are the lower and upper bounds of the irradiance and cell temperature interval, respectively.

In order to analyze the cascading failure process and node importance considering the uncertainties of renewable energy sources, the interval DC-OPF model in [24,25] is adopted in this study to calculate the interval power flow in each transmission line derived from the interval uncertainties of wind power $P_{\mathrm{W}}^{\mathrm{I}}$ and solar power $P_{\mathrm{P}}^{\mathrm{I}}$. In the DC-OPF model, the adjustments on the outputs of generators and load shedding can be implemented to eliminate the transmission line or transformer overloads, and the optimization objective is to minimize the total generation cost [8], as follows,

$$\begin{aligned} \min \quad & F = \sum_{i \in S_{\mathrm{G}}} c_i P_{\mathrm{G}i} \\ \text{s.t.} \quad & \boldsymbol{P}^{\mathrm{PF}} = \boldsymbol{A}\boldsymbol{P}^{\mathrm{SP}} \\ & \sum_{i \in S_{\mathrm{G}}} P_{\mathrm{G}i} - \sum_{j \in S_{\mathrm{D}}} P_{\mathrm{D}j} = 0 \\ & P_{\mathrm{G}i,\min} \leqslant P_{\mathrm{G}i} \leqslant P_{\mathrm{G}i,\max},\ i \in S_{\mathrm{G}} \\ & -P_{ij,\max} \leqslant P_{ij} \leqslant P_{ij,\max},\ i,\ j \in S_{\mathrm{B}} \\ & P_{\mathrm{W}}^{\mathrm{I}} = [P_{\mathrm{W}}^{\mathrm{L}}, P_{\mathrm{W}}^{\mathrm{U}}],\ P_{\mathrm{P}}^{\mathrm{I}} = [P_{\mathrm{P}}^{\mathrm{L}}, P_{\mathrm{P}}^{\mathrm{U}}] \end{aligned} \tag{4}$$

where c_i are the generation cost coefficients for the ith generator; $P_{\mathrm{G}i}$ and $P_{\mathrm{D}j}$ are the active power outputs of generator at node i and load at node j, respectively; $\boldsymbol{P}^{\mathrm{PF}}$, $\boldsymbol{A}$ and $\boldsymbol{P}^{\mathrm{SP}}$ denote the matrix of branch power flow, branch admittance matrix, and the matrix of nodal power injection, respectively; P_{ij} is the power flow in transmission lines; S_{G}, S_{D} and S_{B} represent the sets of generator nodes, load nodes and power system buses, respectively. The problem constraints include the DC power flow equation, power balance equation, load shedding limits, generator output limits and transmission capacity limits [26].

Based on the direct interval matching and range arithmetic principles of extreme value intervals in [21,27], the minimization of interval DC-OPF function $F^{\mathrm{I}}(\boldsymbol{X}) = [F^{\mathrm{L}}(\boldsymbol{X}), F^{\mathrm{U}}(\boldsymbol{X})]$ with the optimal interval $\boldsymbol{X}^*$ can be transformed into two deterministic linear programming problems to minimize the upper and lower bounds of DC-OPF objective functions [25], as follow,