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An interpretative structural modeling based network reconfiguration strategy for power systems

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ABSTRACT

The network reconfiguration is an important stage of restoring a power system after a complete blackout or a local outage. Reasonable planning of the network reconfiguration procedure is essential for rapidly restoring the power system concerned. An approach for evaluating the importance of a line is first proposed based on the line contraction concept. Then, the interpretative structural modeling (ISM) is employed to analyze the relationship among the factors having impacts on the network reconfiguration. The security and speediness of restoring generating units are considered with priority, and a method is next proposed to select the generating unit to be restored by maximizing the restoration benefit with both the generation capacity of the restored generating unit and the importance of the line in the restoration path considered. Both the start-up sequence of generating units and the related restoration paths are optimized together in the proposed method, and in this way the shortcomings of separately solving these two issues in the existing methods are avoided. Finally, the New England 10-unit 39-bus power system and the Guangdong power system in South China are employed to demonstrate the basic features of the proposed method.

Introduction

Reliable power supply is becoming more and more demanding in the modern society. Huge economic losses and severe social impacts can be caused by a large-area blackout. In the past decade, large-area blackouts occurred in many counties or areas, such as the August 14, 2003 blackout in the United States and Canada, the September 23, 2003 blackout in Sweden and Denmark, the September 28, 2003 blackout in Italy, the November 4, 2006 blackout in European countries, the 2008 blackout in South China caused by ice storms and the July 30, 2012 blackout in India. These events show that it is infeasible to completely prevent large-area blackouts from occurrence from the technical aspect, and also highlight the importance of rapid restoration after a blackout [1,2]. Hence, power system restoration after a large-area blackout is still an important area to be further studied.

In the past two decades, much research work has been done on developing strategies for power system restoration. In [3], a multi-agent system consisting of a number of bus agents and a single facilitator agent is proposed for power system restoration, and the bus agent is employed to determine a suboptimal target configuration based on locally available information only, while the single facilitator agent acts as a manager in the decision-making process. In [4], the problem of optimal network reconfiguration is formulated in a multi-objective optimization framework, and the lexicographic optimization method is used to solve. A mixed integer programming model is presented in [5] for determining the start-up sequence of generators. An ordered binary decision diagram (OBDD) based sectionalizing method is presented in [6] to quickly find the splitting points for controlled islanding in power systems. In [7], an artificial neural network (ANN) based method for power system restoration is proposed, and some workable restoration strategies are used as samples to train the ANN. The start-up sequence of generators is optimized by using an ant colony algorithm to maximize the system generation capability in [8]. In [9], a rule-based system is presented to generate and implement a dynamic restoration plan. In [10], the network cohesion after a node contraction is proposed to evaluate the importance of the node in the skeleton-network reconfiguration procedure. Up to

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now, the importance degrees of various lines have not yet been considered in existing methods for determining power system restoration strategies, although various lines usually have different impacts on power system restoration. Given this background, a network reconfiguration strategy will be investigated in this work with the importance degrees of various lines considered.

Interpretative structural modeling (ISM) is proposed by Warfield in 1973 for analyzing the problems in the socio-economic system. ISM is used to develop a multilevel hierarchical structure model by analyzing the relationship matrix of the elements of the system [11–14]. The network reconfiguration optimization is usually divided into two subproblems, i.e., the optimization of the start-up sequence of generating units and that of the restoration paths. Usually, the start-up sequence of generating units is first determined, and the related restoration path is then optimized. Thus, only the characteristics of the generating units are considered in optimizing their restoration sequence, while the impacts of the restoration path overlooked. In this work, ISM is employed in determining the network reconfiguration strategy, and the relationship among the start-up sequence of generating units, the restoration of important paths, the restoration of generators with large capacities, the risks of the restoration failure of the network reconfiguration, the importance degrees of various lines, the restoration time of each line, and the generation capacity of each candidate generator to be restored are considered in developing the interpretative structural model for the network reconfiguration problem.

In this work, an index for evaluating the importance degrees of various lines is first presented based on the line contraction concept. Then, an ISM based method is employed to determine the important elements in the network reconfiguration procedure. The restoration path with the minimum charging capacitance is selected from the candidate paths, which would not delay the restoration of generating units, to restore the generating unit concerned for minimizing the restoration failure. The restoration benefit is next defined so as to select the appropriate generating unit for restoration considering the generation capacity to be restored and the importance of each relevant line. The start-up sequence of generating units and the restoration paths are optimized simultaneously by using the proposed method to find the optimal network restoration strategy.

The evaluation of the importance degrees of various lines

The node contraction concept is proposed in [10] to evaluate the importance of each node. Take node A_{node} as an example, node A_{node} and those nodes directly connected with it will be merged into one node in [10]. In each time, one concerned node will be evaluated. It takes n_{node} times of contraction for evaluating the importance of n_{node} nodes. In this work, the contraction concept is extended for evaluating the importance degrees of various lines in a scale-free network. The line contraction process is shown in Fig. 1, in which the original network is shown in Fig. 1(a), and the network after the line contraction in Fig. 1(b). In Fig. 1, the bold line segment denotes a bus in a power system, and is considered as a node in a topological structure. It can be seen from Fig. 1(b) that after the contraction of line b, the end nodes (node 5 and node 6) of line b converge into a node (node 6′).

The line importance degree after the line contraction is defined as:

$$\alpha_b = \frac{n_b}{d_b} \tag{1}$$

$$n_b = \mathbf{I}_\mathbf{g}^T\mathbf{A}\mathbf{I} + \mathbf{I}_\mathbf{p}^T\mathbf{A}\mathbf{I} - 2 \tag{2}$$

$$W_b = \frac{N_{bi}\cdot(N_{bi}-1)}{2} \tag{3}$$

$$d_b = \frac{\sum_{i,j\in\Psi_{bN}} d_{(i,j)}^{\min}}{W_b} \tag{4}$$

where n_b is the node degree of the node which is converged by the end nodes of line b after the contraction of line b; $\mathbf{A}$ is the adjacency matrix of the network with N nodes; node g and node p are the two end nodes of line b, and $\mathbf{I_g}$ is an N-dimensional column vector, in which only the g-th element equals to 1 and the others equal to 0; $\mathbf{I_p}$ is an N-dimensional column vector, in which only the p-th element equals to 1 and the others equal to 0; $\mathbf{I}$ is an N-dimensional column vector, in which all the elements equal to 1; W_b is the number of the node pairs in the network after the contraction of line b; d_b is the average minimum distance of the network; N_{bi} and Ψ_{bN} are respectively the total number and the set of the nodes in the network after the contraction of line b; With more lines in a path, more time will be needed to reconnect these lines and deliver the cranking power to the destination. Thus, the distance of the path can be measured by the number of the lines in the path. $d_{(i,j)}^{\min}$ is the minimum distance between node i and node j, and represents the number of the lines in the shortest path of the scale-free network. It can be seen from Eq. (1) that the importance degree of a line is related to the connection relationship between two end nodes of the line, the other nodes as well as the location of the line in the network. First, a relationship between the line importance degree evaluation and the node importance degree evaluation is established through the line contraction concept. The larger the node degree of the node converged by the line contraction is, the more the other lines the contracted line is directly connected to will be. Secondly, a line in a key location of the network is of high importance, because the shortest paths of many node pairs pass through that line; thus, the average minimum distance of the network will be decreased if the line is contracted, and this means that the importance degree of this line as shown in Eq. (1) is high. Line b shown in Fig. 1 is now employed to demonstrate the calculation of the line importance

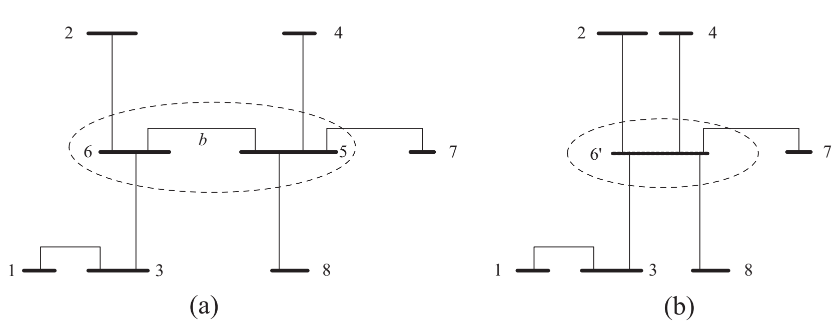

Fig. 1. An illustrative example of the line contraction in a scale-free network.