A Restorative Self-Healing Algorithm for Transmission Systems Based on Complex Network Theory

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***Abstract*—Restorative self-healing is one of the most important features of smart grids. The major purpose of a restorative self-healing control strategy is to steer a power system to secure operating states. In this paper, a self-healing transmission network reconfiguration algorithm based on the complex network theory is proposed. The capacities of generators and the amounts of important loads (i.e., the high priority loads), as well as the distribution and importance of each transmission line in the outage area are considered in the proposed method using the presented electrical "betweenness." Next, the optimal restoration paths and the optimal restorative self-healing strategy can be attained automatically. Finally, the New England 10-unit 39-bus system and a part of the actual Guangdong power system in China are employed to illustrate the features of the proposed method.**

***Index Terms*—Self-healing, network reconfiguration, complex network, electrical betweenness.**

I. Introduction

With the ever-increasing capacities and more extensive interconnections of modern power systems, as well as the restructuring of the power industry, power system operation and maintenance are becoming more complicated and the power systems are more frequently operating closer to operating limits. These factors increase the probability of the occurrence of a blackout. In recent years, several blackouts occurred in actual power systems around the globe, although many measures have been taken for improving the security and stability level of power systems. Given this background, it is very important to investigate the problems about self-healing in smart grids after a complete blackout or a local outage. In [1], a self-healing strategy is proposed for the developed Strategic Power Infrastructure Defense (SPID) system. In [2], an optimization model that produces a minimal cost procurement plan for black-start sources is presented for restorative self-healing. In [3], a restoration subsystem division algorithm based on the complex network theory is proposed. In [4], a sectionalizing method for the build-up strategy in power system restoration is proposed based on the Wide Area Measurement System (WAMS). In [5], the generator start-up strategy is described as a mixed integer linear programming (MILP) problem, and the generator start-up sequencing is optimized. In [6] and [7], self-healing schemes for load curtailment or load restoration in power systems are proposed based on the wide area monitoring and control system. In [8], a transformative architecture for the normal operation and self-healing of networked microgrids is presented. In [9], a hybrid multi-agent framework with a Q-learning algorithm is proposed to support rapid restoration of power systems. In [10], a frame of future self-healing power grid is presented, and effective power system restoration is regarded as an important step toward a self-healing smart grid. An autonomous agent-based framework for a self-healing power system is proposed in [11], which employs advanced failure diagnosis techniques along with autonomous web services. The issues of the multi-agent oriented design for a self-healing urban power grid are discussed in [12]. In [13], a practical methodology for formulating power system restoration strategies, which is synthesized by a combination of generic restoration milestones (GRMs), is presented. In [14], a skeleton-network reconfiguration strategy is proposed based on node importance degrees. In [15], a two-stage method is presented for restoration path selection and skeleton-network determination of the network reconfiguration strategy. In [16], a path selection approach is proposed based on power transfer distribution factors for large-scale power systems. A decision support methodology for restoring interconnected power systems through tie lines is presented in [17]. In [18], a cooperative multi-agent framework for self-healing distribution systems is presented. In summary, it can be seen that the existing research work on restorative self-healing power systems is mainly focused on the framework design of self-healing power systems, the splitting strategy, generator start-up and path selection optimization algorithms, as well as self-healing distribution systems. However, how to implement transmission network reconfigurations for restorative self-healing after an outage is still one

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of the most important issues not well solved for a self-healing smart grid.

Power networks have the features of complex networks [19], [20]. The '*betweenness*' can be employed to evaluate the hub of one edge in the topology structure of a complex network. The major contribution of this paper lies in the development of a new transmission network reconfiguration algorithm for restorative self-healing based on the presented electrical *betweenness*, which could take the relative importance and restoration priority of non-black-start generators and important loads (i.e., high priority loads), and the distribution of nodes into consideration. Moreover, the characteristics of restorative self-healing (such as an equivalent black-start power source, an unrestored region of a power grid, candidate restoration paths, and redundant restoration paths) can be well integrated into the presented electrical *betweenness* and then the optimization of restoration strategies.

The rest of this paper is organized as follows. Section II presents the restorative self-healing of transmission systems. Section III proposes a transmission network restorative self-healing algorithm based on the complex network theory. In Section IV, the New England 10-unit 39-bus system and a part of the actual Guangdong power system in China are employed to demonstrate the features of the proposed restorative self-healing strategy. Conclusions are given in Section V.

II. Restorative Self-Healing of Transmission Systems

Self-healing strategies are control options that are initiated to steer a power system to a more secure, less vulnerable, operating state [21]. These control options are typically initiated in the following modes: the preventive, corrective and restorative self-healing modes [1]. Restorative self-healing strategies are used to drive the power system from a restorative operating state to a normal operating one by control options, such as black-starting, network reconfigurations and load restoration.

The restorative self-healing process could be divided into three phases: the black-start phase, the network reconfiguration phase and the load restoration phase. The restorative self-healing strategies can be divided into two types, i.e., the top-down and the bottom-up strategies. In actual power system restoration, the power system concerned can be divided into subsystems, and each with the required black-start capability. Then, the top-down strategy is applied to each subsystem for restorative self-healing. In the framework of self-healing strategies, the restorative self-healing control after an outage represents a complicated control and decision-making problem for power system operators. The problem can be formulated mathematically as a multi-stage, combinatorial, nonlinear constrained optimization problem. The objective of the restorative self-healing control is to speed the restoration of power supply to interrupted customers, especially important loads (i.e., high priority loads), and to reduce the energy not supplied of the power system. In this paper, the top-down strategy is employed in the network reconfiguration phase, and then transmission lines and nodes are restored one by one.

In the restorative self-healing strategy of transmission systems, the following concepts, i.e., the restored region (or the equivalent black-start power source) and the unrestored region of a power system, candidate restoration paths, and redundant restoration paths, are defined. The restored region of a power system is defined as the part in which nodes and transmission lines (or transformer branches) are restored after a blackout or an outage. In this paper, the restored region of a power system is also regarded as an equivalent black-start power source S_{EBS}. The unrestored region is the part of the system in which nodes and transmission lines are to be restored. Candidate restoration paths are the unrestored transmission lines connecting the restored nodes with the unrestored nodes directly. In the candidate restoration paths, a part of them connects the same unrestored nodes with S_{EBS}, which means that there may have multi-circuited branches between S_{EBS} and one unrestored node. In the restorative self-healing process, only one of these multi-circuited branches is energized for reducing the over-voltage impacts of the transmission lines caused by the line charging capacitance and the loop closing operation. Thus, the transmission lines with less line charging capacitance in the multi-circuited branches is maintained, and the others are removed from the set of the candidate restoration paths. The removed branches are defined as redundant restoration paths.

III. Transmission Network Restorative Self-Healing Algorithm Based on Complex System Theory

A. Complex Network

In this paper, a power network is abstracted as a sparsely connected, unidirectional and weighted graph, and the reactance of each transmission line is taken as the weight of the corresponding edge in the graph for reflecting the electrical distance in the network. Then, the power network can be characterized by its topology. The edge's *betweenness* (or vertex *betweenness*), one of topologic characteristic parameters of a complex network, is defined as the numbers of the shortest paths between pairs of nodes that run through that edge (or vertex) [3]. The *betweenness* is generally employed to evaluate the hub of one edge or one vertex in the topology structure of a complex network. This means that the larger the edge's *betweenness* (or vertex *betweenness*) is, the more important role the edge (or the vertex) plays in the network. Many shortest paths among all pairs of vertices in the network would become longer when the edge (or vertex) with the maximal *betweenness* is removed.

For transmission network reconfiguration of the restorative self-healing, its objective is to optimize the restoration paths (the restoration sequences of transmission lines) and build a destination restoration network, hence the transmission lines in the hub should be first restored for restarting the non-black-start generators and re-supplying power to the important customers after a complete blackout or a local outage. Thus, the optimization of restoration paths for transmission network reconfiguration is similar to the problem of finding out the edges with larger *betweenness* in the complex network.

B. Electrical Betweenness for Restorative Self-Healing Strategy of Power Systems

In actual network reconfiguration, not only the topology of the network but also the capacities of generators, the amounts of important loads (i.e., high priority loads) and the distribution of the generation and load nodes have a significant impact on the restorative self-healing process. However, the network topology is considered in the traditional calculation method [15], [22], [23] of edge *betweenness* only, and each edge is with equal weight (or electrical susceptance is set as the edge's weight). So the traditional method cannot reflect the difference of the importance of different shortest paths for supplying power from S_{EBS} to the unrestored nodes, and cannot consider the relative importance and restoration priority of the generators to be restarted and the important loads to be restored. Therefore, it is necessary to set different importance for each node in the power network. Generally, in the restorative self-healing strategy, the amounts of the important loads in the load nodes or the capacities in the generation nodes are set to the importance of the nodes. Then, different generation nodes and different load nodes can be compared to some extent.

Furthermore, in order to consider the distribution of the nodes to be restored, the shortest path length (i.e., the numbers of transmission lines and transformer branches in the shortest path between any two nodes in power systems) is introduced to describe the impact of the distance between S_{EBS} and the unrestored nodes on the restorative self-healing of power systems. The restoration paths with the shortest electric distance (i.e., minimum of the sum of lines' reactance in the restoration paths) are defined as the shortest restoration paths. The total number of transmission lines and transformer branches in the shortest restoration paths is employed to calculate the shortest path length, so both the electrical distance between S_{EBS} and the unrestored node, and the number of transmission lines and transformer branches to be connected in the restoration paths, which will impact the restorative self-healing speed, can be considered. There is the local interaction characteristic among the nodes of the real complex networks, so the impact of a node on its neighbor nodes decays with the increased topology distance. In power systems, local interaction characteristic mean that if one node is restored, it will greatly accelerate the restoration of the nodes connecting with it directly, and has impact on the nodes connecting with it indirectly. The impact on the *betweenness* of the candidate restoration paths is weakened with the increased topology distance. In this paper, it is assumed that the impact is subject to the exponential decay.

With the relative importance and restoration priority of the non-black-start generators and the important loads to be restored, and the distribution of the nodes to be restored considered, an electrical *betweenness* B_l of the l-th candidate restoration path in a power system graph is defined as

$$B_l = \sum_{j \in \Omega_{UR}} \frac{\alpha P_{Gj} + \beta P_{Lj}}{E^{d_{Sj}-1}} \quad (1)$$

where P_{Gj} is the generation capacity of generating unit in node j; P_{Lj} is the active power of important load in node j; α and β are coefficients for measuring the relatively importance of generation nodes and load nodes in the calculation of electrical *betweenness* of a candidate restoration path, respectively; E is the given coefficient of exponential decay; d_{Sj} is the shortest restoration path length from S_{EBS} to node j, which can be calculated by $d_{Sj} = \sum_{b \in l} Z_b$, where Z_b is equal to 1 if there exists branch b in the l-th restoration path; Ω_{UR} is the set of the nodes in the unrestored region of the power grid. It can be seen from (1) that the impact of the amounts of the important loads and the capacities of the non-black-start generators on the candidate restoration paths is weakened with the larger electrical distance and number of the transmission lines connecting the unrestored node with S_{EBS}. The capacities of non-black-start generators and the amounts of the important loads, as well as the distribution and importance degree of each bus, could be taken into account by the electrical *betweenness* presented. Generally, the generation capacities are greatly larger than important loads in one node. Thus, the electrical *betweennesses* of the paths from S_{EBS} to the generation nodes would be greatly larger than those to the load nodes. So, the generation nodes would be first restored when comparing with most of load nodes. As a result, the candidate restoration path with maximum electrical *betweenness* could be considered as the optimal restoration path for the restorative self-healing strategy of the power system in the given stage, and the other candidate restoration paths could be classified into the set of the alternative restoration paths.

In this paper, the Dijkstra algorithm [24], a well-known algorithm for seeking the shortest path between a pair of vertices, is employed to search the shortest restoration paths between S_{EBS} and each node in the unrestored region of the power grid in this paper, and then the electrical *betweenness* of candidate transmission lines to be restored can be calculated.

C. Restorative Self-Healing Optimization Model

The power system is first divided into the restored region and the unrestored region at a studied time period, and the unrestored transmission lines connecting S_{EBS} with the unrestored nodes at that time period are classified into the set of candidate restoration paths, and the redundant paths should be checked and removed from the set of candidate restoration paths. Selecting one of candidate restoration paths is to pick up one line connecting the unrestored region with S_{EBS} in the power system graph. In the restorative self-healing process, the electrical *betweenness* of the candidate restoration paths is paid more attention, and that of the transmission lines among the unrestored nodes is ignored.

Furthermore, for restarting the non-black-start generators and restoring the important loads quickly, the importance and distribution of the nodes with the non-black-start generators and important loads should also been taken into consideration. As a result, the electrical *betweenness* is employed to optimize restoration paths, and then the optimal sequence of restoration paths and the destination skeleton-network. The restoration path with the maximum electrical *betweenness* is selected from

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the candidate restoration paths for each non-black-start generation or load node in the unrestored region. Thus, based on the presented electrical *betweenness*, the optimization objective of the restoration paths and restorative self-healing strategy of power systems at time period T_i can be defined as

$$\max_{l\in\Omega_{CRPs}^{T_i}} B_l^{T_i} = \sum_{j\in\Omega_{UR}^{T_i}} \frac{\alpha P_{Gj} + \beta P_{Lj}}{E^{d_{Sj}-1}} \tag{2}$$

where T_i is the i-th time period studied in the restorative self-healing process; $\Omega_{UR}^{T_i}$ is the set of the nodes in the unrestored region of the power grid at T_i; $\Omega_{CRPs}^{T_i}$ is the set of candidate restoration paths without redundant paths at T_i; $B_l^{T_i}$ is the electrical *betweenness* of the l-th candidate restoration path in $\Omega_{CRPs}^{T_i}$ at T_i.

When one of candidate restoration path is selected, the power flow constraint of the new power system consisting of the restored region and the selected transmission line should be checked. Furthermore, some security constraints such as bus voltage magnitudes and transmission line capacities could be relaxed to a certain extent in the restorative self-healing procedure so as to recover power supply quickly. The restoration of a generator may be delayed by the long restoration time of a path, thus the candidate restoration paths should be selected from those paths which would not delay the restoration of the concerned generating units.

The following constraints should be respected in the restorative self-healing phase:

(1) The power flow constraints

$$P_{Gx}^{T_i} - P_{ILx}^{T_i} - U_x^{Ti} \sum_{y\in\Omega_{NP}^{T_i}} U_y^{Ti}\left(G_{xy}\cos\theta_{xy}^{T_i} + B_{xy}\sin\theta_{xy}^{T_i}\right) = 0, \quad \forall x \in \Omega_{NP}^{T_i} = \Omega_N^{T_i} \bigcup V_{CRP} \tag{3}$$

$$Q_{Gx}^{T_i} - Q_{ILx}^{T_i} - U_x^{Ti} \sum_{y\in\Omega_{NP}^{T_i}} U_y^{Ti}\left(G_{xy}\sin\theta_{xy}^{T_i} + B_{xy}\cos\theta_{xy}^{T_i}\right) = 0, \quad \forall x \in \Omega_{NP}^{T_i} = \Omega_N^{T_i} \bigcup V_{CRP} \tag{4}$$

where $\Omega_N^{T_i}$ is the set of the nodes in the restored regions of the power system at T_i; V_{CRP} is the node in the unrestored region which connects with the candidate restoration path selected for calculating the electrical *betweenness*; $\Omega_{NP}^{T_i}$ is the set of the nodes which consists of $\Omega_N^{T_i}$and V_{CRP}; $P_{Gx}^{T_i}$ and $Q_{Gx}^{T_i}$ are the real and reactive power generation in node x at T_i; $P_{ILx}^{T_i}$ and $Q_{ILx}^{T_i}$ are the real and reactive power of important load in node x at T_i; U_x^{Ti} and U_y^{Ti} are the voltage amplitude of nodes x and y at T_i, respectively; G_{xy} and B_{xy} are the real and imaginary elements in the x-th row and y-th column of bus admittance matrix; $\theta_{xy}^{T_i}$ is the voltage phase difference between bus x and bus y at T_i.

(2) The generation output constraints

$$P_{Gn}^{\min} \le P_{Gn}^{T_i} \le P_{Gn}^{\max} \quad \forall n \in \Omega_G^{T_i} \tag{5}$$

$$Q_{Gn}^{\min} \le Q_{Gn}^{T_i} \le Q_{Gn}^{\max} \quad \forall n \in \Omega_G^{T_i} \tag{6}$$

where $\Omega_G^{T_i}$ is the set of the restarted generators in the restored region of the power system at T_i; $P_{Gn}^{T_i}$ and $Q_{Gn}^{T_i}$ are the active and reactive power outputs of generator n at T_i, respectively; $P_{Gn}^{\max}$, $P_{Gn}^{\min}$, $Q_{Gn}^{\max}$ and $Q_{Gn}^{\min}$ are the maximum active power, minimum active power, maximum reactive power and minimum reactive power of generator n, respectively.

(3) The constraints of bus voltage magnitudes

$$U_m^{\min} \le U_m^{T_i} \le U_m^{\max} \quad \forall m \in \Omega_N^{T_i} \bigcup V_{CRP} \tag{7}$$

where $U_m^{T_i}$ is the voltage amplitude of node m at T_i; $U_m^{\min}$ and $U_m^{\max}$ are the minimum and maximum amplitude of the voltage of node m, respectively. In the transmission network reconfiguration procedure, the overvoltage issue might be met due to the charging current of a long transmission line under light-load conditions. The constraints are checked in every time period by running power flow program for maintaining the voltage of all the nodes within their limits.

(4) The constraints of transmission line capacities

$$\left|P_{Lb}^{T_i}\right| \le P_{Lb}^{\max} \quad \forall b \in \Omega_L^{T_i} \bigcup l \tag{8}$$

where $\Omega_L^{T_i}$ is the set of the transmission lines in the restored regions of the power system at T_i; $P_{Lb}^{T_i}$ is the actual active power of transmission line b at T_i; $P_{Lb}^{\max}$ is the active power transmission capacity of transmission line b.

(5) The constraints of the system frequency

$$f^{\min} \le f^{T_i} \le f^{\max} \tag{9}$$

where $f^{\max}$ and $f^{\min}$ are the upper and lower limits of the frequency, respectively. f^{T_i} is the power system frequency at T_i. The power system frequency is assumed to be 50Hz or 60Hz when T_i is equal to 0; otherwise, the system frequency $f^{T_i} = f^{T_i-\Delta T} + (\sum_{x\in\Omega_{NP}^{T_i}} \Delta P_{Gx}^{T_i} - \sum_{x\in\Omega_{NP}^{T_i}} \Delta P_{ILx}^{T_i})/(K_L + \sum_{x\in\Omega_{NP}^{T_i}} K_{Gx})$, where K_L is power regulation coefficient of loads per unit; K_{Gx} is power regulation coefficient of the generator in the x-th node per unit; $\Delta P_{Gx}^{T_i}$ is the output power change of the generator in the x-th node from T_i-ΔT to T_i, and $\Delta P_{Gx}^{T_i} = P_{Gx}^{T_i} - P_{Gx}^{T_i-\Delta T}$; and $\Delta P_{ILx}^{T_i}$ is the restored important power in the x-th node from T_i-ΔT to T_i, and $\Delta P_{ILx}^{T_i} = P_{ILx}^{T_i} - P_{ILx}^{T_i-\Delta T}$. In the transmission network reconfiguration procedure, non-black-start units ramping-up processes are critical and should be considered in the decision making of restoration paths during every time period. Thus, $\Delta P_{Gx}^{T_i}$ at one time period ΔT (5 minutes in this paper), should respect the ramping constraint of non-black-start unit in the x-th node, i.e., $\Delta P_{Gx}^{T_i}/\Delta T \le R_{Mx}/60$, where R_{Mx} is hourly ramping power of non-black-start unit in the x-th node. As a result, this constraint could be considered as a quasi-dynamic constraint for maintaining the generation-load balance and the system frequency well in every time period of transmission network reconfiguration.

(6) The constraints of critical maximum or minimum interval of generators

$$0 \le T_{Gn_x}^{T_i} \le T_{Gn_x}^{\max} \quad \forall n_x \in \Omega_{G\max} \tag{10}$$

$$T_{Gn_i}^{T_i} \ge T_{Gn_i}^{\min} \quad \forall n_i \in \Omega_{G\min} \tag{11}$$

where $T_{Gn_x}^{T_i}$ and $T_{Gn_i}^{T_i}$ are respectively the time periods when the generators n_x and n_i obtain the cranking power at T_i; $\Omega_{G\max}$

and $\Omega_{G\min}$ are the sets of the generators with the critical maximum interval and the critical minimum interval, respectively; $T_{Gn_x}^{\max}$ and $T_{Gn_i}^{\min}$ are the critical maximum interval and the critical minimum interval of generator n_x and n_i, respectively. If a generator with the critical maximum interval can obtain the cranking power within this interval, it will restart and supply power to the system quickly. If a generator is with the critical minimum interval, it should be restarted after the critical minimum interval is passed.

Thus, the optimization model for the restorative self-healing strategy of power systems at time period T_i can be summarized as follows.

$$
\begin{aligned}
\max_{l\in\Omega_{CRPs}^{T_i}} \quad & B_l^{T_i} = \sum_{j\in\Omega_{UR}^{T_i}} \frac{\alpha P_{Gj} + \beta P_{Lj}}{E^{d_{Sj}-1}} \\
s.t. \quad & P_{Gx}^{T_i} - P_{ILx}^{T_i} - U_x^{Ti} \sum_{y\in\Omega_{NP}^{T_i}} U_y^{Ti}\Big(G_{xy}\cos\theta_{xy}^{T_i} \\
& \qquad + B_{xy}\sin\theta_{xy}^{T_i}\Big) = 0, \\
& \qquad \forall x \in \Omega_{NP}^{T_i} = \Omega_N^{T_i} \bigcup V_{CRP} \\
& Q_{Gx}^{T_i} - Q_{ILx}^{T_i} - U_x^{Ti} \sum_{y\in\Omega_{NP}^{T_i}} U_y^{Ti}\Big(G_{xy}\sin\theta_{xy}^{T_i} \\
& \qquad + B_{xy}\cos\theta_{xy}^{T_i}\Big) = 0, \\
& \qquad \forall x \in \Omega_{NP}^{T_i} = \Omega_N^{T_i} \bigcup V_{CRP} \\
& P_{Gn}^{\min} \le P_{Gn}^{T_i} \le P_{Gn}^{\max} \quad \forall n \in \Omega_G^{T_i} \\
& Q_{Gn}^{\min} \le Q_{Gn}^{T_i} \le Q_{Gn}^{\max} \quad \forall n \in \Omega_G^{T_i} \\
& U_m^{\min} \le U_m^{T_i} \le U_m^{\max} \quad \forall m \in \Omega_N^{T_i} \bigcup V_{CRP} \\
& \left|P_{Lb}^{T_i}\right| \le P_{Lb}^{\max} \quad \forall b \in \Omega_L^{T_i} \bigcup l \\
& f^{\min} \le f^{T_i} \le f^{\max} \\
& \Delta P_{Gx}^{T_i}/\Delta T \le R_{Mx}/60 \\
& 0 \le T_{Gn_x}^{T_i} \le T_{Gn_x}^{\max} \quad \forall n_x \in \Omega_{G\max} \\
& T_{Gn_i}^{T_i} \ge T_{Gn_i}^{\min} \quad \forall n_i \in \Omega_{G\min}
\end{aligned} \tag{12}
$$

Based on the model in (12), a serial of restoration paths optimized in each time period (i.e., the optimal restoration paths of restorative self-healing strategy) and a restored network which is connected by these restoration paths can be obtained. Thus, the final network restored is denoted as the destination restoration network which is the objective of the network reconfiguration. It consists of the important nodes of the generating units and loads, and key transmission lines (or transformer branches).

Finally, the energy not supplied of the important loads in the power system are calculated by

$$
L_{Energy} = \sum_{T_i=0}^{T_{Total}} \left\{ \sum_{j\in\Omega_{UR}^{T_i}} P_{ILj}^{T_i}(T_i - T_{i-1}) \right\}. \tag{13}
$$

D. The Steps for Restorative Self-Healing Optimization Strategy of Power Systems

In summary, the steps for restorative self-healing optimization strategy of power systems are as follows:

1) Simplify the power system studied and represent it with an undirected and weighted abstraction graph. Set the counting number of time periods i=0.

2) Count the candidate restoration paths and their number.

3) Check if there are redundant transmission lines in the set of candidate restoration paths. If yes, remove the redundant transmission lines from the set of candidate restoration paths.

4) Select one of the candidate restoration paths l, $l \in \Omega_{CPRs}^{T_i}$.

5) Remove the other candidate restoration paths in $\Omega_{CPRs}^{T_i}$ from the unrestored region of the power system.

6) Calculate d_{Sj} by using the Dijkstra algorithm, and then calculate the electrical *betweenness* B_l by using (1).

7) Select another candidate restoration paths in $\Omega_{CPRs}^{T_i}$.

8) Repeat step 4) to step 7) until the electrical *betweenness* of every candidate restoration path in $\Omega_{CPRs}^{T_i}$ is calculated.

9) Rank the candidate restoration paths according to their electrical *betweennesses* calculated. The candidate restoration path with maximum electrical *betweenness* is regarded as the optimal and preferred restoration path for the restorative self-healing strategy, and the other candidate restoration paths are considered as the alternative restoration paths.

10) Restore the optimal and preferred restoration path, and check the constraints in (3)-(11). If the constraints are satisfied, the preferred restoration path and its terminal node in the unrestored region of the power system are removed from the unrestored region and added into the restored region, i.e., S_{EBS}. Otherwise, the alternative restoration path with the largest *betweenness* is selected as the optimal and preferred restoration path, and then the constraints are checked again until one restoration path with the satisfied constraints is found.

11) Update the sets of S_{EBS} and the unrestored region of the power system.

12) Set $T_{i+1} = T_i + \Delta T$, and repeat step 2) to step 11) until all the important nodes of generation units and loads are merged into the restored region, i.e., S_{EBS}.

13) List the optimal and preferred restoration paths in different time periods in series, and then the optimal restoration paths for the restorative self-healing strategy of the power system attained.

14) Attain the destination restoration network by connecting the optimal restoration paths.

IV. Case Study

The New England 10-unit 39-bus power system and a part of the actual Guangdong power system in China are employed to illustrate the features of the proposed restorative self-healing strategy. In this work, it is assumed that both α and β are equal to 1, and E is equal to 2. The initial frequency of the power systems is assumed to be 50Hz, and both the maximum deviations of the voltage magnitude and frequency are set to be $\pm$10%.

A. The New England 10-Unit 39-Bus Power System

The 10-unit 39-bus New England power system is employed to verify the effectiveness and reasonableness of the proposed restorative self-healing strategy. Suppose that the black-start unit locate at bus 34, and it supplies power to bus 33 where non-black-start unit locates in the black-start phase, hence the black-start path are as follows: 34→20→19→33. It is assumed that the amounts of the important loads (i.e., the high priority loads) of the nodes are 30 percent of their loads, respectively. The detailed parameters of the generators and loads can be found in [3], [5], and [7]. It is assumed that the restarting time for an non-black-start generator is 15 minutes, and the times for energizing a transmission line and its another terminal bus or picking up the load in a bus are 5 minutes.

The first step is to simplify the power system before the restorative self-healing strategy is employed to restore the power system after a blackout. The major task in this step is to combine the vertexes in each black-start path as a new vertex, i.e., the initial S_{EBS}, and to find out the set of the unrestored region of the power system. It can be seen that the nodes 19, 20, 33 and 34 and the transmission lines between them are merged into the restored region of the power system which is named as the initial S_{EBS}, i.e., S_{EBS}^0={V_{19},V_{20},V_{33},V_{34},L_{34-20},L_{20-19},L_{19-33}}. Then, the power system is simplified as a sparsely connected, unidirectional and weighted graph. The graph consists of 36 vertexes and 43 edges, and the reactance of each transmission line is selected to be their weight respectively. It can be found that the initial candidate restoration path is line L_{19-16}, i.e., $\Omega_{CRPs}^{T_0}$={L_{19-16}}.

After the optimization of the restorative self-healing strategy is carried out, the electrical *betweennesses* of the candidate restoration paths at all the time periods are calculated, and the results of each iteration are shown in Table I. For demonstrating the meaning of Table I, the second line (i.e., the line of T_1) in Table I is taken as an example. It can be seen that the optimal restoration path optimized in time period T_1(i.e., the fifth minute) is to restore transmission line 16-24 (i.e., L_{16-24}) because its electrical *betweenness* is 199.4 which is maximal among the candidate restoration paths L_{16-15}, L_{16-17}, L_{16-21}, and L_{16-24}; and the other candidate restoration paths (L_{16-21}, L_{16-17}, and L_{16-15},) are considered as alternative restoration paths because their electrical *betweenness* are 191.2, 159.6 and 122.9 respectively which are smaller than that of L_{16-24}. Furthermore, in the optimization process, several redundant restoration paths with larger line charging capacitors are removed from the set of candidate restoration paths at different time periods, such as line L_{22-21} in the 5th iteration, line L_{26-28} in the 15th iteration, line L_{3-18} in the 18th iteration, lines L_{8-9} and L_{6-7} in the 26th iteration, and line L_{15-14} in the 27th iteration.

It can be seen from Table I that one optimal restoration path for restorative self-healing strategy can be found out in each iteration, and several alternative paths are also listed for replacing the optimal restoration path selected if the power system with the selected path at this time period cannot respect all the constraints. The duration time for the whole restorative self-healing process of the power system is 165 minutes. It can be also seen that the electrical *betweenness* calculated of optimal path does not decay with the increasing iteration

TABLE I
OPTIMAL RESTORATION PATHS AND THEIR ELECTRICAL BETWEENNESSES OBTAINED IN EACH ITERATION FOR THE NEW ENGLAND POWER SYSTEM

No. of T_i	Candidate restoration paths (the values of B_l)	
	Optimal paths	Alternative paths
0	19-16(282.4)	———
1	16-24(199.4)	16-21(191.2) 16-17(159.6) 16-15(122.9)
2	24-23(306.2)	16-21(185.4) 16-17(159.6) 16-15(122.9)
3	23-36(330)	23-22(208.1) 16-17(159.6) 16-21(134.9) 16-15(122.9)
4	23-22(208.1)	16-17(159.6) 16-21(134.9) 16-15(122.9)
5	22-35(375)	16-17(159.6) 16-15(122.9) 16-21(41.1)
6	16-17(159.6)	16-15(122.9) 16-21(41.1)
7	17-27(221.0)	17-18(202.4) 16-15(124.0) 16-21(41.1)
8	27-26(288.9)	17-18(201.1) 16-15(123.6) 16-21(41.1)
9	26-25(367.6)	26-29(290.5) 17-18(190.2) 26-28(168.4) 16-15(120.9) 16-21(41.1)
10	25-2(348.1)	25-37(320) 26-29(290.5) 26-28(168.4) 17-18(166.0) 16-15(114.9) 16-21(41.1)
11	2-1(383.6)	25-37(320) 26-29(290.5) 2-3(185.7) 2-30(175) 26-28(168.4) 17-18(110.6) 16-15(109.4) 16-21(41.1)
12	1-39(767.1)	25-37(320) 26-29(290.5) 2-3(185.7) 2-30(175) 26-28(168.4) 17-18(110.6) 16-15(109.4) 16-21(41.1)
13	25-37(320)	26-29(290.5) 2-30(175) 26-28(168.4) 2-3(163.3) 16-15(108.0) 39-9(103.0) 17-18(99.4) 16-21(41.1)
14	26-29(290.5)	2-30(175) 26-28(168.4) 2-3(163.3) 16-15(108.0) 39-9(103.0) 17-18(99.4) 16-21(41.1)
15	29-38(465)	L2-30(175) 2-3(163.3) 16-15(108.0) 39-9(103.0) 17-18(99.4) 16-21(41.1) 29-28(30.9)
16	2-30(175)	2-3(163.3) 16-15(108.0) 39-9(103.0) 17-18(99.4) 16-21(41.1) 29-28(30.9)
17	2-3(163.3)	16-15(108.0) 39-9(103.0) 17-18(99.4) 16-21(41.1) 29-28(30.9)
18	3-4(206.3)	16-15(100.5) 39-9(99.3) 16-21(41.1) 29-28(30.9) 17-18(23.7)
19	4-5(215.8)	4-14(91.5) 39-9(89.9) 16-15(81.7) 16-21(41.1) 29-28(30.9) 17-18(23.7)
20	5-6(372.881)	5-8(179. 8) 4-14(91.5) 39-9(89.9) 16-15(81.7) 16-21(41.1) 29-28(30.9) 17-18(23.7)
21	6-31(574.2)	6-11(97.4) 5-8(95.8) 6-7(74.2) 16-15(71.6) 4-14(71.2) 39-9(47.9) 16-21(41.1) 29-28(30.9) 17-18(23.7)
22	6-11(97.4)	5-8(95.8) 6-7(74.2) 16-15(71.6) 4-14(71.2) 39-9(47.9) 16-21(41.1) 29-28(30.9) 17-18(23.7)
23	11-10(193.8)	5-8(95.8) 6-7(74.2) 16-15(71.7) 4-14(71.2) 11-12(54.2) 39-9(47.9) 16-21(41.1) 29-28(30.9) 17-18(23.7)
24	10-32(375)	5-8(95.8) 6-7(74.2) 16-15(48.2) 39-9(47.9) 16-21(41.1) 29-28(30.9) 4-14(24.3) 17-18(23.7) 10-13(12.6) 11-12(7.3)
25	5-8(95.8)	6-7(74.2) 16-15(48.2) 39-9(47.9) 16-21(41.1) 29-28(30.9) 4-14(24.3) 17-18(23.7) 10-13(12.6) 11-12(7.3)
26	16-15(48.2)	16-21(41.1) 8-7(35.07) 29-28(30.9) 4-14(24.3) 17-18(23.7) 10-13(12.6) 11-12(7.3) 39-9(0)
27	16-21(41.1)	8-7(35.1) 29-28(30.9) 17-18(23.7) 11-12(1.3) 10-13(0.6) 4-14(0.31875) 39-9(0)
28	8-7(35.1)	29-28(30.9) 17-18(23.7) 11-12(1.3) 10-13(0.6) 4-14(0.3) 39-9(0)
29	29-28(30.9)	17-18(23.7) 11-12(1.3) 10-13(0.6) 4-14(0.3) 39-9(0)
30	17-18(23.7)	11-12(1.3) 10-13(0.6) 4-14(0.3) 39-9(0)
31	11-12(1.35)	10-13(0.6) 4-14(0.3) 39-9(0)
32	——	39-9(0) 4-14(0) 10-13(0)

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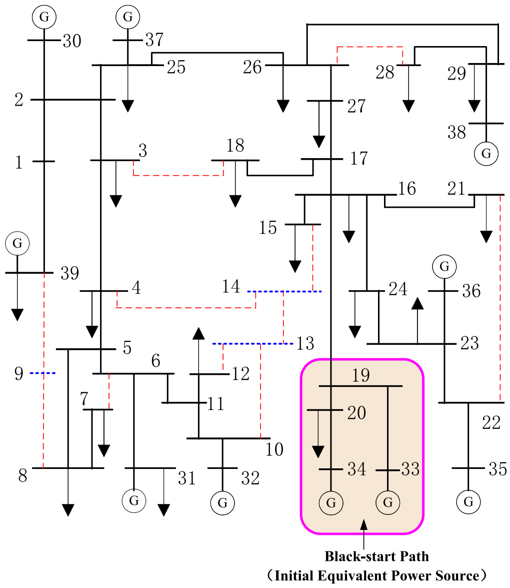

Fig. 1. The destination skeleton network in the network reconfiguration of the New England power system.

TABLE II
COMPARISONS OF THE OPTIMIZATION RESULTS OBTAINED BY THREE RESTORATION STRATEGIES FOR NEW ENGLAND POWER SYSTEM

	Duration Times (Minutes)	Energy Not Supplied (MWh)
Traditional restoration strategies [14, 22, 23]	165	2301.09
Maximum generation capability strategy [5]	165	2332.05
Restorative Self-healing strategy proposed	165	2238.62

(i.e., the decreasing scale of the unrestored region of the power system), which shows that the importance of some transmission lines changes in the restorative self-healing process. Based on the restorative self-healing results in Table I, the destination skeleton network in the network reconfiguration shown in Fig. 1 can be obtained. It can be seen from Fig. 1 that most of transmission lines and nodes are restored, except for 3 nodes without loads (i.e., the nodes V_9, V_{13} and V_{14}) and 11 transmission lines which consist of the redundant lines removed by the restorative self-healing strategy, and the transmission lines connected with the 3 nodes without loads.

For comparisons, the optimization results obtained by the traditional restoration strategies [14], [22], [23], which did not take the relative importance and restoration priority of the important loads to be restored, or the distribution of the nodes to be restored (i.e., every edge with equal weight, or electrical susceptance as the weight) into consideration, are presented in Table II. In this paper, the strategy with equal line weight, and that in which electrical susceptance of each line is set as the weight are taken for comparisons. The optimal restoration paths for both the traditional restoration strategies are as follows: $S \to 16 \to 21 \to 22 \to 35 \to 23 \to 36 \to 17 \to 27 \to 26 \to 25 \to 37 \to 2 \to 1 \to 39 \to 29 \to$

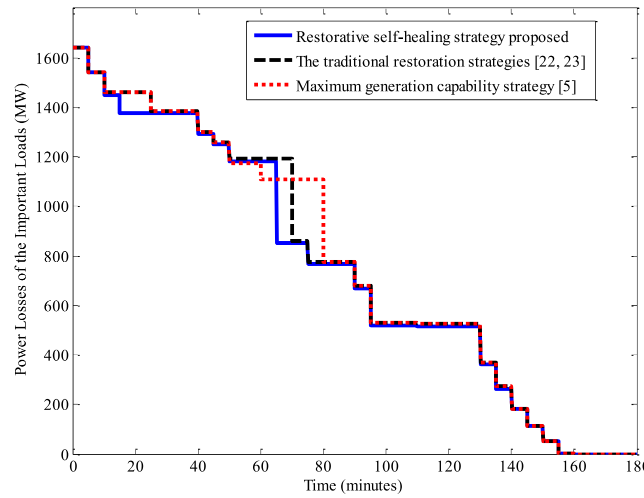

Fig. 2. Comparisons of power losses of the important loads at different time periods for the New England power system.

$38 \to 30 \to 3 \to 4 \to 5 \to 6 \to 31 \to 11 \to 10 \to 32 \to 8 \to 15 \to 24 \to 7 \to 28 \to 18 \to 12$. The duration time is 165 minutes, which is same to that optimized by the proposed restorative self-healing strategy. Furthermore, the generator start-up strategy which takes maximum generation capability as the optimization objective objective in [5] is also performed for comparisons. The strategy in [5] considers the optimal startup of the generators, but the restoration of load nodes is ignored. So, the load nodes are restored according to the amounts of the load in each node after all the nodes of the generators are restored for considering the comparability with the restorative self-healing strategy proposed. The optimal restoration paths for this maximum generation capability strategy are as follows: $S \to 16 \to 21 \to 22 \to 35 \to 23 \to 36 \to 17 \to 27 \to 26 \to 29 \to 38 \to 25 \to 37 \to 2 \to 1 \to 39 \to 30 \to 3 \to 4 \to 5 \to 6 \to 31 \to 11 \to 10 \to 32 \to 8 \to 15 \to 21 \to 7 \to 28 \to 18 \to 12$. The duration time is also 165 minutes. Table III shows that the comparison of the optimization results obtained by the traditional restoration strategy, maximum generation capability strategy and the proposed restorative self-healing strategy. The power losses of the important loads at different time periods, which optimized by the traditional restoration strategies, maximum generation capability strategy and the proposed restorative self-healing strategy, are plotted in Fig. 2. It can be obtained that the energy not supplied of the important loads optimized by traditional restoration strategies is 2301.09MWh, and that by the proposed restorative self-healing strategy and maximum generation capability strategy are 2238.62MWh and 2332.05MWh. As a result, the energy not supplied of the important loads can be reduced by 62.47MWh (2.71% comparing with traditional restoration strategies) and 93.43MWh (4.01% comparing with maximum generation capability) after the proposed restorative self-healing strategy are employed in the network reconfiguration of the power system. The average computation times for optimizing every step of restoration paths of the traditional restoration strategies, maximum generation capability strategy and the proposed restorative self-healing strategy are 0.33s, 0.02s and 0.33s, respectively. Though the average computation

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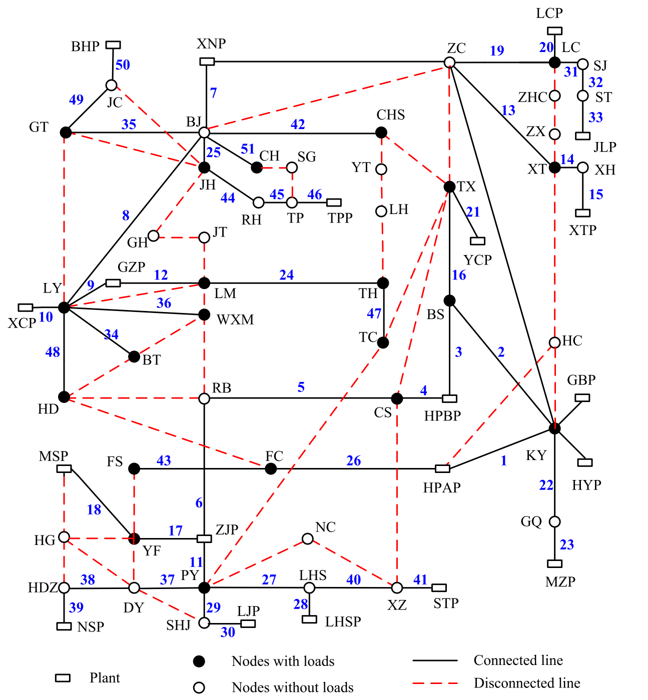

Fig. 3. The destination skeleton network for a part of the Guangdong power grid in China.

time of the proposed strategy is not better than the other strategies, it is far less than the time period (5 minutes) of one restoration step, so it is enough for obtaining the next restoration step and can be employed in the restorative self-healing.

Finally, the sensitivity on the proportion of the important loads is performed for checking the solution stability of the restorative self-healing algorithm. It can be obtained that the proportions for keeping optimal restoration paths unchanged are from 22% to 35%, which means that the same result is obtained with a certain proportion range of the important loads.

B. Part of the Guangdong Power System

A part of the Guangdong power grid in China as shown in Fig. 3 is also employed to verify the effectiveness of the proposed strategy. It consists of 22 generators, 66 nodes and 95 transmission lines. The black-start units locate at bus XNP, and it supplies power to bus KY where non-black-start units HYP and GBP locates in the black-start phase, hence the black-start path are as follows: XNP→ZC→KY→HYP&GBP. Thus, the nodes XNP, ZC, KY, HYP and GBP are merged into the restored region of the power system which is named as the initial S_{EBS}, i.e., S^{0}_{EBS}={V_{XNP},V_{ZC},V_{KY}, V_{HYP},V_{GBP},$L_{\mathrm{XNP\text{-}ZC}}$,$L_{\mathrm{ZC\text{-}KY}}$,$L_{\mathrm{KY\text{-}HYP}}$,$L_{\mathrm{KY\text{-}GBP}}$}. The amounts of the important loads (i.e., the high priority loads) of the nodes are 10 percent of their loads, respectively. Then, the power system is simplified as a sparsely connected, unidirectional and weighted graph. The graph consists of 62 vertexes and 91 edges, and the reactance of each transmission line is selected to be their weight

TABLE III
COMPARISONS OF THE OPTIMIZATION RESULTS OBTAINED BY THREE RESTORATION STRATEGIES FOR GUANGDONG POWER SYSTEM

	Duration Times (Minutes)	Energy Not Supplied (MWh)
Traditional restoration strategies [14, 22, 23]	255	1626.2
Maximum generation capability strategy [5]	260	1712.6
Restorative Self-healing strategy proposed	260	1208.7

respectively. It can be found that the set of the initial candidate restoration paths $\Omega^{T_0}_{\mathrm{CRPs}}$ ={$L_{\mathrm{XNP\text{-}BJ}}$,$L_{\mathrm{ZC\text{-}LC}}$, $L_{\mathrm{ZC\text{-}XT}}$,$L_{\mathrm{ZC\text{-}TX}}$,$L_{\mathrm{KY\text{-}HC}}$,$L_{\mathrm{KY\text{-}GQ}}$,$L_{\mathrm{KY\text{-}HPAP}}$,$L_{\mathrm{KY\text{-}BS}}$} when the redundant restoration line $L_{\mathrm{ZC\text{-}BJ}}$ is removed. Then, the proposed restorative self-healing strategy is applied to the simplified power system, and the optimization results are shown in Fig. 3. In Fig. 3, the numbers which is close to each transmission line and with blue color are the optimal sequence of restoration paths optimized. The red dotted lines are the transmission lines which consist of the redundant lines removed by the restorative self-healing strategy, and the transmission lines connected with the nodes without loads.

Table III and Fig. 4 show that the comparison of the optimization results obtained by the traditional restoration strategies, maximum generation capability strategy and the proposed restorative self-healing strategy. It can be seen from Table III that the restoration duration time optimized by the traditional one, which is 255 minutes, is less than that optimized by the proposed one and maximum generation capability strategy, which are 260 minutes. However, the energy not supplied of the important loads optimized by the proposed restorative self-healing strategy is 1208.7MWh, which is far less than that by the traditional restoration strategies and maximum generation capability strategy. As a result, the energy not supplied of the important loads can be reduced by 417.5MWh (25.7% comparing with traditional restoration strategies) and 503.9MWh (29.4% comparing with traditional restoration strategies) after the proposed restorative self-healing strategy are employed in the network reconfiguration of the power system, though its restoration duration time is slightly more than the traditional one. The average computation times for optimizing every step of restoration paths by the traditional restoration strategies, maximum generation capability strategy and the proposed restorative self-healing strategy are 15.92s, 1.10s and 15.59s, respectively. It can be seen that average computation time of the proposed strategy is slightly less than that of traditional ones. Though the average computation time of the proposed strategy is not better than maximum generation capability strategy, it is far less than the time period (5 minutes) of one restoration step, so it is enough for obtained the next restoration step and can be employed in the restorative self-healing.

Finally, the sensitivity on the proportion of the important loads is performed for checking the solution stability of the algorithm. It can be obtained that the proportions for keeping

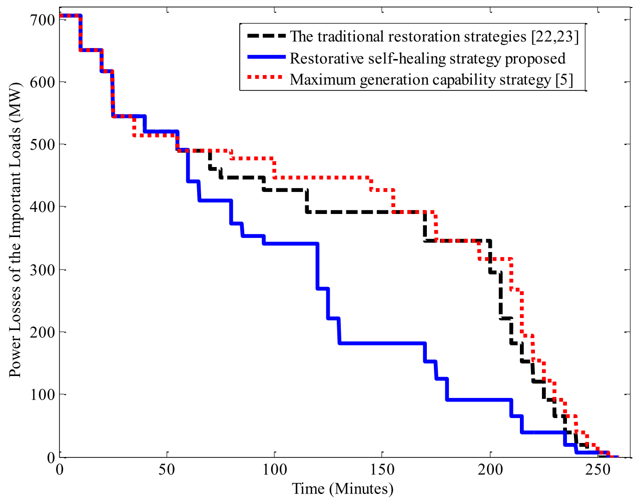

Fig. 4. Comparisons of power losses of the important loads at different time periods for Guangdong power system.

optimal restoration paths unchanged are from 9% to 20%, which means that the same result is obtained with a certain proportion range of the important loads.

V. Conclusion

The restorative self-healing of transmission systems is first presented. Then, the electrical *betweenness*, which can reflect not only the relative importance and restoration priority of the non-black-start generators to be restarted and the important loads to be restored, but also the distribution of the nodes to be restored, is defined based on the complex network theory. Based on the presented electrical *betweenness*, a restorative self-healing optimization model and strategy are proposed for determining the optimal restoration path and the destination skeleton network of power systems. Finally, the New England 10-unit 39-bus system and a part of the actual Guangdong power system in China are employed to illustrate the feature of the proposed strategy. The numerical examples show that the energy not supplied of the important loads can be reduced by using the proposed restorative self-healing strategy when comparing to the traditional restoration strategies and maximum generation capability strategy.

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