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An Improved Label Propagation Algorithm-Based Method to Develop Sectionalizing Strategies for Parallel Power System Restoration

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ABSTRACT The first task of parallel power system restoration is to sectionalize the blackout system into multiple subsystems. This paper applies the complex network community discovery theory into this sectionalizing problem and proposes an improved label propagation algorithm-based sectionalizing method considering the system topology and operation before blackouts. Firstly, each blackstart (BS) unit bus is marked with a different subsystem label. A label propagation matrix is calculated based on the active power of branches before the blackout. Then, to avoid the label oscillation, a novel label impact strategy considering the influence of the bus label itself is developed to improve the label propagation matrix. The buses' labels propagate to neighboring buses as the improved label propagation matrix until they do not change. The initial sectionalizing strategy is obtained through classifying the buses with the same label in the same subsystem. Finally, the sectionalizing constraints are used to evaluate the feasibility of the initial strategy. For the initial strategy that does not satisfy the constraints, a refining method to minimize the absolute value of active power exchange among subsystems is proposed to determine the final sectionalizing strategy based on it. Case studies on IEEE 39-bus and IEEE 118-bus test systems verify the effectiveness of the proposed method. The results indicate that the proposed method has advantages in creating strongly connected subsystems.

INDEX TERMS Power system restoration, sectionalizing strategy, label propagation algorithm, tie line.

I. INTRODUCTION

In the past decade, several major blackouts caused by various reasons have happened around the world, e.g., the blackout of India caused by the high-temperature weather in 2012 [1], the blackout in Ukraine caused by the cyber-attack in 2015 [2], and the blackout in the South Australian power grid caused by the extreme weather in 2016 [3]. Lots of researches and practical experience show that reasonable and effective power system restoration strategies can shorten the outage time [4], [5], and reduce the economic loss and the negative impact on the public of blackouts [6].

In order to accelerate the restoration process following a blackout, parallel power system restoration is commonly applied, which is to sectionalize the blackout system into multiple subsystems to be restored in parallel [5], [7]. The main process of parallel restoration comprises three stages: Preparation, system restoration, and load restoration [7].

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In the preparation stage, the blackout system is sectionalized into several subsystems considering the status of the blackout system and the constraints of parallel restoration, including the blackstart (BS) generators, generation-load balance, etc. Accordingly, the determination of suitable sectionalizing strategies is the first task for the system dispatchers during the preparation stage of parallel power system restoration.

Many utilities and ISOs (Independent System Operators), e.g., the British network [8], the Italian network [9], the PJM (Pennsylvania-New Jersey-Maryland Interconnection) [10] and the Philadelphia Electric Company [11] in the United States, have designed their sectionalizing strategies for parallel restoration. These strategies are mainly based on expert experience and geographic information, ignoring the physical characteristics of the blackout system. In recent years, much attention has been paid to the theoretical investigations on sectionalizing strategies for parallel restoration. The sectionalizing problem is usually formulated as an optimization model with objectives to minimize the difference of restoration time among subsystems, minimize the number of tie lines, maximize the number of buses monitored, etc. Many methods, e.g., mathematical programming [12]–[15], artificial intelligence algorithms [16], [17], have been proposed to solve it. Generally, these methods to generate a sectionalizing strategy are usually based on a specific restoration strategy. There is no guarantee that the specific restoration strategy is applied successfully during the restoration process. Thus, practical sectionalizing strategies satisfying fundamental sectionalizing constrains should be studied. Since a power system can be abstracted as a graph, the graph theory has been applied to the sectionalizing problem of the power system [18]–[22]. The determination of the sectionalizing strategy is to find the tie lines among subsystems with consideration of sectionalizing constraints. The complex combination of possible lines makes the solution space huge. To reduce the solution space, Reference [18] proposed a sectionalizing method based on the ordered binary decision diagram (OBDD). Reference [19] identified a branch/node incidence matrix and a partition indicator vector for obtaining the sectionalizing strategy with objectives of minimizing cuts and maximizing the power imbalance between subsystems. Reference [20] proposed a method based on the theory of the cut-set matrix. Multiple strategies can be obtained for dispatchers. The complexity of the method is low. Based on [20], Reference [21] proposed a sectionalizing model to get an optimal strategy with the objectives of minimizing the number of tie lines and maximizing the electrical distance of the lines between subsystems. Reference [22] proposed a heuristic-based method to assess the total restoration time. The sectionalizing strategy was determined by searching the optimal cut-set lines. Since these methods can only get two new subsystems in one iteration, multiple iterations are needed to generate multiple subsystems.

Since the community structure is a common characteristic of actual networks, e.g., power systems, and transportation systems, the complex network theory has been applied to the power system sectionalization for parallel restoration [23]–[29]. In the complex network theory, a network can be composed of several communities. The nodes within the community are closely connected, whereas that between communities is relatively sparser [24]. The community discovery theory can be used to calculate the tightness of nodes in the network, then put the close nodes into the same community. Hence, the community structure reveals the topology and the functional characteristics of the network [25]. Community discovery methods have been used in the sectionalizing problems of the power system. Reference [26] proposed the edge betweenness to reflect the relationship between nodes and applied the Girven Newman (GN) algorithm into the power system sectionalization for parallel restoration. The high-betweenness lines were selected as the tie lines between different subsystems. Reference [27] used the spectral clustering method to determine the controlled islands for preventing the blackout. Based on the method in [27], Reference [28], [29] considered the distance from the BS unit buses to every bus and sectionalized the system into multiple subsystems, which depended on the eigenvalues of the Laplacian matrix of the system network.

The methods mentioned above worked well for the power system sectionalizing problem. However, these methods focused on the topology of the power system and ignored the operating characteristics before a blackout occurred. The target of system restoration is to restore the blackout system to the pre-blackout condition as soon as possible. Hence, the topology and operation of power systems in the normal condition have effects on the determination of subsystems. The power flow of the power system in normal conditions is a key index to reflect the relationship between different buses. Thus, it should be used as an essential factor in the sectionalization for parallel restoration. Furthermore, the challenge of power system sectionalization is to handle a large number of the possible tie lines with consideration of the requirements of parallel restoration. For a large-scale power system, increasing the number of subsystems will increase the computational complexity for determining sectionalizing strategies.

Based on the above discussion, this paper proposes an improved label propagation algorithm-based method to determine sectionalizing strategies for parallel restoration. The label propagation algorithm is widely used because of its low complexity and excellent classification ability [25]. A power system is abstracted as a weighted graph. The weight of each edge, representing a transmission line or a transformer, is specified with its transporting active power. Thus, the operation condition of the system before a blackout is considered as a critical sectionalizing factor. To deal with the label oscillation, an improved label impact strategy is proposed for generating the initial sectionalizing strategy rapidly. If the initial strategy does not satisfy sectionalizing constraints, a refining method with an objective of minimizing the power exchange among different subsystems is proposed to determine the final strategy. The main contributions of this paper are as follows:

- The active power of transmission lines, as well as the power system topology before blackouts occurr, is considered in the problem formulation. It helps to obtain the subsystems with the tight inner-connection.
- The proposed sectionalizing method can generate multiple subsystems directly with low complexity. With consideration of the influence of the bus label itself, the proposed method can avoid the label oscillation, and its convergence is improved.
- A refining method with the objective of minimizing the absolute value of active power exchange among subsystems is proposed. It helps to generate strongly connected and self-sufficient subsystems to improve the efficiency of parallel restoration.

The remainder of this paper is organized as follows. Section II introduces the principles of subsystem determination for parallel restoration. Section III describes the proposed method. Simulation results for the IEEE 39-bus and IEEE 118-bus test systems are presented in Section IV. Section V concludes the paper.

II. THE PRINCIPLES OF SUBSYSTEM DETERMINATION FOR PARALLEL RESTORATION

A sectionalizing strategy is to use suitable generating units, substations, transformers, transmission lines, and load to form different subsystems. This paper considers the following principles to determine suitable sectionalizing strategies [4], [18], [21], [30]:

1) To have the self-restoration capacity, each subsystem should contain at least one BS generating unit. Thus, the number of subsystems is not larger than the number of BS generating units:

$$S \leq N_{\mathrm{BS}} \tag{1}$$

where S is the number of subsystems, and N_{BS} is the number of BS units.

2) The relationship between the nodes in the same subsystem should be strong, whereas that between the nodes in different subsystems should be weak. It helps to guarantee the success and independence of the subsystem restoration.

3) The size of the subsystem should be approximately equal. It is beneficial to reduce the difference of restoration complexity between different subsystems and improve the efficiency of parallel restoration. In this paper, the distance between neighboring nodes is defined as 1 [31]. For subsystem s, its size refers to the maximum value of the shortest distance from the BS node to other nodes:

$$V_s = \max\left\{m_{\mathrm{BS},i}\right\} \tag{2}$$

where V_s is the size of subsystem s, and $m_{\mathrm{BS},i}$ denotes the number of lines in the shortest path from the BS unit to node i. The number of branches in the shortest path from the BS node to node i in the subsystem can be obtained by Dijkstra algorithm.

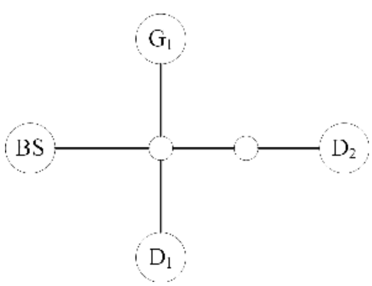

FIGURE 1. An example of a 6-node network.

For example, there is a 6-node network in Fig. 1. The $m_{\mathrm{BS},i}$ of the shortest paths from BS to G_1 or D_1 is equaled to 2, while that of the path from BS to D_2 is 3. V_s is the maximum $m_{\mathrm{BS},i}$, i.e., $V_s = \max\{m_{\mathrm{BS,G1}}, m_{\mathrm{BS,D1}}, m_{\mathrm{BS,D2}}\} = \max\{2, 2, 3\}$. Therefore, V_s of the 6-node network is 3.

4) A subsystem must contain sufficient load to maintain the power balance between the available generation and the load. Since each unit has its minimum output power, the total load should not be less than the minimum output power of all the units in each subsystem:

$$\sum_{i=1}^{N} P_{\mathrm{G}i}^{\min} - \sum_{i=1}^{N} P_{\mathrm{D}i} \leq 0 \quad i = 1, 2, \ldots, N \tag{3}$$

where $P_{\mathrm{G}i}^{\min}$ is the minimum rated output power of generator i, $P_{\mathrm{D}i}$ is the demand of load at node i.

5) The active power output of generators should be approximately balanced with loads in each subsystem. The balance can ensure that each subsystem has the possibility of independent restoration and is prevented from exceeding the frequency limit when subsystems cannot be interconnected with each other. This constraint is mainly used to ensure that the frequency remains within an acceptable range:

$$\left|\sum_{i=1}^{N} P_{\mathrm{G}i} - \sum_{i=1}^{N} P_{\mathrm{D}i}\right| \leq d \quad i = 1, 2, \ldots, N \tag{4}$$

where $P_{\mathrm{G}i}$ is the rated output power of generator i, d is the imbalanced active power in each subsystem.

For instance, the imbalanced active power d limit is set as $0.11P_{\mathrm{subG}}$ (P_{subG} is the overall active power output of units in each subsystem) in [18] when the lowest system average frequency is 57 Hz. The frequency should be higher than 58.5Hz for the sake of security in the 60Hz power system [32]. Therefore, the allowable threshold of imbalanced active power d of each subsystem should be less than $0.065P_{\mathrm{subG}}$, which can improve the frequency response capability of the power system. A low d could improve the frequency responseability of a power system.

III. SECTIONALIZING METHODOLOGY

In this section, an improved label propagation algorithm-based method, as shown in Fig. 2, is proposed to make decisions on sectionalizing strategy considering all sectionalizing principles of Section II. The proposed method includes three parts: a) initialize; b) generate the initial sectionalizing strategy; c) evaluate and refine the sectionalizing strategy.

Part 1 is to input data about the topology and the operation state of the power system before a blackout occurs. The number of subsystems is determined based on the BS generating units. Considering principles 1-3, part 2 applies the label propagation algorithm to generate the initial sectionalizing strategy. To avoid the oscillation of label propagation among buses, a novel label impact strategy is proposed to improve the convergence of the algorithm. Part 3 is to evaluate the feasibility of the initial strategy by the constraints of principles 4-5. If the initial strategy satisfies sectionalizing constraints, it will be the final strategy for application; otherwise, a refining method is used to find the final tie lines based on the initial strategy.

Subsections *A-C* illustrate all parts of the proposed method in detail.

A. PART 1: INITIALIZE

A power system is abstracted as an undirected weighted graph. In the power system, generating unit, substation, and

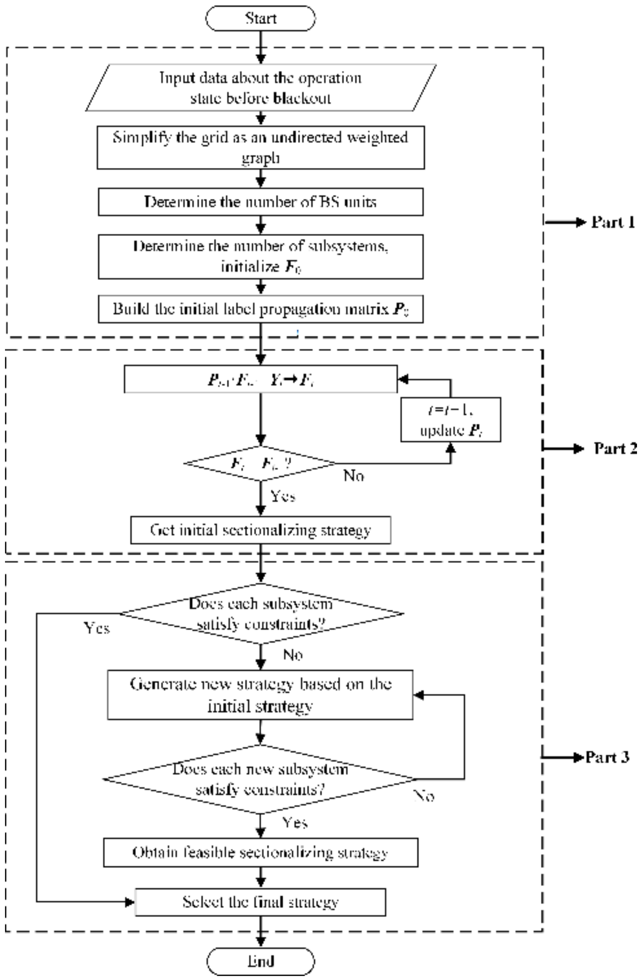

FIGURE 2. Flowchart diagram of the proposed sectionalizing method.

load buses are the set of undifferentiated nodes, the transmission lines and transformers are the set of edges in the graph. In this paper, the active power value of a transmission line or transformer is set as the weight of the corresponding edge. This paper defines the subsystem discriminant matrix $\boldsymbol{F} = [f_{is}]_{N\times S}$, where N is the number of nodes in the power system, and S is the number of subsystems. The element f_{is} in $\boldsymbol{F}$ can be expressed as:

$$f_{is} = \begin{cases} 1, & \text{node } i \text{ in subsystem } s \\ 0, & \text{node } i \text{ not in subsystem } s \end{cases} \tag{5}$$

where $i = 1,2,\ldots,N$; $s = 1, 2, \cdots, S$. Thus, the sectionalizing strategy for the power system can be obtained by $\boldsymbol{F}$.

To satisfy constraint (1), the number of subsystems is not larger than the number of BS units. In order to accelerate the restoration process and shorten the outage time, the power system should be sectionalized into as many subsystems as possible. Hence, it is assumed that there is only one BS unit in each subsystem in this paper. The number of subsystems equals to the number of BS units. Based on the number and the position of BS units, the initial subsystem discriminant matrix $\boldsymbol{F}_0$ is obtained.

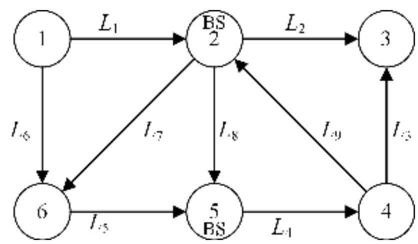

FIGURE 3. The diagram of a 6-bus system.

Figure 3 shows a system with 6 nodes and 9 edges. There are two BS units located at nodes 2, and 5, respectively. Thus, the system is divided into two subsystems. The initial subsystem discriminant matrix is:

$$\boldsymbol{F}_0 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}^{\mathrm{T}}$$

B. PART 2: GENERATE THE INITIAL SECTIONALIZING STRATEGY BASED ON IMPROVED LABEL PROPAGATION ALGORITHM

This part is to determine the initial sectionalizing strategy for parallel restoration by applying the improved label propagation algorithm. First, the conventional label propagation algorithm is introduced. Then, a novel label propagation strategy is proposed to avoid the label oscillation and improve the convergence. The process of generating the initial sectionalizing strategy is presented at last.

1) LABEL PROPAGATION ALGORITHM

In a network, some nodes have the initial certain labels based on the prior knowledge, while other nodes have no labels. In the label propagation algorithm, each node can propagate its label to the neighboring nodes, and update its label by the influence of the neighboring node's label. During the propagation process, labels are easy to propagate between the closely connected nodes. The label propagation process continues until the labels of all nodes no longer change [33]. Since the initial nodes' labels are certain, they do not change their labels during the process of label propagation. In this paper, the BS unit bus is used as a certain label node in the grid, and their label does not change during the label propagation.

2) SUBSYSTEM SECTIONALIZING BASED ON LABEL PROPAGATION ALGORITHM

This paper is based on the label propagation algorithm to divide the power system after a blackout. The active power of each branch before the blackout is taken as the weight of its corresponding branch. The larger the active power value of an edge is, the higher the tightness of nodes at both ends of the edge is. Since the tightness of nodes is evaluated by the active power value of branches, the direction of the power flow is ignored in this paper. Therefore, an undirected weighted graph is used to represent the grid. The network weighted adjacent matrix $\boldsymbol{W}$ can be expressed as:

$$\boldsymbol{W} = [w_{ij}]_{N\times N} = \begin{cases} |P_{ij}|, & i \neq j \text{ and } i,\ j \text{ directly connected} \\ 0, & i = j \text{ or } i,\ j \text{ are not directly connected} \end{cases} \tag{6}$$

where N is the number of nodes; w_{ij} is the weight between nodes i and j; P_{ij} is the active power value of branches.

In the label impact strategy of the conventional label propagation algorithm, node i's label is updated according to the label of its neighboring nodes in the $(t-1)^{\text{th}}$ iteration result. The influence matrix after the t times of the label propagation is defined as $\boldsymbol{Y}_t$, and then the conventional label impact strategy can be expressed as

$$\boldsymbol{Y}_t = [y_{t,is}]_{N\times S} = \boldsymbol{P}\boldsymbol{F}_{t-1} \tag{7}$$

$$\boldsymbol{P} = [p_{t,ij}]_{N\times N} = \begin{cases} \dfrac{w_{ij}}{\sum\limits_{k=1}^{N} w_{kj}}, & i \neq j \\ 0, & i = j \end{cases} \tag{8}$$

where $\boldsymbol{P}$ is the label propagation matrix. The element p_{ij} of $\boldsymbol{P}$ indicates the probability that the label propagates from node j to node i. In the conventional label propagation algorithm, nodes are only affected by their neighboring nodes' labels, i.e., $p_{ij} = 0$ $(i = j)$. The influence matrix $\boldsymbol{Y}_t$ reflects the extent to which all nodes of the system are affected by each subsystem label after the t times iteration.

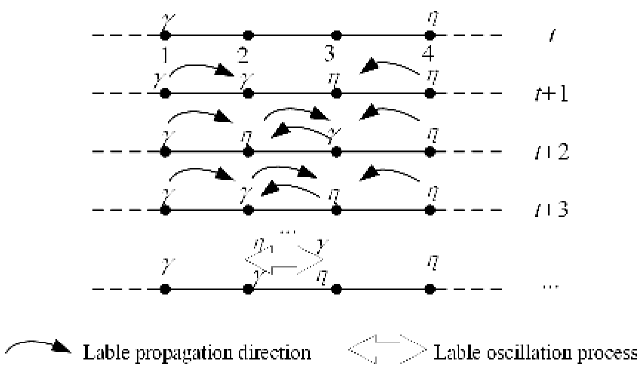

FIGURE 4. The oscillation of nodes' labels.

The label oscillation may occur in the conventional label propagation algorithm [24], shown in Fig. 4. In the t^{th} iteration, node 1 and node 4 are with label γ and label η, respectively, while node 2 and node 3 are without any label. The label oscillation starts between node 2 and node 3 in the $(t+3)^{\text{th}}$ iteration. Node 2 and node 3 update their labels only based on the labels of their neighboring nodes. If the influence between node 2 and node 3 is greater than that from node 1 to node 2, and that from node 4 to node 3, label γ and label η will be repeatedly propagated between node 2 and node 3. Hence, the label oscillation reduces the speed and accuracy of convergence.

Considering the influence of the node label itself, a new label strategy is proposed to improve the label propagation matrix, which can effectively prevent the label oscillation phenomenon and accelerate the convergence. Each node's label is updated according to its neighboring nodes' labels and its own current label.

3) STEPS FOR GENERATING THE INITIAL SECTIONALIZING STRATEGY

The proposed improved label propagation algorithm to generate the initial sectionalizing strategy includes four steps.

Step 1: The BS unit buses are marked as certain labels to obtain the initial subsystem discriminant matrix.

Step 2: In each iteration of the propagation process, each node's label is determined by its neighboring nodes' labels in the $(t-1)^{\text{th}}$ iteration result and its own current label, i.e.,

$$\boldsymbol{Y}_t = [y_{t,is}]_{N\times S} = \boldsymbol{P}_{t-1}\boldsymbol{F}_{t-1} \tag{9}$$

The improved label impact strategy updates the diagonal elements of the propagation matrix $\boldsymbol{P}_{t-1}$ during the process of label propagation. After each iteration of label propagation, the influence of the current label of node i is added to the subsystem node impact indicator $K_{t,is}$, that is:

$$K_{t,is} = \begin{cases} K_{t-1,is} + y_{t,is}, & f_{t,is} = 1 \text{ and } f_{t-1,is} = 0 \\ K_{t-1,is}, & \text{other} \end{cases} \tag{10}$$

where $y_{t,is}$ represents the influence of the current label of node i in subsystem s during the t-th iteration.

Step 3: In the initial stage, the value of K_0, is is 0. The updated K_{is} will be the value of p_{ij} in $\boldsymbol{P}$ of the next iteration. The influence of node i label itself is:

$$p_{t,ii} = \begin{cases} K_{t,is}, & \text{node } i \text{ belongs to subsystem } s \\ 0, & \text{other} \end{cases} \tag{11}$$

Step 4: The improved label propagation matrix $\boldsymbol{P}$ can be expressed as after t $(t > 0)$ times iteration.

$$\boldsymbol{P}_t = [p_{t,ij}]_{N\times N} = \begin{cases} \dfrac{w_{ij}}{\sum\limits_{k=1}^{N} w_{kj}}, & i \neq j \\ K_{t,is}, & i = j \in s, \text{ otherwise } 0 \end{cases} \tag{12}$$

For the initial propagation matrix $\boldsymbol{P}_0$, its value is

$$\boldsymbol{P}_0 = [p_{t,ij}]_{N\times N} = \begin{cases} \dfrac{w_{ij}}{\sum\limits_{k=1}^{N} w_{kj}}, & i \neq j \\ 0, & i = j \end{cases} \tag{13}$$

The nodes' labels will propagate among different nodes by $\boldsymbol{P}_t$. Since the node label itself is a key factor in the proposed label impact strategy, the label oscillation can be effectively avoided. With the propagation of labels, the threshold of each node for labels updated is increasing. Nodes are not easily affected by the labels of remote nodes. Therefore, the random propagation of individual labels as the weights of topological paths can be stopped. Huge subsystems cannot be generated by applying the proposed label influence strategy.

C. PART 3: EVALUATE AND REFINE THE SECTIONALIZING STRATEGY

The initial sectionalizing strategy is obtained in part 2, considering the principles 1-3 in section 2. To ensure the practicability of each subsystem, principles 4 and 5 in section 2 should be considered. For example, principle 5 describes that the total capacity of the generators and the total demand of the loads in each subsystem should be approximately balanced. If each subsystem in the initial sectionalizing strategy satisfies all constraints, the initial strategy is feasible and can be used for system dispatchers; otherwise, the initial strategy should be refined by using the proposed refining method in part 3.

1) SECTIONALIZING CONSTRAINTS FOR EVALUATION

a: ACTIVE POWER OUTPUT CONSTRAINT FOR EACH GENERATING UNIT

In the actual power grid, the unbalanced reactive power can be compensated by local reactive power compensators. So only the active power balance constraint is considered during the power system restoration [18]. To ensure the stable operation of the unit, there should be sufficient load in each subsystem [13], [21]:

$$\sum_{i=1}^{N} \alpha P_{\mathrm{G}i} - \sum_{i=1}^{N} P_{\mathrm{D}i} \leq 0 \quad i = 1, 2, \ldots, N \tag{14}$$

where α is the minimum technical output coefficient.

The load is generally divided into level I, II, and III loads due to the importance of the load and the loss caused by the power outage. It should ensure that there is enough power generation capacity in the subsystem to ensure the restoration of such load [34]. The total capacity of the subsystem is not less than the total amount of the most important loads, i.e., the level I loads:

$$\sum_{i=1}^{N} P_{\mathrm{G}i} - \sum_{i=1}^{N} \beta_i P_{\mathrm{D}i} \geq 0 \quad i = 1, 2, \ldots, N \tag{15}$$

where β_i is the proportion of the level I loads at node i.

b: POWER BALANCE CONSTRAINT

The constraint on power balance, as shown in (4), can maintain the subsystem frequency within an acceptable range. A low imbalanced active power d could improve the frequency response-ability of a power system. This paper refers to [21], which sets d as $0.05P_{\mathrm{subG}}$. The power balance constraint should be accommodated for any subsystem [18], [21], [35].

c: NETWORK CONNECTIVITY CONSTRAINT

Each subsystem should satisfy the constraint on the network connectivity [15], that is,

$$\boldsymbol{J} = 0 \tag{16}$$

$$\boldsymbol{J} = (\boldsymbol{F} \oplus (\boldsymbol{F} \wedge (\boldsymbol{FA})))\boldsymbol{F}^{\mathrm{T}} \tag{17}$$

where $\boldsymbol{J}$ is a $S \times S$ matrix and $\boldsymbol{A}$ denotes the adjacency matrix. $\oplus$ represents the logical operation of exclusive disjunction, and $\wedge$ is the logical operation of conjunction. $\boldsymbol{J}$ is used to judge whether the subsystem is suitable for practicality. If a non-zero element appears in $\boldsymbol{J}$, the corresponding subsystem does not satisfy the constraint on the network connectivity.

2) THE PROPOSED METHOD FOR REFINING THE INITIAL STRATEGY

a: DEFINITION OF TIE LINES AMONG SUBSYSTEMS

When a blackout occurs, sectionalizing restoration of the system can speed up the process of system restoration. The tie lines power, i.e., the power exchange among subsystems, is an important factor indicating the subsystem stability. Simultaneously, the less the power exchange of the tie lines between subsystems, the weaker the connection between subsystems.

This paper defines an incidence matrix $\boldsymbol{B}$ of the directed graph for describing a system with N nodes and L edges [36]. If node i is a vertex of edge l and the direction of the edge start at node i, the b_{li} is 1; If node i is a vertex of edge l and the direction of the edge points to node i, the b_{li} is -1; otherwise, the b_{li} is 0.

$$\boldsymbol{B} = [b_{li}] = \begin{cases} 1 & \text{if branch } l \text{ is incident from node } i \\ -1 & \text{if branch } l \text{ is incident to node } i \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

According to the subsystem discriminant matrix $\boldsymbol{F}$, this paper defines a subsystem indicator column vector $\boldsymbol{X}$. Its elements include -1, 0 or 1. An L-dimensional column vector $\boldsymbol{R}$ is defined as the multiplication of the incidence matrix $\boldsymbol{B}$ and the indicator vector $\boldsymbol{X}$, that is:

$$\boldsymbol{R} = \boldsymbol{BX} \tag{19}$$

The tie lines can be obtained according to the elements of $\boldsymbol{R}$. If the element r_l of $\boldsymbol{R}$ equals to 0, edge l is within one of the subsystems; otherwise, edge l is a tie line between subsystems. That is,

$$\boldsymbol{R} = \begin{cases} 1, & r_l \neq 0 \\ 0, & \text{other} \end{cases} \tag{20}$$

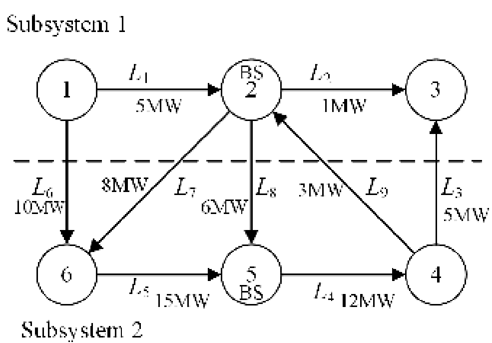

FIGURE 5. Initial sectionalizing strategy of a 6-bus system.

There is a process of identifying tie lines of a 6-bus system with two subsystems, as shown in Fig. 5. The subsystem discriminant matrix $\boldsymbol{F}$ is as follows:

$$\boldsymbol{F}=\begin{bmatrix}1&1&1&0&0&0\\0&0&0&1&1&1\end{bmatrix}^{\mathrm{T}}$$

The value of x_i (node i belongs to subsystem 1) in the indicator vector $\boldsymbol{X}$ is set as -1, while the value of x_j (node j belongs to subsystem 2) in the indicator vector $\boldsymbol{X}$ is 1. The subsystem indicator column vector is $\boldsymbol{X}=[-1, -1, -1, 1, 1, 1]^{\mathrm{T}}$. Thus, $\boldsymbol{R}=\boldsymbol{BX}=[0, 0, 2, 0, 0, -2, -2, -2, 2]^{\mathrm{T}}$. It means that edges L_3, L_6, L_7, L_8 and L_9 are the tie lines between subsystem 1 and subsystem 2.

The proposed method is also suitable for S ($S \geq 3$) subsystems. It needs to calculate $S-1$ times to get $\boldsymbol{R}$: $\boldsymbol{R}=\boldsymbol{R}_1+\boldsymbol{R}_2+\ldots+\boldsymbol{R}_{S-1}$. There is an example for identifying the tie lines of a 6-bus system with three subsystems in Appendix.

b: OBJECTIVE OF THE REFINING METHOD

If the initial sectionalizing strategy does not satisfy the constraints, the refining method is used to change tie lines accordingly. Hence, the power exchange among subsystems also changes. After a blackout, each subsystem should be self-sufficient as much as possible, which is conducive to maintaining the stability of each subsystem. Therefore, the smaller the power exchange among different subsystems, the better the power balance can be achieved in each subsystem. The risk of transmission line overload or subsystem instability caused by power imbalance can be reduced. The objective of minimizing the absolute value of the power exchange among subsystems can be described as:

$$\min f=\boldsymbol{P}_L\boldsymbol{R} \tag{21}$$

where $\boldsymbol{P}_L$ is an L-dimensional row vector. The element P_l is the absolute value of active power in edge l.

3) STEPS FOR DETERMINING THE FINAL STRATEGY

Step 1: Each subsystem is evaluated by the sectionalizing constraints. If all subsystems satisfy the constraints, the initial strategy is used as the final strategy. Otherwise, the initial strategy needs to be refined by the refining method to get the final strategy.

Step 2: The incidence matrix $\boldsymbol{B}$ and the subsystem indicator column vector $\boldsymbol{X}$ are used to get the tie lines of the initial sectionalizing strategy. The corresponding boundary nodes can be recognized according to the tie line discriminant matrix $\boldsymbol{R}$. Based on the exhaustive algorithm, all boundary nodes are sequentially divided into adjacent subsystems for generating new sectionalizing strategies. For each new strategy, all subsystems are evaluated by the sectionalizing constraints. Feasible sectionalizing strategies can be obtained.

There is an example, shown in Fig. 5, for the work of applying the exhaustive algorithm.

Edges L_3, L_6, L_7, L_8, and L_9 are the tie lines between subsystem 1 and subsystem 2. Since nodes 2 and 5 are the BS nodes, the boundary nodes are nodes 1, 3, 4 and 6. The exhaustive algorithm is used to generate new sectionalizing strategies by dividing boundary nodes sequentially into adjacent subsystems. There are six cases:

Case 1: Node 1 is divided into subsystem 2. Edges L_1, L_3, L_7, L_8, and L_9 are the tie lines in this strategy. The absolute value of power exchange among subsystems is 27MW.

Case 2: Node 3 is divided into subsystem 2. Edges L_2, L_6, L_7, L_8, and L_9 are the tie lines in this strategy. The absolute value of power exchange among subsystems is 28MW.

Case 3: Node 4 is divided into subsystem 1. Edges L_4, L_6, L_7, and L_8 are the tie lines in this strategy. The absolute value of power exchange among subsystems is 36MW.

Case 4: Node 6 is divided into subsystem 1. Edges L_3, L_5, L_8, and L_9 are the tie lines in this strategy. The absolute value of power exchange among subsystems is 29MW.

Case 5: Node 3 is divided into subsystem 2, node 6 is divided into subsystem 1. Edges L_2, L_5, L_8, and L_9 are the tie lines in this strategy. The absolute value of power exchange among subsystems is 25MW.

Case 6: Node 1 is divided into subsystem 2, node 4 is divided into subsystem 1. Edges L_1, L_4, L_7, and L_8 are the tie lines in this strategy. The absolute value of power exchange among subsystems is 31MW.

It is assumed that all cases satisfy the sectionalizing constraints. Case 5 with the minimum absolute value of power exchange between subsystems is selected as the final strategy, as shown in Fig. 6:

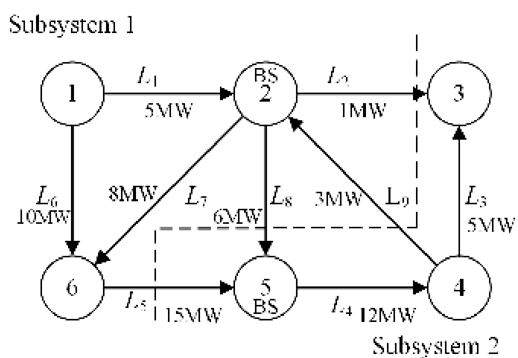

FIGURE 6. **Final sectionalizing strategy of a 6-bus system.**

Step 3: The absolute value of power exchange among subsystems in each feasible strategy is calculated by (21). The strategy with the minimum absolute value of power exchange among subsystems is selected from all feasible strategies as the final strategy.

IV. CASE STUDIES

The proposed sectionalizing method has been implemented in MATLAB R2018b. To illustrate the validity of the proposed method, simulations are performed with the IEEE 39-bus and IEEE 118-bus test systems.

A. IEEE 39-BUS TEST SYSTEM

1) SECTIONALIZING RESULT

There are 10 generating units, 39 buses, and 46 branches in the IEEE 39-bus test system [37]. Units G30, G31, and

G34 are the BS units. Therefore, the number of the subsystem is three in this paper. Buses 30, 31, and 34 are in subsystems 1, 2, and 3, respectively. Then the initial subsystem discriminant matrix $\boldsymbol{F}_0$ is obtained. The initial label propagation matrix $\boldsymbol{P}_0$ is calculated by the topology of the system and the active power of the branches before blackouts. α is set as 0.35, and β is set as 0.2. The initial sectionalizing strategy, shown in Fig. 7 and Table 1, is obtained by iterating 7 times.

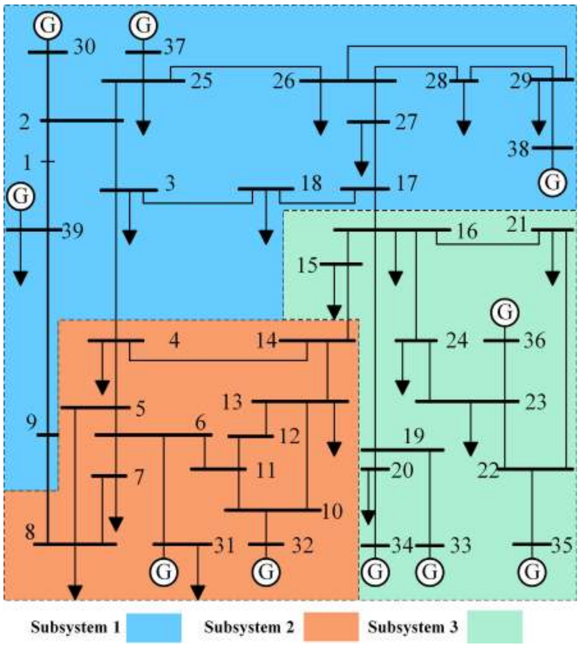

FIGURE 7. Initial sectionalizing strategy of IEEE 39-bus test system.

TABLE 1. Subsystems in initial strategy of IEEE 39-bus test system.

Subsystem	Node
1	1, 2, 3, 9, 17, 18, 25, 26, 27, 28, 29, 30, 37, 38, 39
2	4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 31, 32
3	15, 16, 19, 20, 21, 22, 23, 24, 33, 34, 35, 36

Edges 3-4, 8-9, 14-15 and 16-17 sectionalize this system into three subsystems. Each subsystem contains one BS unit. V_1 is 5, V_2 is 4, and V_3 is 6, thus, the size of each subsystem is roughly balanced. Since the labels do not propagate in the last iteration, the propagation process of each subsystem label from the BS unit bus to the other buses includes 6 times label propagations, as shown in Table 2.

The imbalance indexes of each subsystem are shown in Table 3. U_1 is the imbalance of the active power between the minimum output of generating units and the demand of loads. U_2 is the imbalance of the active power between generation capacity and the demand of level I loads. U_3 is the imbalance of the active power among generation capacity, load, and d. The U_3 of subsystem 1 is 70.6MW, and that of subsystem 3 is 73.4MW. Therefore, subsystems 1 and 3 do not satisfy the constraint (4). It is necessary to use the refining method to adjust the boundary nodes based on the initial strategy.

TABLE 2. Subsystem labels propagation process.

Sub.	1st update	2nd update	3rd update	4th update	5th update	6th update
1	2	1,3,25	18,26, 37,39	9,17,27, 28,29	38	
2	6	5,7,11	4,8,10, 12	13,14, 32		
3	20	19	16,33	15,21, 24	22,23	35,36

TABLE 3. Imbalance indexes of subsystems in initial strategy.

Subsystem	U_1/MW	U_2/MW	U_3/MW
1	-1904.6	2055.7	70.6
2	-1336.7	1918.2	-12.05
3	-808.7	1073.2	73.4

First, the value of x_i (node i belongs to subsystem 1) in $\boldsymbol{X}_1$ is set as -1, while the value of x_j (node j belongs to subsystem 2 and subsystem 3) in $\boldsymbol{X}_1$ is 1. $\boldsymbol{R}_1$ is obtained by (19):

$$\boldsymbol{R}_1 = \left[0\ 0\ 0\ 0\ 0\ {-2}\ {-2}\ \underbrace{0\cdots0}_{8}\ 2\ \underbrace{0\cdots0}_{14}\ 2\ \underbrace{0\cdots0}_{15}\right]^{\mathrm{T}}$$

That is, the tie lines between subsystem 1 and a combined subsystem (subsystem 2 and subsystem 3) are 3-4, 8-9, and 16-17.

Then, for $\boldsymbol{X}_2$, the value of x_i (node i belongs to subsystem 1) is set as 0, the value of x_j (node j belongs to subsystem 2) is set as -1, and the value of x_q (node q belongs to subsystem 3) is 1. According to (19), $\boldsymbol{R}_2$ is obtained:

$$\boldsymbol{R}_2 = \left[0\,0\,0\,0\,0\,1\ {-1}\ \underbrace{0\cdots0}_{8}{-1}\ \underbrace{0\cdots0}_{7} - 2\underbrace{0\cdots0}_{6}1\underbrace{0\cdots0}_{15}\right]^{\mathrm{T}}$$

Therefore, the tie line between subsystem 2 and subsystem 3 is 14-15.

Edges 3-4, 8-9, 14-15 and 16-17 are the tie lines in the initial strategy. The corresponding boundary nodes are 3, 4, 8, 9, 14, 15, 16 and 17. Based on the exhaustive algorithm, 120960 new sectionalizing strategies are generated as the candidates for sectionalizing constraints evaluation. There is a feasible sectionalizing strategy satisfying sectionalizing constraints. Thus, the feasible strategy is selected as the final strategy.

Edges 3-4, 8-9, 3-18, 14-15 and 17-27 are the tie lines in the final strategy. The absolute value of power exchange among subsystems is 187.27MW. As shown in Table 4, each subsystem in the final strategy contains a BS unit, and all constraints are satisfied. $V_1 = 5$, $V_2 = 4$, and $V_3 = 6$. The size of each subsystem is roughly balanced. The final sectionalizing strategy is shown in Fig. 8. The nodes of each subsystem are shown in Table 5.

This paper introduces the modularity Q to evaluate the subsystem quality of the power grid [38]. The calculation

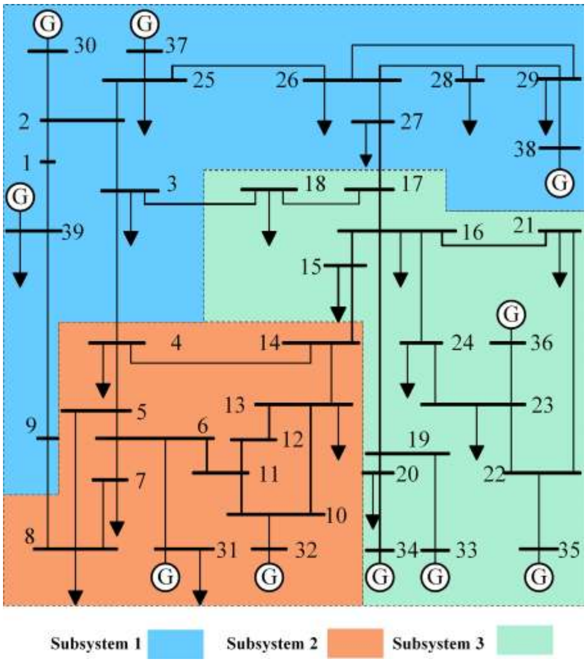

FIGURE 8. Final sectionalizing strategy of IEEE 39-bus test system.

TABLE 4. Imbalance indexes of subsystems in final strategy.

Subsystem	U_1/MW	U_2/MW	U_3/MW
1	-1746.6	2087.7	-84.6
2	-1494.6	1886.2	-12.05
3	-808.7	1073.2	-87.4

TABLE 5. Subsystems in final strategy of IEEE 39-bus test system.

Subsystem	Node
1	1, 2, 3, 9, 25, 26, 27, 28, 29, 30, 37, 38, 39
2	4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 31, 32
3	15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 33, 34, 35, 36

equation is as follows:

$$Q = \frac{1}{2L}\sum_{i=1}^{N}\sum_{j=1}^{N}\left(w_{ij} - \frac{k_i k_j}{2L}\right)\delta\left(s_i, s_j\right) \tag{22}$$

where k_i is the number of neighboring nodes connected to node i; s_i indicates the subsystem including node i. The function δ represents the subsystem relationship between nodes, that is:

$$\delta\left(s_i, s_j\right) = \begin{cases} 1, & i \text{ and } j \text{ are in the same subsystem} \\ 0, & i \text{ and } j \text{ are not in the same subsystem} \end{cases} \tag{23}$$

The closer to 1 the Q value is, the clearer the community structure will be. For the actual network, the Q value is generally between 0.3-0.7 [26].

In the initial strategy, the absolute value of power exchange among subsystems is 345.6MW, and the modularity Q obtained is 0.6381. Subsystem 1 and subsystem 3 do not satisfy the constraint on the power balance. By applying the proposed refining method, the final strategy is determined. The absolute value of power exchange among subsystems in the final strategy is 187.27MW, which is smaller than that of the initial strategy. The Q value of the final strategy is 0.6452, which is larger than that of the initial strategy. It indicates that the sectionalizing characteristics of the final strategy are obvious. In addition, all subsystems of the final strategy satisfy the sectionalizing constraints.

2) COMPARISON AND DISCUSSION

Table 6 shows the comparison of the proposed method and other two methods in [26] and [28].

TABLE 6. Comparison of different sectionalizing methods on IEEE 39-bus test system.

Sectionalizing method	f/MW	Q value
This paper	187.27	0.6452
[26] and [28]	387.71	0.6341

The sectionalizing strategies obtained by using the methods in [26] and [28] are the same. So the corresponding index values are the same. As shown in Table 6, the absolute value of power exchange among subsystems obtained by the proposed method is the smallest. The power exchange between subsystems is less, and the connection between subsystems is weaker. According to the Dijkstra algorithm, these three methods obtain the same maximum subsystem size V_s. According to the quality of the power network sectionalizing, the Q value obtained by the proposed method is 0.6452, which is the largest of the above methods. It indicates that the sectionalizing characteristics of the strategy in this paper are obvious. Therefore, the nodes within the subsystem are closely connected, and between subsystems are sparse.

B. IEEE 118-BUS TEST SYSTEM

The IEEE 118-bus test system has 54 generators, 118 buses, and 186 branches. In this case, the BS units are located at buses 24, 59 and 100, respectively. Therefore, the IEEE 118-bus system is sectionalized into 3 subsystems. Buses 24, 59 and 100 are in subsystems 1, 2 and 3, respectively. After the labels propagate 9 times, the initial sectionalizing strategy is obtained, as shown in Fig. 9.

TABLE 7. Subsystems imbalance indexes of IEEE 118-bus test system in initial strategy.

Subsystem	U_1/MW	U_2/MW	U_3/MW
1	-719.69	1214.7	156.817
2	-983.85	1076.4	25.55
3	-1052.4	1106.4	61.20

In the initial strategy, edges 33-37, 19-34, 30-38, 47-69, 49-69, 68-69, 65-68, 69-77, 75-77, and 76-118 sectionalize this system into three subsystems. Each subsystem contains one BS unit. The absolute value of power exchange among subsystems is 432.37MW. As shown in Table 7, the U_3 of subsystems 1, 2 and 3 is 156.817MW, 25.55MW and

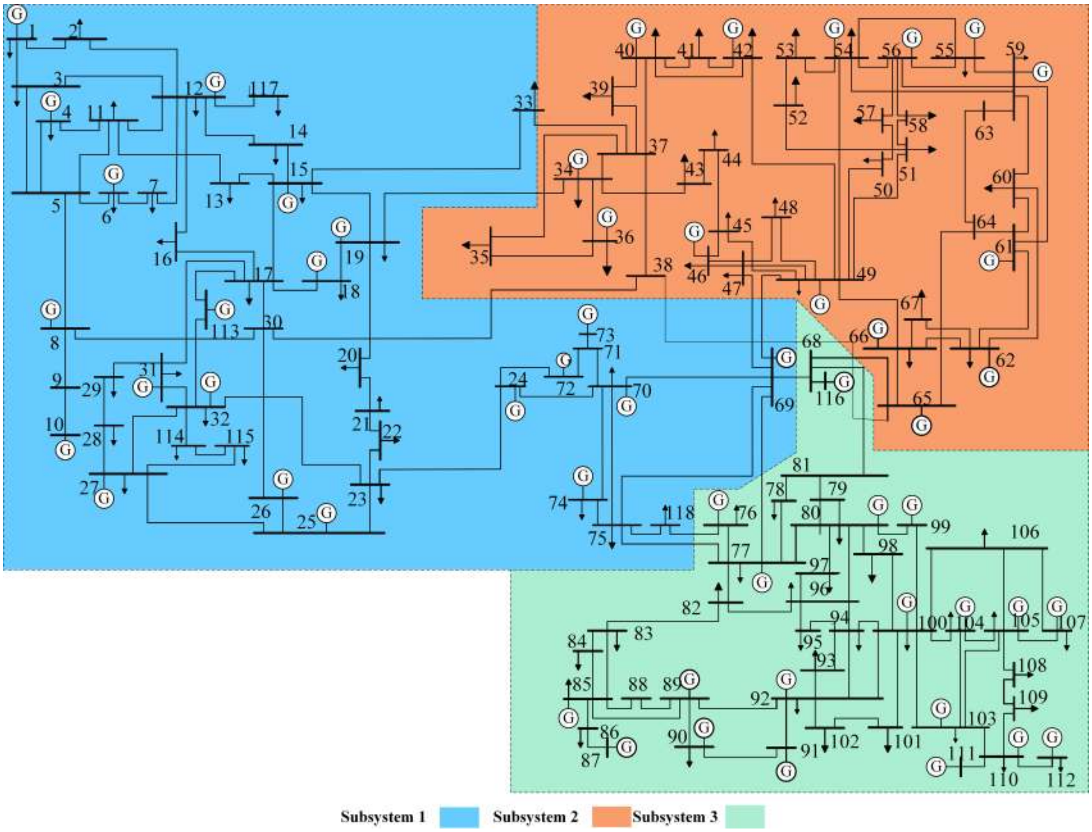

FIGURE 9. Initial sectionalizing strategy of IEEE 118-bus test system.

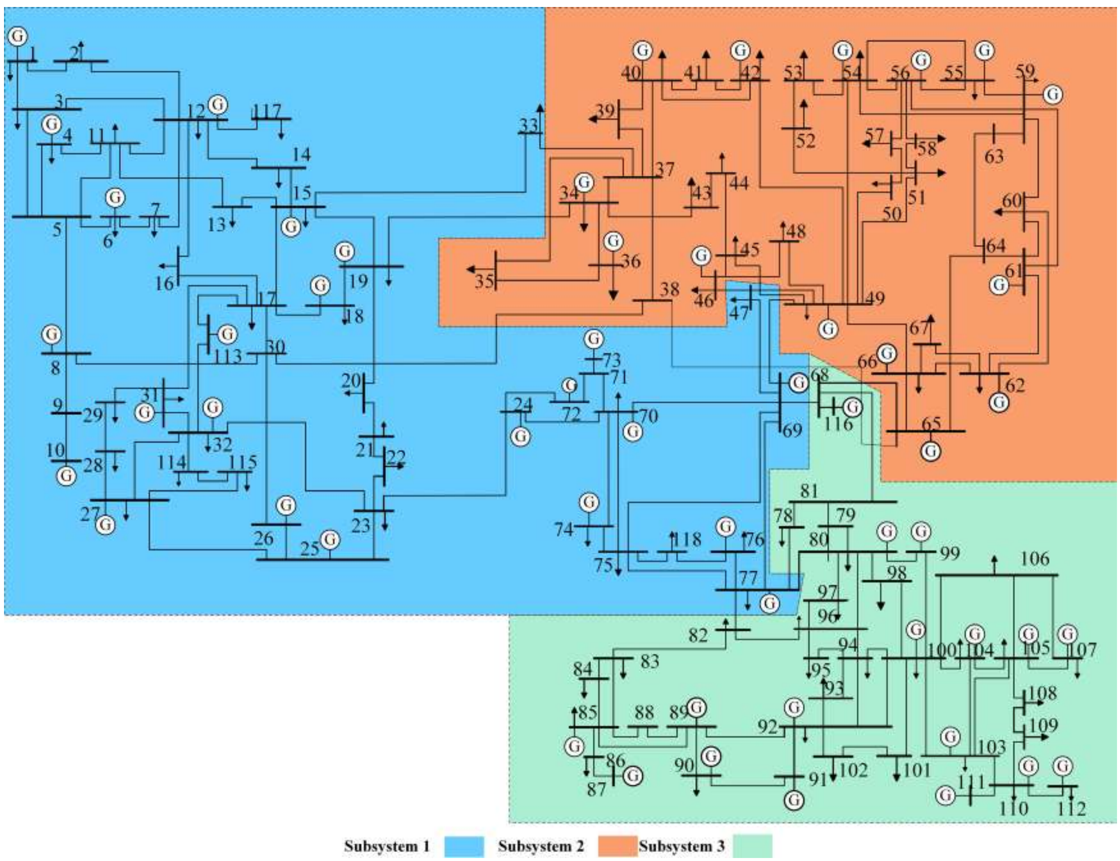

FIGURE 10. Final sectionalizing strategy of IEEE 118-bus test system.

61.2 MW, respectively. Therefore, these three subsystems do not satisfy the constraint (4). The refining method should be used to adjust the boundary nodes based on the initial strategy.

TABLE 8. Subsystems imbalance indexes of IEEE 118-bus test system in final strategy.

Subsystem	U_1/MW	U_2/MW	U_3/MW
1	-882.69	1182.1	-6.183
2	-949.85	1083.2	-8.45
3	-923.4	1132.2	-67.8

Based on the exhaustive algorithm, 10886400 new sectionalizing strategies are generated as the candidates for sectionalizing constraints evaluation. There are 3 feasible sectionalizing strategy satisfying sectionalizing constraints. Thus, the strategy with the minimum absolute value of power exchange among subsystems is selected from all feasible strategies as the final strategy. Edges 33-37, 19-34, 30-38, 46-47, 47-49, 49-69, 68-69, 65-68, 77-78, 77-80, and 77-82 are the tie lines in the final strategy. The absolute value of power exchange among subsystems is 404.95MW. As shown in Table 8, all constraints are satisfied in the final strategy. $V_1 = 8$, $V_2 = 7$, and $V_3 = 5$. The size of each subsystem is roughly balanced. The final sectionalizing strategy is shown in Fig. 10.

In the initial strategy, the absolute value of power exchange among subsystems is 432.37MW, and the modularity Q obtained is 0.6106. Subsystems 1, 2 and 3 do not satisfy the constraint on the power balance. By applying the proposed refining method, the final strategy is determined. The absolute value of power exchange among subsystems in the final strategy is 404.95MW, which is smaller than that of the initial strategy. The Q value of the final strategy is 0.5947. It indicates that the sectionalizing characteristics of the final strategy are obvious. In addition, all subsystems of the final strategy satisfy the sectionalizing constraints as shown in Table 8.

TABLE 9. Comparison of different sectionalizing methods in IEEE 118-bus test system.

Sectionalizing method	f/MW	Q value
This paper	404.95	0.5947
[26]	470.87	0.6029
[28]	490.49	0.5865

As shown in Table 9, the absolute value of power exchange among subsystems in the strategy by the proposed method is the smallest. The Q value of these three methods is not much different. This case indicates that the proposed sectionalizing method is suitable for large-scale power systems.

V. CONCLUSION

This paper presents a novel sectionalizing method for parallel system restoration based on an improved label propagation algorithm, considering the topological and the operational characteristics of the power system before blackouts occur. An improved label impact strategy with consideration of the impact of the node's label itself is proposed to accelerate the convergence as well as avoid the label oscillation. A refining method for determining the final feasible sectionalizing strategy is proposed. Simulations on the IEEE 39 and 118-bus test systems are performed to evaluate the effectiveness of the proposed method. The proposed method can be regarded as a coherency identification method considering sectionalizing constraints of parallel restoration, which divides the coherent generator buses and load buses into one strongly connected subsystem [39]. The subsystems generated by the proposed method are for the further application of parallel restoration strategies.

As renewable energy and energy storage systems develop rapidly, they can be used as new BS units for system restoration. However, the uncertainty of renewable energy and the controllability of energy storage systems increase the complexity of the sectionalizing problem. In addition, faulted devices cannot be restored before they are repaired or replaced. Thus, they have effects on sectionalizing strategies. For instance, faulted lines cannot be used as tie lines between subsystems. Our future research will address these issues.

APPENDIX

There is the identification process of the tie lines among three subsystems in Fig. 11, including two steps for calculation.

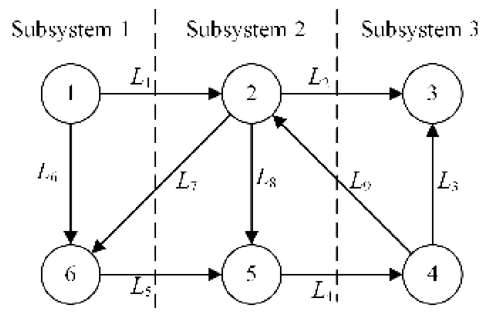

FIGURE 11. An example of a 6-bus system with 3 subsystems.

The subsystem discriminant matrix $\boldsymbol{F}$ is as follows:

$$\boldsymbol{F} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix}^{\mathrm{T}}$$

➢ The first step:

The value of x_i (node i belongs to subsystem 1) in the indicator vector $\boldsymbol{X}$ is set as -1, while the value of x_j (node j belongs to subsystem 2 and subsystem 3) in the indicator vector $\boldsymbol{X}$ is 1. The subsystem indicator column vector is $\boldsymbol{X}_1 = [-1, 1, 1, 1, 1, -1]^{\mathrm{T}}$. R is obtained by $\boldsymbol{R}_1 = \boldsymbol{B}\boldsymbol{X}_1 = [-2, 0, 0, 0, -2, 0, 2, 0, 0]^{\mathrm{T}}$. The tie lines, i.e., edges L_1, L_5 and L_7, between subsystem 1 and a combined subsystem (subsystem 2 and subsystem 3) can be identified according to the elements of $\boldsymbol{R}_1$.

➢ The second step:

For $\boldsymbol{X}_2$, the value of x_i (node i belongs to subsystem 1) is set as 0, the value of x_j (node j belongs to subsystem 2) is set as -1, and the value of x_q (node q belongs to subsystem 3) is 1. $\boldsymbol{R}_2 = \boldsymbol{B}\boldsymbol{X}_2 = [1, -2, 0, -2, 1, 0, -1, 0, 2]^{\mathrm{T}}$. thus, edges L_1, L_2, L_4, L_5, L_7 and L_9 are identified as the tie lines among these subsystems.

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