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Agglomerative Clustering Based Network Partitioning for Parallel Power System Restoration

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***Abstract*—After a blackout, it is essential to restore the blackout area rapidly to minimize possible losses. In parallel restoration, the blackout area is first partitioned into several subsystems which will then be restored in parallel to accelerate the restoration process. In order to ensure restoration reliability, each subsystem should have enough generation power and satisfy a set of constraints before triggering the parallel restoration process. This paper models this as a constrained optimization problem and proposes a partitioning strategy to solve it in three steps. In the first step, some existing methods and expert knowledge are used for initialization of partitioning process. The second step ensures the satisfaction of modelled constraints. The third step operates greedily to find suitable partitions for parallel restoration. The proposed strategy is implemented and evaluated on IEEE 39- and 118-bus power systems. Evaluation results show that it provides adequate subsystems for parallel restoration. Unlike some existing partitioning strategies, the proposed strategy can be used to partition a power system into multiple subsystems in a single execution.**

***Index Terms*—Power systems, smart grid, network partitioning, sectionalising, parallel restoration, agglomerative clustering.**

I. Introduction

IN countries with booming economy, demands on electricity are getting higher and higher. In recent years, sizes of the power systems over the world keep growing, and their network structures and dynamic characteristics are getting more and more complicated. Operating experiences in different countries indicate that although automatic control devices and new technologies can enhance the robustness of a power system to some extent, due to of its complexity and uncertainty, however, it is almost impossible to avoid power outages or blackouts completely. For example, the blackout in USA in August 2003 has lead to significant economic losses and negative social influences [1], [2]. Therefore, a quick and safe power system restoration after a blackout has a vital importance in modern society.

The objective of a restoration mechanism is to recover the power system to normal conditions safely with a minimum loss and a shortest time [3]. In order to analyze the power system restoration process effectively, it is summarized into three stages: black-start, network reconfiguration, and load restoration [3]. Network partitioning strategies are used in the black-start stage of parallel power system restoration processes. In the black-start stage, which is the preparation period, non-black-start generators are restarted by the cranking power provided by black-start generators. Those black-start generators together with the non-black-start generators known as a cranking group. Before providing the cranking power, a power system restoration strategy should be determined. It can be classified into serial and parallel types. The serial strategy is to synchronize the individual generators one by one. However, this approach may take a long time to restore a large power system which is very common in complete blackouts. The parallel power system restoration strategy partitions the blackout area into multiple partitions (islands) and restores partitions simultaneously. It achieves the restoration of the entire system by further reconnecting the partitions. Obviously, parallel power system restoration is more time efficient comparing with the serial power system restoration in nation-wide power outages. Therefore, the partition methodology plays an important role in the parallel restoration.

The partitioning strategy defines a set of lines, which is known as the cut-set that separates the entire blackout area into multiple partitions. A suitable partitioning strategy will provide necessary guidance for transmission system operators after a blackout to accelerate the system restoration process. To ensure that each subsystem can be independently restored and successfully synchronized, a proper partitioning strategy is an important precondition. In order to ensure restoration reliability, the following requirements should be satisfied before triggering the parallel restoration process [4]–[10]:

1) Each partition should have at least one black-start generator to ensure the partition can be restored independently. The connectivity within cranking groups should be maintained as well.
2) Each partition should have sufficient voltage control resources to maintain system voltage stability.
3) The tie-lines between the partitions should have monitoring equipment to measure the phase angle across the lines during synchronization of adjacent partitions.

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4) Each partition should have sufficient power generators to maintain the frequency within an acceptable range by matching power generation and consumption.

Moreover, it is also necessary to ensure correct operation of each partition via continuous monitoring from a power system control centre [4], [5]. Thus, finding a desirable partitioning strategy becomes an optimization problem under complex conditions.

Network partitioning problem for parallel power system restoration has drawn a considerable attention of researchers in the last decade. In [11], a clustering approach based on the fuzzy C-medoid algorithm is proposed for partitioning large power systems into partitions. The algorithm is based on real-time data measured by a phasor measurement unit, which is not applicable to partition the entire system in a complete blackout. A partitioning strategy based on a wide area measurement system is proposed in [7], which ensures the observability of all partitions so as to guarantee a fast and secure restoration. In [8], an ordered binary decision diagram based three-phase strategy is introduced for parallel restoration, which provides guidance to the transmission system operators on how parallel restoration could be performed. In [12], an algorithm based on the community structure in complex networks theory is presented for dividing restoration subsystems, which does not require any heuristics and expert experience.

Recent researches concentrate more on graph theory based strategies for developing network partitioning strategies. In [5], a strategy based on spectral graph clustering for determining a suitable network partitioning strategy is proposed. This strategy uses the physical and inherent properties of the network with the maximum electrical cohesiveness within the partitions created. It also makes use of a refining algorithm proposed in [13] to reduce load consumption within each partition. In [4], a strategy that uses a constrained cut-set matrix to determine multiple sets of network partitions, which enables transmission system operators to select a desired set of partitions for parallel restoration. In [14], a two-step partitioning strategy for power system restoration is presented and modeled. The programming problem of two proposed models is solved by AMPL/CPLEX. However, this strategy ignores the requirements on voltage stability and synchronization, thus its practical importance is questionable. Many existing partitioning strategies [4], [5], [14] are designed for partitioning network into only two partitions. If more than two partitions are required, those strategies should be repetitively executed on partitions that carry more than one black-start generators.

In order to maintain the system frequency within an acceptable range, the output power of generators and the power requirement of loads should be balanced within each partition. Even though the maximum power generation capabilities of generators are available before the restoration takes place, the actual load consumption within each partition is not obvious by that time. Hence, network partitioning strategies usually rely on predicted load consumption values. If the maximum generation capability of each network partition can only marginally satisfy the predicted power requirements of the loads in that partition, it might fail to satisfy actual power requirements of the loads as they can be well over the predicted values. Hence, it is important to partition a power system such that each partition has enough generation capability to maintain the system stability. This paper aims to develop a novel network partitioning strategy for parallel power system restoration which can maximize the capability of each partition to handle such a situation while satisfying all requirements mentioned above. Moreover, the proposed strategy can partition a power system into any desired number of partitions in a single execution if the black-start availability can be ensured.

The rest of the paper is organized as follows. Preliminaries are described in Section II. The network partitioning problem is formulated in Section III. The proposed network partitioning strategy is presented and illustrated using IEEE 9-bus power system in Section IV. Performances of the proposed strategy is evaluated using IEEE 39- and 118-bus power systems in Section V. Properties of the proposed strategy are further discussed in Section VI. Concluding remarks are given in Section VII.

II. Preliminaries

In power systems engineering, it is a common practice to use single line diagrams to illustrate power systems in details. Such a single line diagram of IEEE 9-bus power system is given in Fig. 1(a). The diagram carries many details which can be irrelevant in the process of network partitioning, thus, power system representations can be further abstracted using concepts in network theory.

A. Graph representation of a power system

In this paper, a power system is represented using an undirected graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ that consists of a set of nodes $\mathcal{V} = \{v_1, v_2, \dots, v_{|\mathcal{V}|}\}$ representing buses in the power system and a set of edges $\mathcal{E} = \{e_1, e_2, \dots, e_{|\mathcal{E}|}\}$ representing branches connecting those buses. A graph representation of IEEE 9-bus power system is given in Fig. 1(b). The connectivity of nodes in $\mathcal{V}$ can be represented using an adjacency matrix, each term a_{ij} of which is equal to 1 if nodes v_i and v_j is connected to each other, and 0 otherwise.

In the power system restoration process, nodes in $\mathcal{V}$ are categorized under several other subsets. Two such important subsets are generation nodes $\mathcal{V}^{\mathrm{GN}}(\subset \mathcal{V})$ and black-start nodes $\mathcal{V}^{\mathrm{BS}}(\subset \mathcal{V}^{\mathrm{GN}})$ which respectively represent the buses that are connected with all generators and only black-start generators. Some of the generation nodes and the black-start nodes are separated into cranking groups to facilitate the power restoration. High priority loads which need to be restored as quickly as possible after a blackout are called critical loads. Any load that is connected to a generation bus is also considered as a critical load since they usually represent local services that support the generator [5]. A set of buses that is connected to critical loads is denoted by $\mathcal{V}^{\mathrm{CL}}(\subset \mathcal{V})$ in graph representation.

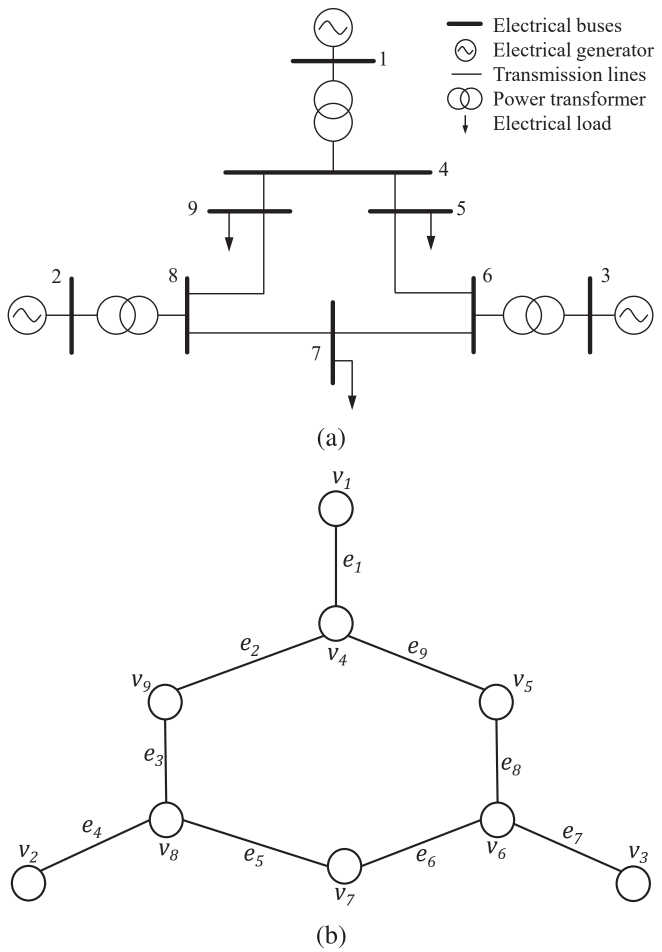

Fig. 1. IEEE 9-bus power system: (a) a single line diagram and (b) a graph representation.

B. Generation-load difference

The generation-load balance of individual partitions can be considered as a major concern in network partitioning for parallel power system restoration. The generation-load difference of nodes in the k^{th} network partition during power system restoration process can be obtained by [5]

$$\varphi(\mathcal{V}_k) = \sum_{\forall v_i \in \mathcal{V}_k} \widetilde{P}(v_i), \tag{1}$$

where $\mathcal{V}_k$ is the k^{th} partition. Here, $\widetilde{P}(v_i)$ is the generation-load difference at the node v_i which is calculated as [5]

$$\widetilde{P}(v_i) = P_{\text{MG}}(v_i) - \alpha(v_i) P_{\text{LD}}(v_i). \tag{2}$$

Here, $P_{\text{MG}}(v_i)$ and $P_{\text{LD}}(v_i)$ respectively represent the maximum active power generation capability and the expected active power consumption at v_i. The value of $\alpha(v_i)$ is a representative measure of the percentage of loads at v_i to be restored before the synchronization of the network partitions. Therefore, $\alpha(v_i) = 1$ if $v_i \in \mathcal{V}^{\text{CL}}$. For non-critical nodes, *i.e.* $v_i \in \mathcal{V} \setminus \mathcal{V}^{\text{CL}}$, the value of $\alpha(v_i)$ depends on the maximum generation capability of the power system. For example, if 50% of non-critical loads at each node are decided to be restored during the parallel restoration, then the value of $\alpha(v_i)$ is set to 0.5 in the network partitioning. Usually, the value of $\alpha(v_i)$ varies from 0.4 to 0.75 [15]. Similar to the previous work [4], [5], here we assume that $\alpha(v_i) = 0.7$ if $v_i \in \mathcal{V} \setminus \mathcal{V}^{\text{CL}}$.

III. Problem Formulation

The rationale of network partitioning is to facilitate the simultaneous restoration of multiple network partitions and thus to accelerate the network restoration after a blackout. However, network partitions cannot be defined arbitrarily due to a set of physical constraints. Therefore, the design process of a network partitioning strategy can be considered as a constrained optimization problem in which all four requirements introduced in Section I need to be satisfied. In this section, each of those requirements are expressed using graph notations to obtain an objective function with a set of constraints.

Let there be M $(2 \leq M \leq |\mathcal{V}^{\text{BS}}|)$ parallel restoration processes. Thus, a network partitioning strategy must separate the network into M partitions such that

$$\mathcal{V}_i \cap \mathcal{V}_j = \emptyset, \tag{3}$$

$$\mathcal{V}_1 \cup \mathcal{V}_2 \cup \ldots \cup \mathcal{V}_M = \mathcal{V}, \tag{4}$$

for $i, j \in \{1, 2, \ldots, M\}$ and $i \neq j$. In order to restore each partition independently, there must be M disjoint cranking groups. Let the k^{th} cranking group be denoted by $\mathcal{V}_k^{\text{CR}}$. It is necessary to ensure that the connectivity within cranking groups when the partitioning is completed, thus,

$$\mathcal{V}_k^{\text{CR}} \subseteq \mathcal{V}_k, \tag{5}$$

for all $k \in \{1, 2, \ldots, M\}$. From (3) and (5), we have that $\mathcal{V}_i^{\text{CR}} \cap \mathcal{V}_j^{\text{CR}} = \emptyset$ for $i, j \in \{1, 2, \ldots, M\}$ and $i \neq j$. Black-start generators provide the cranking power to energize non-black-start generators within the same cranking group during power system restorations. Therefore, there must be at least one black-start node in each of the cranking group, *i.e.*

$$\left|\mathcal{V}_k^{\text{CR}} \cap \mathcal{V}^{\text{BS}}\right| \geq 1, \tag{6}$$

for all $k \in \{1, 2, \ldots, M\}$. The number of elements in a set X is denoted by $|X|$.

Let a set of critical lines that helps to maintain the voltage stability of the power system be denoted by $\mathcal{E}_{\text{CL}}(\subset \mathcal{E})$. The removal of a critical line from the power system usually results in a more excessive difference in reactive power than the removal of other lines [4]. Hence, critical lines should not be included in the cut-set that separate the blackout area into partitions. Moreover, the tie-lines between the partitions should be equipped to monitor synchronization of the partitions. Therefore, a set of lines without monitoring equipment denoted by $\mathcal{E}_{\text{NM}}(\subset \mathcal{E})$ should not be used as tie-lines and they should be excluded from the cut-set. Finally, let the set of any other branches that are classified as unsuitable to be used as tie-lines between partitions due to various reasons (e.g. necessary reserves [9]) be denoted by $\mathcal{E}_{\text{U}}(\subset \mathcal{E})$ and the cut-set be denoted by $\mathcal{E}_{\text{CS}}(\subset \mathcal{E})$. Thus,

$$(\mathcal{E}_{\text{CL}} \cup \mathcal{E}_{\text{NM}} \cup \mathcal{E}_{\text{U}}) \cap \mathcal{E}_{\text{CS}} = \emptyset. \tag{7}$$

Now, by defining an excluded set $\mathcal{E}_{\text{E}} = \mathcal{E}_{\text{CL}} \cup \mathcal{E}_{\text{NM}} \cup \mathcal{E}_{\text{U}}$, we have $\mathcal{E}_{\text{E}} \cap \mathcal{E}_{\text{CS}} = \emptyset$.

In order to maintain the stability of the power system under load variations and uncertainties over time, a network partitioning strategy must reserve enough generation power in each of the partitions. Therefore, the objective of the network partitioning is to find a set of partitions that maximizes the minimum generation-load differences of the partitions over different cut-sets, *i.e.*

$$\{\mathcal{V}_1, \mathcal{V}_2, \ldots, \mathcal{V}_M\} = \underset{\{\mathcal{V}_1', \mathcal{V}_2', \ldots, \mathcal{V}_M'\}}{\arg\max} \left(\min_{k \in \{1,2,\ldots,M\}} \varphi(\mathcal{V}_k') \right), \quad (8)$$

subjected to (3)–(7). Note that the internal minimization term is taken over all the partitions in one partitioning option, while the outer maximization term considers all possible options for partitioning the network.

IV. The Proposed Network Partitioning Strategy

Before partitioning of a power system after a blackout for parallel restoration, it is necessary to gather information about the current status of important elements, such as black-start generators and critical loads in the power system. By assuming all such information are available, this section introduces a network partitioning strategy as a solution to the constrained optimization problem defined in the previous section. This strategy is executed in three steps: initialization, initial partitioning, and agglomerative clustering. Procedures in each step are illustrated using IEEE 9-bus power system for the ease of understanding.

A. Initialization

After identifying the blackout area of the power system, it is represented using an undirected graph as explained in Section II-A. In order to complete the graph representation for further processing, it is necessary to define several important node and edge sets in this step. Such definitions are carried out using already established methods in power systems engineering.

First, $\mathcal{V}^{\text{BS}}$ needs to be initialized using black-start generators that are capable of starting and generating power without being energized from the power systems. In North America, resources with black-start capability are contracted by independent system operators to provide this vital service after a possible blackout [16]. Optimal allocation of black-start resources from the candidates available in the network to satisfy restoration requirements are discussed in [17]. Usually, information on black-start generators are readily available by the time of restoration and can be used to initialize $\mathcal{V}^{\text{BS}}$. In IEEE 9-bus power system, $\mathcal{V}^{\text{BS}} = \{v_1, v_2\}$ (*i.e.* $M = 2$) [4].

The next step is to define cranking groups such that it satisfies (6). Each of the cranking group should include a black-start generator which provides cranking power to the non-black-start generators within that group. The duration of a restoration process depends on the speed of the cranking task. This work utilizes the method proposed in [18] as it groups generators in such a way to accelerate the cranking task. In [18], the generator start-up sequencing is formulated as a mixed integer linear programming problem based on a 4-step transformation by introducing new decision variables. This linear formulation has led to an optimal solution to the generator start-up sequencing problem. For IEEE 9-bus power system, cranking groups can be defined as $\mathcal{V}_1^{\text{CR}} = \{v_1\}$ and $\mathcal{V}_2^{\text{CR}} = \{v_2, v_3\}$. As described in Section II-A, critical nodes are defined based on the importance of the loads and it is assumed that $\mathcal{V}^{\text{CL}} = \{v_7, v_9\}$ in IEEE 9-bus power system.

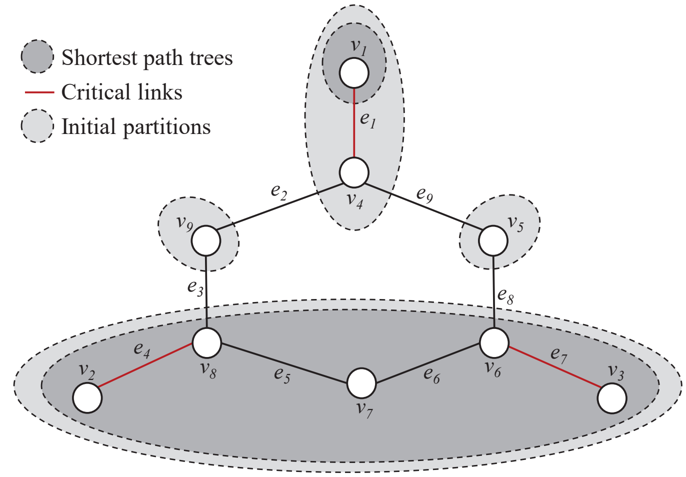

Fig. 2. Partitions resulting from initial partitioning of IEEE 9-bus power system.

For wrapping up the initialization, we need to define the set of edges that needs to be excluded from the cut-set, *i.e.* $\mathcal{E}_{\text{E}} = \mathcal{E}_{\text{CL}} \cup \mathcal{E}_{\text{NM}} \cup \mathcal{E}_{\text{U}}$. The formal definitions of $\mathcal{E}_{\text{NM}}$ and $\mathcal{E}_{\text{U}}$, themselves, imply how to define those two sets and the necessary information for such definitions are usually available prior to the restoration process. In our example of IEEE 9-bus power system, it is assumed that $\mathcal{E}_{\text{NM}} = \mathcal{E}_{\text{U}} = \emptyset$, *i.e.* $\mathcal{E}_{\text{E}} = \mathcal{E}_{\text{CL}}$. Usually the tie-lines between network partitions are kept disconnected during the parallel restoration process. The critical lines can be identified by performing $N-1$ voltage stability analysis and contingency analysis for every line in the power system [8]. The voltage stability margin is used in the classification of critical line contingencies. Disconnecting critical lines results in excessive reactive power difference between pre- and post-contingencies. According to the voltage stability analysis, $\mathcal{E}_{\text{CL}} = \{e_1, e_4, e_7\}$ for IEEE 9-bus power system. These critical lines are indicated using red lines in Fig. 2.

B. Initial partitioning

The primary objective of initial partitioning is ensuring the satisfaction of those essential constraints defined in Section III. Given a cranking groups, it is necessary to guarantee that there is a path from a black-start generator to all non-black-start generators in the cranking group. In the proposed strategy, this is achieved by using the shortest path trees in which the root node is a black-start generator and leaf nodes are non-black-start generators. Such shortest path trees can be obtained by using graph search algorithms such as Dijkstra's algorithm [19]. After that, the nodes belong to each of the shortest path tree are grouped as separate partitions. It is assumed that the set of nodes within those partitions are mutually exclusive. In IEEE 9-bus power system, the cranking groups

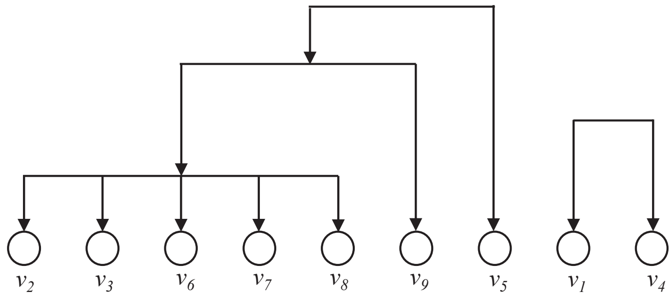

Fig. 3. A dendrogram illustrating the hierarchical partition structure of IEEE 9-bus power system.

were defined as $\mathcal{V}_1^{\text{CR}} = \{v_1\}$ and $\mathcal{V}_2^{\text{CR}} = \{v_2, v_3\}$. Since $\mathcal{V}_1^{\text{CR}}$ only consists of a black-start node, the corresponding shortest path tree can be defined as $\mathcal{G}_1^{\text{SP}} = \{\{v_1\}, \emptyset\}$. Nevertheless, in $\mathcal{V}_2^{\text{CR}}$, there are both black-start and non-black-start nodes. Therefore, it is necessary to guarantee a path that can supply cranking power from v_2 to v_3. Using Dijkstra's algorithm, the corresponding shortest path tree can be obtained as $\mathcal{G}_2^{\text{SP}} = \{\{v_2, v_3, v_6, v_7, v_8\}, \{e_4, e_5, e_6, e_7\}\}$.

After obtaining shortest path trees, the proposed strategy divides the graph into a set of partitions such that (5)–(7) are satisfied. Thus, all the nodes belong to a given shortest path tree are placed within one partition. As an example, all nodes in $\mathcal{G}_2^{\text{SP}}$, *i.e.* v_2, v_3, v_6, v_7, and v_8, are considered to be in one partition. If there is any node that is connected to a shortest path tree via an edge in $\mathcal{E}_{\text{E}}$, the node will be merged with the same partition. From the same example, nodes v_1 and v_4 are merged into one partition. Now, if there are any other nodes which are connected via edges in $\mathcal{E}_{\text{E}}$, those nodes are considered as separate partitions. If there are any other nodes that do not belong to any of above mentioned partitions, those sole nodes are considered as separate partitions. Thus, in IEEE 9-bus power system, nodes v_5 and v_9 are considered as two partitions, resulting in four partitions. Those are indicated as initial partitions in Fig. 2. If the number of initial partitions is equal to M, the proposed network partitioning strategy terminates here. Otherwise, agglomerative clustering is performed based on (8) subjected to (3)–(7).

C. Agglomerative clustering

In the final step of the proposed network partitioning strategy, the initial partitions are first divided into two groups: partitions with black-start generators (say black-start partitions) and partitions without black-start generators (say non-black-start partitions). Obviously, there should be M black-start partitions. Then, a black-start partition is temporarily merged with each of the non-black-start partitions which is connected with it in $\mathcal{G}$ and the generation-load difference of the merged partition in each instance is calculated. The partition pair that produces a minimum generation-load difference is saved for future use. This process continues iteratively for all black-start partitions. Now we have M partition pairs, each of which consists of a black-start partition. Out of those M pairs, the pair with a maximum generation-load difference is selected and those two partitions are merged together to form a new black-start partition. This process continues until all non-black-start partitions are merged with the black-start partitions.

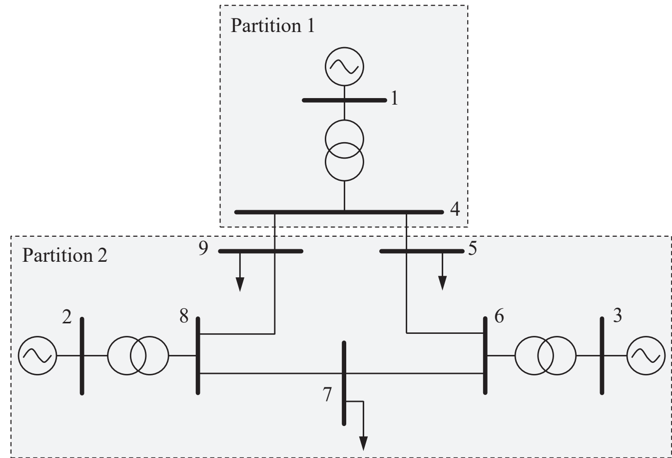

Fig. 4. Final network partitions of IEEE 9-bus power system obtained by using the proposed network partitioning strategy.

In the on going example of IEEE 9-bus power system, there are two black-start partitions and two non-black-start partitions at the beginning of this step. Results of each iteration of the proposed agglomerative clustering technique are illustrated in Fig. 3 in form of a dendrogram. The final network partitions obtained by the proposed strategy satisfy all constraints in (3)–(7) and they are illustrated in Fig. 4. The generation-load difference of partitions 1 and 2 are 250 MW and 282 MW, respectively.

V. Case Studies

The proposed network partitioning strategy was implemented in MATLAB and evaluated against the spectral clustering based network partitioning strategy proposed in [5]. All the simulations were conducted on a computer with 2.67 GHz processor, 12GB memory, and Windows 7 operating system. IEEE 39- and 118-bus power systems are selected as the test cases and their data are obtained from MATPOWER [20]. It is assumed that all generators and breakers in those power systems are available after the blackout.

A. IEEE 39-bus power system

The first set of simulations was performed using IEEE 39-bus power system. Following parameters remained same for both strategies under test: the number of partitions $M = 2$, the set of black-start generators $\mathcal{V}^{\text{BS}} = \{v_{33}, v_{37}\}$, the sets of cranking groups $\mathcal{V}_1^{\text{CR}} = \{v_{30}, v_{31}, v_{32}, v_{37}, v_{39}\}$ and $\mathcal{V}_2^{\text{CR}} = \{v_{33}, v_{34}, v_{35}, v_{36}, v_{38}\}$, the set of critical loads $\mathcal{V}^{\text{CL}} = \{v_3, v_4, v_8, v_{16}, v_{20}\}$, and the set of excluded lines $\mathcal{E}_{\text{E}} = \{e_{(5,6)}, e_{(6,7)}, e_{(6,11)}, e_{(10,11)}, e_{(13,14)}, e_{(15,16)}, e_{(21,22)}, e_{(23,24)}, e_{(26,29)}, e_{(28,29)}\}$.

In the initial partitioning step, the proposed network partitioning strategy came up with two shortest path trees using Dijkstra's algorithm; one consists of 15 nodes and the other with 16 nodes. Based on these shortest path trees and the edges in $\mathcal{E}_{\text{E}}$, initial partitions are formed. For this test case, there are

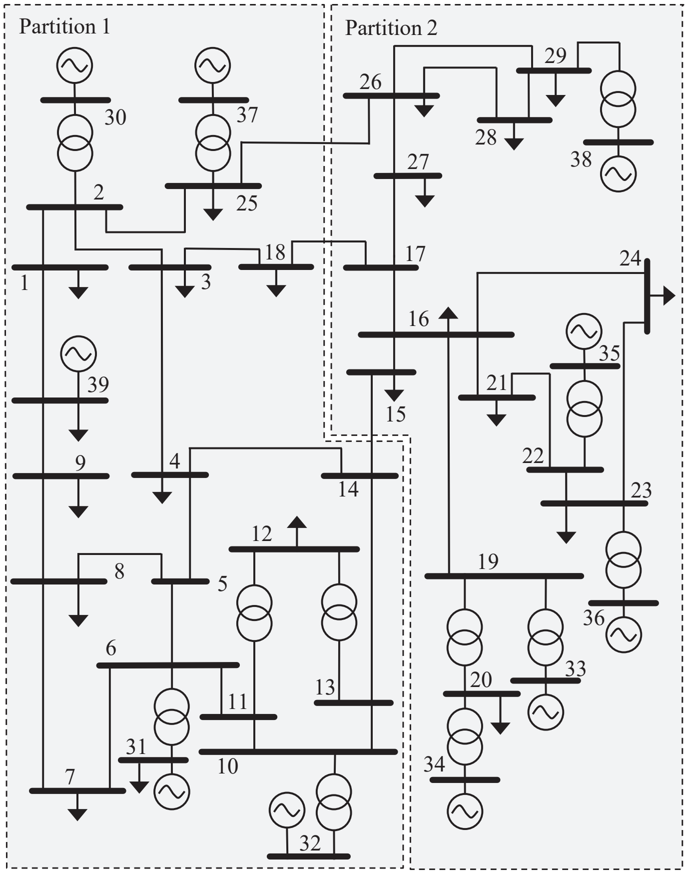

Fig. 5. Final network partitions of IEEE 39-bus power system obtained by using the proposed network partitioning strategy.

6 initial partitions formed by the proposed strategy. Finally, the agglomerative clustering approach works on these initial partitions to obtain desired network partitions for parallel restoration. The final partitions obtained by the proposed strategy for IEEE 39-bus power system is shown in Fig. 5. The cut-sets and the generation-load difference of the partitions resulted by the strategies under test are given in TABLE I.

According to the obtained results, network partitions generated by both strategies are similar to each other, except that v_{18} is grouped with Partition 1 when using the proposed strategy and it is grouped with Partition 2 when using the spectral clustering based method [5]. However, such a move causes to a quite considerable change in the minimum generation-load difference of the partitions. Even though both strategies result in a positive minimum generation-load difference, the proposed strategy in this paper achieves a higher value (841.280 MW) for that compared to the referred strategy under test (730.680 MW). Due to that higher minimum generation-load difference value, the proposed strategy can provide better stability and safety margin to the network partitions by matching generation and consumption.

B. IEEE 118-bus power system

The second set of simulations was performed using IEEE 118-bus power system. Following parameters remained same for both strategies under test: $M = 2$,

TABLE I
PARTITIONING RESULTS FOR IEEE 39-BUS POWER SYSTEM.

Partitioning method	$\mathcal{E}_{\text{CS}}$	φ (MW)	
		Partition 1	Partition 2
Spectral clustering based method [5]	$\{e_{(3,18)}, e_{(14,15)}, e_{(25,26)}\}$	1218.499	730.680
Proposed method	$\{e_{(14,15)}, e_{(17,18)}, e_{(25,26)}\}$	1107.899	841.280

$\mathcal{V}^{\text{BS}} = \{v_{31}, v_{87}\}$, $\mathcal{V}_1^{\text{CR}} = \{v_{10}, v_{12}, v_{25}, v_{26}, v_{31}\}$, $\mathcal{V}_2^{\text{CR}} = \{v_{49}, v_{54}, v_{59}, v_{61}, v_{65}, v_{66}, v_{69}, v_{80}, v_{87}, v_{89}, v_{100}, v_{103}, v_{111}, v_{46}\}$, $\mathcal{V}^{\text{CL}} = \{v_6, v_{11}, v_{15}, v_{18}, v_{27}, v_{34}, v_{40}, v_{56}, v_{60}, v_{62}, v_{70}, v_{74}, v_{76}, v_{78}, v_{92}, v_{112}\}$, and $\mathcal{E}_{\text{E}} = \{e_{(5,8)}, (e_{8,9}), e_{(9,10)}, e_{(34,43)}, e_{(37,38)}, e_{(38,65)}, e_{(40,42)}\}$.

In the initial partitioning step, the proposed network partitioning strategy came up with two shortest path trees using Dijkstra's algorithm; one consists of 12 nodes and the other with 23 nodes. For this test case, there are 81 initial partitions formed by the proposed strategy and 76 of them are sole nodes. The final two partitions obtained by the proposed strategy for IEEE 118-bus power system are shown in Fig. 6. The cut-sets and the generation-load difference of the partitions resulted by the strategies under test are given in TABLE II. Even though both strategies result in a positive minimum generation-load difference, the proposed strategy in this paper achieves a higher value (1113.8 MW) for that compared to the referred strategy under test (746.8 MW). Therefore, the proposed strategy can provide better stability and safety margin to the network partitions by matching generation and consumption.

The third set of simulations was also performed using IEEE 118-bus power system with the objective of illustrating the capability of the proposed approach in partitioning a network into more than two partitions in a single execution. Simulation results are given in TABLE III. The average run times given in TABLE III were obtained by using 10 simulations per each case. According to the simulation results, the minimum generation-load difference of the partitions of all test cases are positive. Average run times of the proposed network partitioning strategy have slightly increased as the number of partitions increases. Nevertheless, the average run time of each case is quite insignificant. This computationally efficient partitioning capability can be considered as a major advantage of the proposed network partitioning strategy over some existing strategies when a power system is divided into more than two subsystems.

VI. Discussion

Depending on the $\alpha(v_i)$ selected, the total generation-load difference of some existing power systems [20] can be a negative value. In such cases, it is impossible to produce network partitions such that the generation-load difference of each partition is a positive value. Even though the proposed network partitioning strategy tries to find a cut-set that maximizes the minimum generation-load difference of all possible partitions

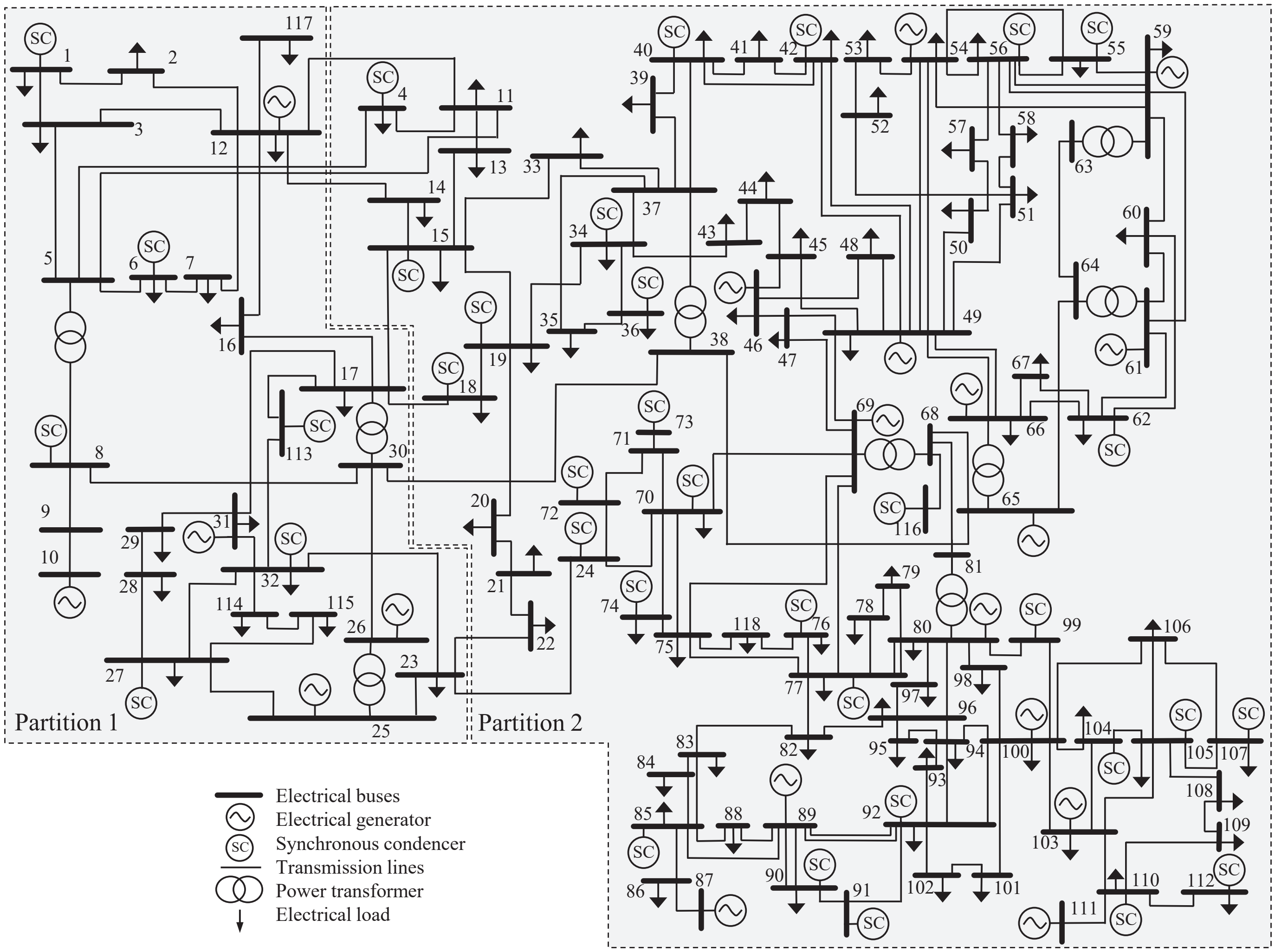

Fig. 6. Final network partitions of IEEE 118-bus power system obtained by using the proposed network partitioning strategy.

TABLE II
PARTITIONING RESULTS FOR IEEE 118-BUS POWER SYSTEM.

Partitioning method	$\mathcal{E}_{\text{CS}}$	φ (MW)	
		Partition 1	Partition 2
Spectral clustering based method [5]	$\{e_{(19,34)}, e_{(24,70)}, e_{(24,72)}, e_{(30,38)}, e_{(33,37)}\}$	746.8	2168.9
Proposed method	$\{e_{(4,5)}, e_{(5,11)}, e_{(11,12)}, e_{(12,14)}, e_{(15,17)}, e_{(17,18)}, e_{(22,23)}, e_{(23,24)}, e_{(30,38)}\}$	1113.8	1801.9

TABLE III
AVERAGE RUN TIMES OF THE PROPOSED NETWORK PARTITIONING STRATEGY FOR PARTITIONING IEEE 118-BUS POWER SYSTEM.

Number of partitions	$\min(\varphi)$ (MW)	Average run time (s)
2	1113.8	0.7443
3	949.2	0.7799
4	352.3	0.8513
5	352.3	0.9155

rather than producing some partitions with positive generation-load differences and the rest with large negative generation-load differences, certain partitions can still result in negative generation-load differences. In such cases, transmission system operators can either decide to repartition with a reduced $\alpha(v_i)$ value or not to restore non-critical loads in the partitions with negative generation-load difference as they can be restored after the synchronization of the partitions.

In the proposed strategy, the number of partitions are mainly based on the number of cranking groups. The probability of having small partitions increases as the number of partitions increases. Small network partitions help to accelerate the restoration process after a blackout. However, due to lack of size balancing mechanism in existing network partitioning strategies, some of the partitions can be larger than the rest. Therefore, they are unable to guarantee same restoration time for all network partitions. Due to some exceptionally large partitions, the completion of the whole restoration process can be delayed. Such a drawback might be alleviated by imposing size constraints on the network partition process.

In this paper, it is assumed that a power system is fully observable after a blackout and it can be continuously monitored from a power system control centre. However, such an assumption might not be valid in practice as some of the monitoring equipment can be malfunctioning due to the blackout. Moreover, it is assumed that all generators and breakers in the power system are available after the blackout. However, some of those resources might be unavailable immediately after the blackout, thus, they must be abstain from restoration. Future work should focus on partitioning of partially observable power systems after a blackout. It may also be important to investigate the impact of the reactive power balance in each partition.

VII. Conclusion

In this paper, we proposed a novel network partitioning strategy for parallel restoration after a blackout. The proposed three-step strategy can separate a power system into multiple partitions in a single execution. It maximizes the minimum generation-load difference of partitions which helps to maintain the system stability. In the initialization step, a power system is transformed into an undirected graph using network theory concepts and some essential node and edge sets are defined. In the initial partitioning step, the proposed network partitioning strategy makes sure some important physical requirements are satisfied for the proper operation of individual partitions and the overall power system. Finally, an agglomerative clustering approach is utilized to maximize the minimum generation-load difference of network partitions in each step. Simulation results obtained using IEEE 39- and 118-bus power systems verify the applicability of the proposed strategy in network partitioning for the parallel power system restoration.

References

[1] B. Liscouski and W. Elliot, "Final Report on the Augugst 14, 2003 Blackout in the United States and Canada: Causes and Recommendations." US Canada Power System Outage Task Force, Tech. Rep., April 2004, http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf.

[2] A. Atputharajah and T. K. Saha, "Power system blackouts-literature review," in *2009 International Conference on Industrial and Information Systems (ICIIS)*. IEEE, 2009, pp. 460–465.

[3] L. Yutian, F. Rui, and V. Terzija, "Power system restoration: a literature review from 2006 to 2016," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 3, pp. 332–341, 2016.

[4] J. Quirós-Tortós, M. Panteli, P. Wall, and V. Terzija, "Sectionalising methodology for parallel system restoration based on graph theory," *IET Generation, Transmission & Distribution*, vol. 9, no. 11, pp. 1216–1225, 2015.

[5] J. Quirós-Tortós, P. Wall, L. Ding, and V. Terzija, "Determination of sectionalising strategies for parallel power system restoration: A spectral clustering-based methodology," *Electric Power Systems Research*, vol. 116, pp. 381–390, 2014.

[6] N. Ganganath, C.-T. Cheng, H. H.-C. Iu, and T. Fernando, "Subsystem size optimization for efficient parallel restoration of power systems," in *IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2017, pp. 2504–2507.

[7] S. A. N. Sarmadi, A. S. Dobakhshari, S. Azizi, and A. M. Ranjbar, "A sectionalizing method in power system restoration based on WAMS," *IEEE Transactions on Smart Grid*, vol. 2, no. 1, pp. 190–197, 2011.

[8] C. Wang, V. Vittal, and K. Sun, "OBDD-based sectionalizing strategies for parallel power system restoration," *IEEE Transactions on Power Systems*, vol. 26, no. 3, pp. 1426–1433, 2011.

[9] L. H. Fink, K.-L. Liou, and C.-C. Liu, "From generic restoration actions to specific restoration strategies," *IEEE Transactions on power systems*, vol. 10, no. 2, pp. 745–752, 1995.

[10] M. M. Adibi, W. Alexander, and B. Avramovic, "Overvoltage control during restoration," *IEEE Transactions on Power Systems*, vol. 7, no. 4, pp. 1464–1470, 1992.

[11] I. Kamwa, A. K. Pradhan, G. Joos, and S. R. Samantaray, "Fuzzy partitioning of a real power system for dynamic vulnerability assessment," *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1356–1365, 2009.

[12] Z. Lin, F. Wen, C. Chung, K. Wong, and H. Zhou, "Division algorithm and interconnection strategy of restoration subsystems based on complex network theory," *IET generation, transmission & distribution*, vol. 5, no. 6, pp. 674–683, 2011.

[13] G. Karypis and V. Kumar, "Multilevel k-way partitioning scheme for irregular graphs," *Journal of Parallel and Distributed computing*, vol. 48, no. 1, pp. 96–129, 1998.

[14] L. Sun, C. Zhang, Z. Lin, F. Wen, Y. Xue, M. A. Salam, and S. P. Ang, "Network partitioning strategy for parallel power system restoration," *IET Generation, Transmission & Distribution*, vol. 10, no. 8, pp. 1883–1892, 2016.

[15] S. Nourizadeh, M. Karimi, A. Ranjbar, and A. Shirani, "Power system stability assessment during restoration based on a wide area measurement system," *IET Generation, Transmission & Distribution*, vol. 6, no. 11, pp. 1171–1179, 2012.

[16] W. Sun, C.-C. Liu, and S. Liu, "Black start capability assessment in power system restoration," in *IEEE Power and Energy Society General Meeting*. IEEE, 2011, pp. 1–7.

[17] F. Qiu, J. Wang, C. Chen, and J. Tong, "Optimal black start resource allocation," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2493–2494, 2016.

[18] W. Sun, C.-C. Liu, and L. Zhang, "Optimal generator start-up strategy for bulk power system restoration," *IEEE Transactions on Power Systems*, vol. 26, no. 3, pp. 1357–1366, 2011.

[19] E. W. Dijkstra, "A note on two problems in connexion with graphs," *Numerische mathematik*, vol. 1, no. 1, pp. 269–271, 1959.

[20] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 12–19, 2011.