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Research Article

Agglomerative Hierarchical Clustering Methodology to Restore Power System considering Reactive Power Balance and Stability Factor Analysis

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Despite there are significant advancements in modern power systems, blackouts remain a potential risk, necessitating efficient restoration strategies. This paper introduces an innovative concept for power system restoration, focusing on balancing active and reactive power while ensuring voltage stability. For instance, this paper employs an agglomerative clustering technique, which partitions the power system into segments with balanced reactive power, facilitating swift restoration postblackout. Central to this methodology is the use of the line stability factor, which assesses the voltage stability of individual lines, identifying the system's stronger and weaker sections based on voltage stability levels. This paper demonstrates the effectiveness of the proposed methodology through case study analysis, comparing voltage stability levels across agglomerative clusters and their geographical locations. The power system is divided into two stable partitions, considering the number of black-start generators, available reactive power, and voltage stability levels. This partitioning reveals that the clusters formed by the agglomerative method are inherently stable, suggesting enhanced system stability, dependability, and availability during the restoration phase following a blackout. In addition, this paper discusses the potential causes of blackouts, offering insights into their prevention, and finishes with a novel clustering methodology for power systems, considering reactive power and voltage stability. This method facilitates the parallel restoration of the system's independent partitions, significantly reducing restoration time; it addresses critical challenges and outcomes, underscoring the methodology's potential to revolutionize blackout recovery processes in modern power systems.

1. Introduction

The risk of system blackouts still cannot be avoided entirely, even though extensive research has been conducted on the power system's resilience against outages, because modern power systems have turned into a complex network attributed to the significant integration of different renewable energy sources [1]. Expeditious development and broad application of emerging technologies have increased the probability of complex studies on the occurrence of blackouts [1]. There can be several causes for the blackout while looking at the history of blackouts worldwide, including failure of the equipment or/and protection or/and control systems, cyber-attacks, natural disasters, inadequate maintenance work, and ice coating on the power lines [2]. The impact of blackouts is enormous because it affects every normal daily-life activity of the people along with disrupting the critical infrastructure for life, incurring economic losses of the people to the financial losses of the nation, and disrupting the power system network itself, spreading from a small region to a larger region [3]. The occurrence of a blackout can be minimized but cannot be avoided with complete certainty. There should be a suitable restoration strategy that can restore the power system quickly and reliably. There are various ways to perform the restoration of the power system, but a process should be chosen such that it is very efficient and faster in restoration. Hence, the objective of modern power system is not only to completely nullify the chances of a blackout but rather to provide a corrective measure for facilitating the effective restoration of the power system considering different factors, such as the system's operating status, availability of the equipment, restoration time, and the rate of success of the restoration process, so that the power system can return to the normal operating condition quickly and securely eventually leading to minimum loss potentially incurred by the blackouts [1].

A concept of generic restoration action (GRA) is elaborated in [4], which can be used to perform specific restoration strategies. The restoration is faster when the main system is sectionalized into two or more subsystems, and those subsystems are restored parallelly all at a time [5–7]. Each subsystem consists of a cranking group, including at least one black start generator with a self-starting ability, which cranks one or more nonblack start generators simultaneously for parallel restoration of the subsystems [8, 9]. To supply the cranking power, there should be the shortest path between the black start generator and the nonblack start generator. The shortest path can be calculated using various algorithms, such as (a) Floyd–Warshall algorithm [10–12], (b) Johnson's algorithm [11], (c) Greedy algorithm [12], and (d) Dijkstra's algorithm [11, 13]. Floyd–Warshall algorithm is a highly used algorithm to find the shortest path in a weighted graph for all pairs of nodes. It is efficient to use when there are a relatively smaller number of nodes [11]. On the other hand, Dijkstra's algorithm is also an easy and widely used algorithm to find the shortest path between a pair of nodes, which makes it highly efficient for graphs having a high number of nodes [14]. In [14], Dijkstra's algorithm is used to find the shortest path as there were many nodes, and the path between only two nodes was to be found. The black start generators were taken as the root node and the nonblack start generators as the leaf nodes, and then, the shortest path was found between the root and leaf nodes [13]. When a proper cranking path is ensured, there is a necessity for a proper generator startup sequence. The generator startup sequencing affects the restoration time and plays a crucial factor during the restoration of a system [15]. For fast and efficient restoration of a system, a study [15] shows a new serial generator startup sequencing (GSUS) optimization model with flexible reenergizing times of transmission lines. The GSUS is formulated considering mixed integral linear programming (MILP), in which variables are restoration time constraints for the transmission lines, startup time constraints for the buses on the restoration paths, and a serial restoration constraint, whereas the restart time constraints of the generators and the transient frequency requirements were modeled as mixed integer linear constraints.

When a proper cranking sequence is ensured, then the system is ready to be sectionalized in subsystems with the help of clustering. Clustering helps to divide a blackout area into multiple subsystems or sections. The different types of strategies used for clustering of the power system are as follows: (a) fuzzy partitioning of a real power system for dynamic vulnerability assessment [16], (b) sectionalizing method in power system restoration based on WAMS [17], (c) hierarchical clustering-based zone formation in power networks [18], and (d) agglomerative hierarchical clustering [19]. In [19], the agglomerative hierarchical approach has been chosen as compared to the other clustering methodologies because of its advantage of being able to make a dendrogram using a bottom-up approach. It clearly shows the nodes and the generation-load differences. Due to its simplicity, it is easier to track and form possible clusters. Also, agglomerative clustering partitions the complete system into a certain number of clusters based on the number of black start generators in the system.

Several literatures show different kinds of restoration strategies based on clustering or partitioning of a system and network reconfiguration, whereas some literature shows ways for resiliency improvements in existing grids such that there are lesser chances of blackouts. Current trends in research and future research directions concerning transmission network reconfiguration are shown in [20]. Transmission network reconfiguration for grid resilience is a second-stage action plan in the process of power system restoration. To assess the present state of the system and future upgrades, CNT-based indices applied for transmission network reconfiguration are presented and discussed. Also, there is a detailed description of optimization techniques, challenges, and technical issues during network reconfiguration [20]. A complicated network community discovery-based label propagation algorithm (LPA) is presented in [7] in which bus label and ranked node influence index are used to partition a system into subsystems with a minimal number of cut sets and minimal active power flow. The author of [21] shows the crucial problems in the European Transmission system which may lead to large-scale blackout due to reasons, such as variability of output of RES and cyber-attacks. In solution to the expected blackout, the paper presented a parallel restoration strategy using the A$*$ algorithm which can be used by TSOs. Here, the optimum restoration path is found using both the BS units (bottom-up restoration principle) and the available tie lines (stepdown restoration principle) in IEEE 39-bus and IEEE 68-bus systems [21]. An approach to improve the resiliency of the power system on the preexisting infrastructure is presented in [22]. The study uses network reconfiguration through transmission line switching as a temporary corrective tool in dealing with the forthcoming contingencies. It also shows a way to harness the full control of the system's resilience during severe vulnerabilities and extreme emergencies [22]. A two-stage mixed integer linear programming- (MILP-) based NR strategy for grid-resilience enhancement is presented in [23] which helps to minimize the impact of emergency power outages on power systems. The strategy is presented majorly in a two-stage optimization model. In the first stage of optimization, line charging and generator startup sequencing are determined, and in the second-stage, the optimization model determines the optimal skeleton network by determining the target transmission lines and critical load pickup during the NR phase [23]. Modern grids are complex grids due to integration of RES and multienergy system technologies. So, for the restoration of renewable-dominated electric power systems, the author of [24] presents a review of relative restoration strategy on three phases, i.e., the black-start, network reconfiguration, and the load restoration phases. This study reviews the current research status of the restoration technologies, real-world applications, and future challenges on restoration of renewable-dominated electric power systems. A novel restoration strategy in microgrids after a blackout using DGs for the restoration of critical loads is shown in [25]. The study uses MILP using load weight and node importance degree as variable to simulate the issue and restore the system. The main priority is given to the critical loads and maximum number of critical loads will be restored in a radial feeder.

Black-start resource allocation, such as black-start and nonblack-start units, should be appropriately carried out before starting the clustering process [26]. An extensive study on the properties and status of the system, such as critical lines, critical loads, and the condition of equipment used in lines, should be considered before initiating the clustering of the power system such that the restoration process can run smoothly without any complications [5]. The lines that interconnect two or more partitions are called tie lines. Taking active power into consideration, the loads that are connected to the generator bus or the loads for which continuous power supply is critical, such as hospitals, are called crucial (critical) loads. The nodes connecting those critical loads are called critical nodes [8]. Taking reactive power into consideration, the loads that are prone to voltage instabilities are critical loads and the nodes connecting those loads are critical nodes [27]. These critical nodes are identified based on the power system network structure [27]. A bus (node) that has a high probability of experiencing voltage instability when subjected to an increment of load values is called a weak node [28]. The lines that show the large fluctuation of active and reactive power flow when subjected to sudden disturbance are critical. These lines are identified using $N-1$ contingency analysis in [29]. Power flow between-ness is used to calculate critical lines in [30]. The identification of critical lines is very important because their removal while forming the cut-set can lead to excessive voltage instability and excessive difference of reactive power in the system [31]. The critical lines may include large transformers and other devices that may be affected by the overvoltages during restoration, so critical lines must be known, and proper precautions are necessary while restoring and energizing a large part of the power system [32].

The agglomerative clustering approach has been used in [19], where active power balance has been performed by maximizing the minimum generation-load difference. It showed the partitions formed are only based on active power flow in the system. However, only an active power balance is not enough to ensure the overall stability, reliability, and availability of the partitions during and after their restoration. In a power system, reactive power flows in proportion to active power. So, it becomes necessary to check the reactive power flow concerning active power and the effects that can be imposed on the system if there is a change in the flow of the reactive power. Also, the voltage stability of the system is directly related to reactive power flow in the system, and the reactive power balance and voltage stability should be checked in the system. This paper proposes a methodology to split a system into multiple partitions concerning reactive power balance using agglomerative clustering so that the identified partitions can be compared to those partitions by active power balance. Also, these partitions will be further used for the parallel restoration of the system. Also, the voltage stability level of individual buses and the partitions should be known before starting the restoration process, as the voltage stability of the elements of the power system is governed by the reactive power flow, as explained in [33]. To check the voltage stable and unstable regions, a method of clustering using line stability factor [34] can be performed. This approach provides the voltage stability of different regions in a power system, indicating all strong and weaker regions in the form of clusters. Finally, the agglomerative clusters can be compared to the strong and weak voltage stability regions to validate the clusters for real-time use during the restoration of a power system.

With the concept mentioned above, this paper proposes a method of clustering power systems considering only the reactive power balance. Also, voltage stability is directly related to reactive power; a further study on voltage stability is proposed to validate the voltage stability of the clusters. This work has the specific objectives as follows: (a) to perform agglomerative hierarchical clustering of power system with reactive power balance, (b) to calculate line stability factors and investigate the voltage stability, (c) to justify the clusters concerning voltage stability and load generation differences, and (d) to make the final clusters ready to undergo restoration with proper recommendations.

This research work is organized into five major sections. In Section 1, the introduction provides background and a literature review on different types of clustering techniques, recent related works, and objectives. In Section 2, the methodology includes the algorithm to perform agglomerative hierarchical clustering concerning reactive power balance and voltage stability analysis concerning line stability factors. Section 3 test cases include the IEEE test-bus system in which the clustering algorithm is implemented, and all the results are discussed. Finally, in Sections 4 and 5, the discussion and conclusions are presented, respectively.

2. Methodology

The overall block diagram of the proposed methodology is shown in Figure 1. As shown in Figure 1, the network partitioning strategy has three steps: step 1: initialization, step 2: initial partitioning, and step 3: agglomerative clustering. The detailed descriptions of these steps are given in the following sections.

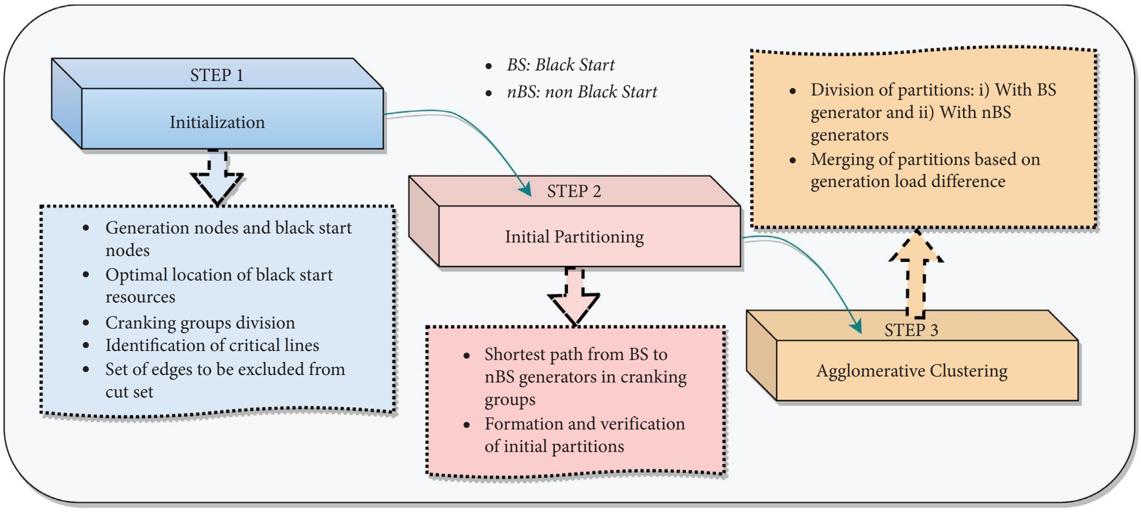

Figure 1: Block diagram of methodology.

2.1. *Step 1: Initialization.* The graph of the power system can be represented as $G=\{V, E\}$, where $V=\{v_1, v_2, \ldots\ldots\ldots, v_{|V|}\}$ represents the set of buses in the power system taken as a set of nodes and $E=\{e_1, e_2, \ldots\ldots\ldots, e_{|E|}\}$ represents the set of branches connecting those buses taken as a set of edges. A graph of the IEEE 9-bus system is shown in Figure 2 [19].

The set of nodes is divided into two subsets: generation nodes V^{GN} $(\subset V)$ and black-start nodes $V^{\mathrm{BS}}(\subset V^{\mathrm{GN}})$. The generation nodes are grouped with nonblack start generators to form a cranking group such that cranking power can be supplied to the nonblack-start generators (V^{GN}) from the black-start generators (V^{BS}) during the restoration process. Similarly, the set of weak nodes connecting the critical loads is represented by V^{CN} $(\subset V)$. The important nodes and edges that play a key role while partitioning the system, i.e., black-start nodes (V^{BS}), nonblack-start nodes (V^{GN}), and critical nodes (V^{CN}), are initialized. M partitions are supposed to be formed at the end of clustering and given by equations (1)–(3).

$$2 \leq M \leq \left|V^{\mathrm{BS}}\right|, \tag{1}$$

$$v_i \cap v_j = \phi, \tag{2}$$

$$v_1 \cup v_2 \cup v_3 \ldots \cup v_M = V. \tag{3}$$

For $i, j \in \{1, 2, \ldots\ldots, M\}$ and $i \neq j$. Hence, there should be M disjoint cranking groups so that each of the M partitions can be restored independently as given by the following equation:

$$V_k^{\mathrm{CR}} \subseteq V_k. \tag{4}$$

For all $k \in \{1, 2, \ldots, M\}$, where the k^{th} network partition is represented by V_k and the k^{th} cranking group is represented by V_k^{CR}. The connectivity within the cranking groups should be maintained at the end of clustering before starting the restoration process. From equations (2) and (4), it can be written as $V_i^{\mathrm{CR}} \subseteq V_j^{\mathrm{CR}} = \phi$ for $i, j \in \{1, 2, \ldots\ldots, M\}$ and $i \neq j$.

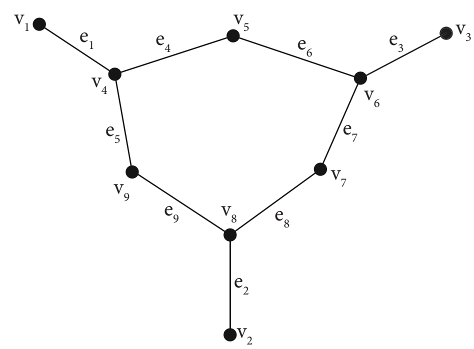

Figure 2: Graph of the IEEE 9-bus power system.

There must be at least one black start generator in each cranking group, which can be seen in the following equation:

$$\left|V_k^{\mathrm{CR}} \cap V^{\mathrm{BS}}\right| \geq 1\, k \in \{1, 2, \ldots, M\}. \tag{5}$$

The critical lines should not be used as tie lines. Also, the lines without monitoring equipment should not be used as tie lines; they should be avoided in the cut-set. Moreover, other unsuitable lines can be included in the cut-set due to different reasons, which should be analyzed before heading towards initial partitioning.

$$\left(E_{\mathrm{CL}} \cup E_{\mathrm{NM}} \cup E_U\right) \cap E_{\mathrm{CS}} = \phi, \tag{6}$$

$$E_E = \left(E_{\mathrm{CL}} \cup E_{\mathrm{NM}} \cup E_U\right), \tag{7}$$

where E_{CL} represents the critical lines, E_{NM} represents the line without monitoring equipment, E_U represents the unsuitable lines to be included in the cut-set due to different reasons, and E_{CS} represents the cut-set. The excluded set in this study is represented by E_E. Combining (6) and (7), equation (8) can be achieved.

$$\left(E_E \cap E_{\mathrm{CS}}\right) = \phi. \tag{8}$$

For the IEEE test-bus system, an assumption (i.e., $E_{NM} = E_U = \phi$) was made in [19], which gives $E_E = E_{CL}$.

2.2. Step 2: Initial Partitioning. It is ensured that the black start generator can start all nonblack start generators in each cranking group. This is carried out by finding the shortest path trees using Dijkstra's algorithm [13]. To obtain a certain number of initial partitions, equations (4)–(6) can be used. Then, all the nodes belonging to the shortest path tree are grouped as separate partitions for each cranking group, and the set of nodes within them is assumed to be mutually exclusive. Any other nodes that are connected to the shortest path tree by any edges within a set of excluded lines (E_E) are merged into the same partition. The remaining nodes not connected to any partitions as formed above are taken as separate partitions. The detailed process for the initial partitioning of the power system is shown in Figure 3.

2.3. Step 3: Agglomerative Clustering. The main basis of network partitioning for parallel power system restoration is to evaluate the generation-load difference of the individual partitions, which can be determined by equations (9) and (10) [8].

$$\varphi(V_k) = \sum_{\forall v_i \in v_k} Q(v_i), \tag{9}$$

where V_k is the k^{th} partition and $Q\ (v_i)$ is the reactive generation-load difference at node v_i, which can be determined through the following equation:

$$Q(v_i) = Q_{MG}(v_i) - \beta(v_i) Q_{LD}(v_i). \tag{10}$$

Here, in equation (10), $Q_{MG}(v_i)$ and $Q_{LD}(v_i)$ represent the maximum reactive power generation capability and the expected reactive power consumption at v_i and $\beta(v_i)$ represents the percentage of load that should be restored before synchronizing the network partitions. For critical nodes, the value of $\beta(v_i)$ is taken as 1 [35].

First of all, it is ensured that there is availability of sufficient line charging power. If there is sufficient power, then only the restoration process of each cluster is possible [36]. For this, the generator should be capable of supplying all the reactive power. If a generator is not able to supply the required power, there should be compensating devices to supply the reactive power needed for the line to be charged [37]. Then, only the load is taken into consideration to be restored. A set of partitions over different cut sets that had the maximum generation-load difference is formed so that there would always be some extra reactive power to take care of load variations and uncertainties which is given by the following equation:

$$\{V_1, V_2, V_3, \ldots\ldots\ldots\ldots V_M\} = \arg \max_{\{V_1', V_2', V_3', \ldots\ldots\ldots\ldots V_M'\}} \left(\min_{k \in \{1, 2, 3 \ldots\ldots\ldots\ldots, M\}} \varphi(V_k') \right). \tag{11}$$

After finding the initial partitions, they are categorized into two groups: (a) one consisting of black start generators (black-start partition) and (b) another with nonblack start generators (nonblack start partition). Then, the black start partition is merged with every nonblack start partition temporarily, and the respective generation-load differences for all black start partitions are calculated. In this study, the value of $\beta(v_i)$ is taken as 0.5 if $v_i \in V/V^{CL}$ after initializing that there is enough reactive power available for charging the line. This implies only 50% of the load is restored, including all the critical loads for which $\beta(v_i)$ is taken as 1, which ensures the stability of the partitions after their synchronization. All the merged pairs are compared with each other to find the pair with the maximum generation-load difference. The pair with the maximum generation-load difference is merged permanently to form a new black-start partition. This process is continued iteratively until all the nonblack start partitions are merged with the black-start partition, as shown in Figure 4.

The same methodology can be used for both active and reactive power balance, where the number of final output partitions is equal to the number of black start generators so that every output partition obtained after agglomerative clustering can be restored independently.

2.4. Line Stability Factor for Voltage Stability Analysis. The line stability factor for voltage stability analysis is started by calculating the line stability factors for individual lines. The factors that determine the voltage stability level of all the lines in a system are line stability factors. For this study, there are four-line stability factors, i.e., LPP, LQP, LPN, and LQN, for a single line. These factors can be derived using Figure 5 and are given by equations (12)–(15) [34].

$$\text{LPP} = 4\left(\frac{R}{V_i^2}\right)\left(P_r + \frac{RQ_i^2}{V_i^2}\right), \tag{12}$$

$$\text{LQP} = 4\left(\frac{X}{V_i^2}\right)\left(Q_r + \frac{XP_i^2}{V_i^2}\right), \tag{13}$$

$$\text{LPN} = 4\left(\frac{R}{V_{i+1}^2}\right)\left(-P_i + \frac{RQ_r^2}{V_{i+1}^2}\right), \tag{14}$$

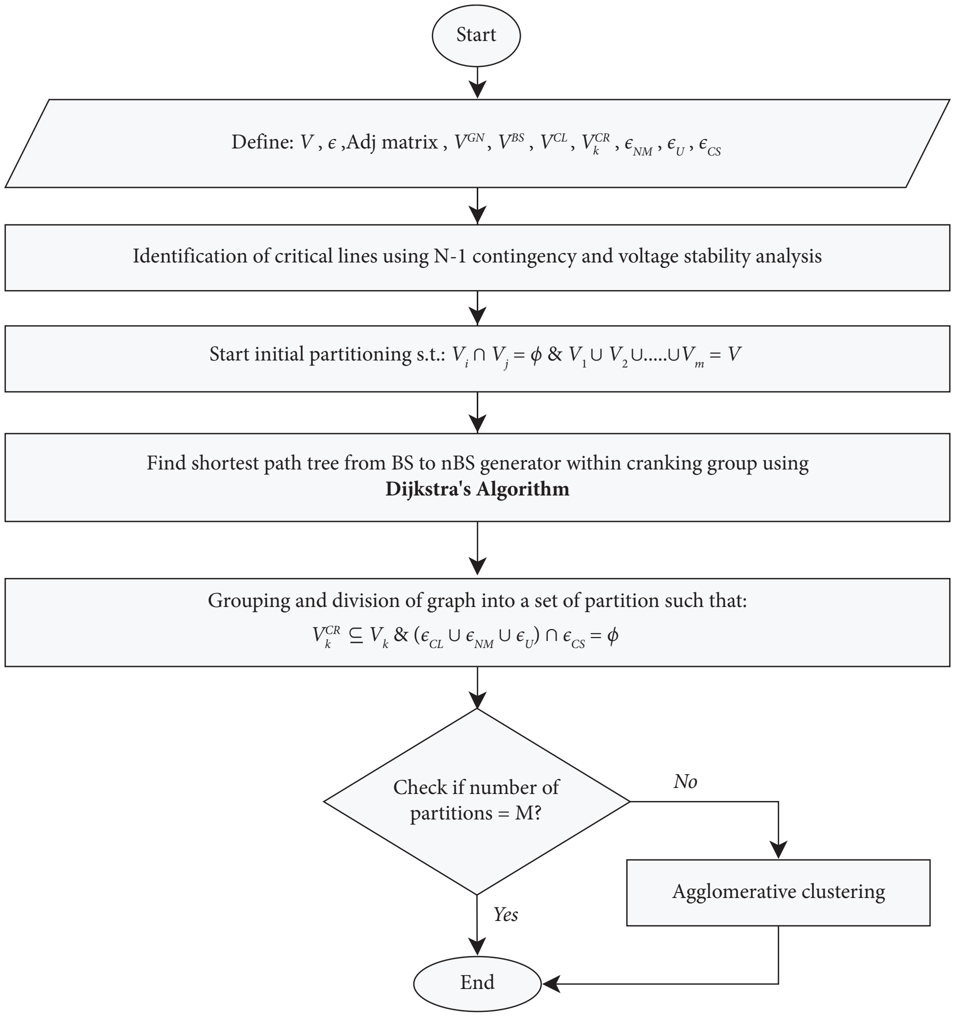

Figure 3: Flowchart for initial partitioning of the power system (step 2).

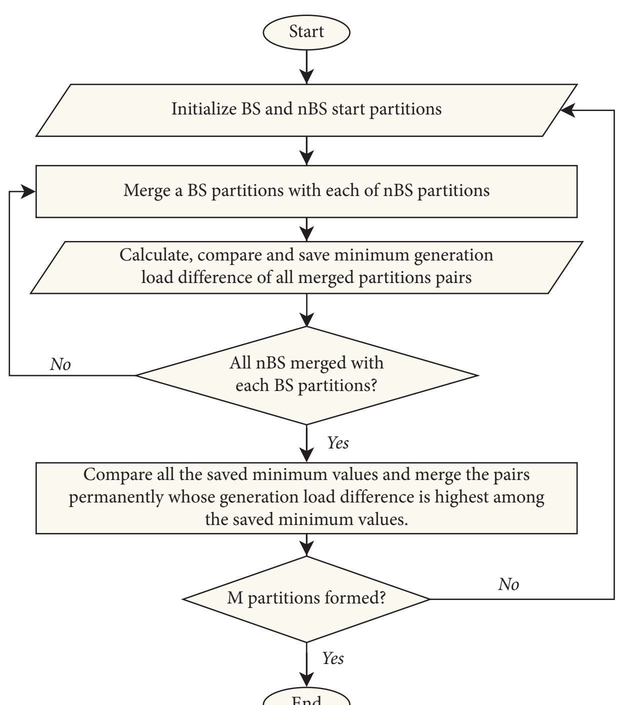

Figure 4: Flowchart for agglomerative clustering of the power system (step 3).

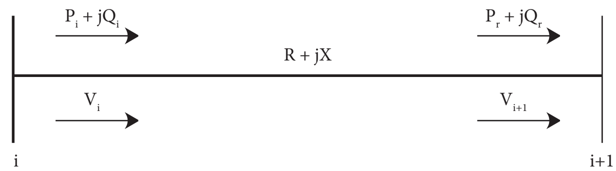

Figure 5: Power flow from node i to node $i+1$.

$$\mathrm{LQN} = 4\left(\frac{X}{V_{i+1}^{2}}\right)\left(-Q_i + \frac{XP_r^{2}}{V_{i+1}^{2}}\right), \quad (15)$$

where V_i is the voltage at the i^{th} node, V_{i+1} is the voltage at $(i+1)^{th}$ node, $P_r + jQ_r$ is the receiving end power, $P_i + jQ_i$ is the sending end power, and $R + jX$ is the impedance of the line.

The line stability factor values are calculated using equations (12)–(15). The line stability factors show four different values for a single line. The critical limit is 1.0 for all the factors. The largest positive value nearest to 1 among the four factors is selected for every line. This largest line stability factor value is called LQPN. The LQPN values signify the voltage stability level of a particular line. The line having the LQPN value near the critical limit is considered a weak or/ and critical line of the power system. A ranking table is then formed by positioning all the LQPN values of every line from smallest to largest values. A cutoff value is determined from the ranking table based on the coherent nature of buses within the cluster. All the LQPN values that are greater than the cutoff value can be considered the most critical lines (weak lines) and can be eliminated to determine the cut sets and the weak boundaries that encircle the bus clusters. Now, the coherency of all the buses is checked again so that the voltage and angle changes for the buses remain the same for any disturbance that occurs outside that group of buses. If the buses are found to be not coherent, then another cutoff value must be chosen and checked for coherency until all the buses are coherent inside a cluster [34]. The complete flowchart for the clustering method using the line stability factor is shown in Figure 6.

3. Results

3.1. Agglomerative Hierarchical Clustering. To assess the proposed method, the authors considered three standard benchmarks: IEEE 9-bus [38], IEEE 39-bus [39], and IEEE 118-bus [40] systems. In the IEEE 9-bus system, there are 3 generators, of which all 3 are committed generators. The total generation capacity and online capacity of the generators are 820 MW and −900 to 900 MVAr. The actual generation is 319.6 MW and 22.8 MVAr. There are 3 loads and the total load capacity is 315 MW and 115 MVAr, all of which are fixed loads (not dispatchable). The total loss is 4.64 MW and 48.38 MVAr. The total line charging power required is 140.5 MVAr. In the IEEE 39-bus system, there are 10 generators in this system of which all 10 are committed generators. The total generation capacity and online capacity of the generators is 7367 MW and −160 to 2807 MVAr. The actual generation is 6297.9 MW and 1274.9 MVAr. There are 21 loads and the total load capacity is 6254.2 MW and 1387.1 MVAr, all of which are fixed loads (not dispatchable). The total loss is 43.64 MW and 1000.59 MVAr. The total line charging power required is 1112.8 MVAr. In the IEEE 118-bus system, there are 54 generators in this system of which all 54 are committed generators. The total generation capacity and online capacity of the generators is 9966.2 MW and −7345 to 11777 MVAr. The actual generation is 4374.9 MW and 795.7 MVAr. There are 99 loads and the total load capacity is 4242 MW and 1438 MVAr all of which are fixed loads (not dispatchable). The total loss is 132.86 MW and 783.79 MVAr. The total line charging power required is 1341.7 MVAr [36].

The initializing parameters for these three bus systems are listed in Table 1. For the IEEE 9-bus system, the set of black-start nodes are $V^{BS} = \{v_1, v_2\}$, cranking group are $V_1^{CR} = \{v_1\}$, as in [19], and $V_2^{CR} = \{v_2, v_3\}$, critical nodes are $V^{CL} = \{v_4, v_6, v_8\}$, as in [27], and set of excluded lines are $E_{CL} = \{e_1, e_2, e_3\}$.

After initializing the above parameters, it is identified that V_1^{CR} only consists of black-start nodes, so its shortest path is simply as $G_1^{SP} = \{\{v_1\}, \varnothing\}$. However, for V_2^{CR}, it contained both black-start and nonblack-start nodes. During partitioning, cranking power is to be supplied from v_2 to v_3 through a shortest path tree which is identified by using Dijkstra's algorithm as $G_2^{SP} = \{\{v_2, v_3, v_6, v_7, v_8\}, \{e_2, e_3, e_7, e_8\}\}$. All the nodes in this shortest path tree are considered to be in one partition. Since V_4 is connected to V_1 by E_E, it is taken in the same partition as node V_1. Then, V_5 and V_9 are not connected to any nodes by E_E. Hence, they are considered as two separate partitions. As shown in Table 1, four initial partitions are obtained for the IEEE 9-bus system. As there are two black-start generators, two partitions can be made by making one black-start available on each partition. Here, in this case, a single node named V_{10} is used to represent a set of nodes V_2, V_3, V_6, V_7, and V_8. Similarly, a single node named V_{11} is used to represent a set of nodes of V_1 and V_4.

From the dendrogram shown in Figure 7, it identified the required number of partitions. The dendrogram represents the linkage among the nodes concerning the generation-load differences of those sole nodes. It can be seen that after removing the linkages temporarily, three major partitions can be formed for generation-load difference: first including nodes V_5 and V_{11}, second including node V_{10}, and third including node V_9. However, to satisfy the conditions stated in equation (4) and (5), buses, namely, V_9 and V_{10} are taken in a single cluster. From the dendrogram obtained after removing the linkages, V_{11} and V_5 are obtained in the first partition and V_9 and V_{10} are obtained in the second partition. The final required partition of the system for the IEEE 9-bus system with reactive power balance is shown in Figure 8.

As shown in Figure 8, the cutting sets to separate the partitions are e (4, 9) and e (5, 6), and the maximum generation-load difference of the 1st partition is 12.05 MVAR, and the 2nd partition is −71.71 MVAR.

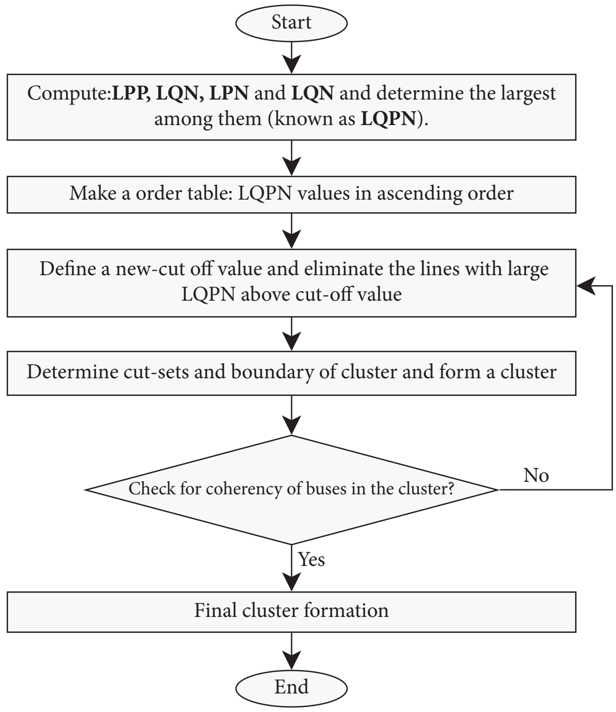

Figure 6: Flowchart for clustering using line stability factor for voltage stability analysis of a power system.

The main purpose of the proposed strategy is to find a cut-set that maximizes the minimum generation-load difference in the possible partitions rather than producing some partitions with a positive generation-load difference, while some partitions with the probability of producing a negative generation-load difference. Here, in the second partition, the total reactive generation-load difference is in negative value. The generation-load difference can be negative depending on $\beta(\nu_i)$. A partition with a negative value indicates that there is more load than the generation capability, and the generators cannot supply enough power to all the loads in the partitions. When a network partition produces a negative generation-load difference, it becomes impossible to take it as a separate partition because each partition must give a positive value. When such cases of negative generation-load difference occur, there are three choices for the system operator in case of reactive power. The first one is to change the value of $\beta(\nu_i)$, as $\beta(\nu_i)$ is directly responsible for the difference in generation-load, and then repeat all the procedures of agglomerative clustering once again to obtain a positive generation-load difference. The second choice can be that the operator may not restore only a few noncritical loads in those partitions where there is a negative generation-load difference, and they can be restored after the synchronization of that partition or the whole grid [19]. The third choice can be supplying extra reactive power using reactive power compensation devices such as synchronous condensers. Even though compensation can be carried out, economic feasibility should also be considered while restoring the loads. If the loads are very critical for use, they must be restored using the extra reactive power, which should be available and supplied through compensation. If the loads are not critical, methods of load-shedding can be used, which is more feasible than using compensation devices, to make the generation-load difference positive and start the restoration efficiently.

For the IEEE 39-bus system, six initial partitions are formed, which can be seen in the dendrogram given in Figure 9. From those initial partitions, the final two partitions are identified, as shown in Figure 10. The set of nodes belonging to some initial partitions are represented by a single node for simplification, $V40 = \{V1, V2, V3, V4, V5, V6, V7, V10, V11, V13, V14, V25, V30, V31, V32, V37\}$ and $V41 = \{V15, V16, V17, V19, V20, V21, V22, V23, V24, V26, V27, V28, V29, V33, V34, V35, V36, V38\}$. The cutting sets to separate the partitions are $e\,(14, 15)$, $e\,(3, 18)$, and $e\,(25, 26)$, where the maximum generation-load difference of the 1st partition is −96.11 MVAR and the 2nd partition is 321.18 MVAR.

The proposed method is also applied to the IEEE 118-bus system, which creates two clusters, as shown in Figure 11. The cutting sets to separate partitions are $e\,(15, 33)$, $e\,(19, 34)$, $e\,(30, 38)$, $e\,(71, 72)$, and $e\,(24, 70)$, and the maximum generation-load difference of 1st partition is 104.53 MVAR and that of 2nd partition is 63.72 MVAR.

3.2. Line Stability Factor for Voltage Stability Analysis. The ranking table for the IEEE 9-bus system is shown in Table 2. Initially, the cutoff value is taken to be 0.1; then, all the LQPN values are compared with other cutoff values. Three lines are above the cutoff values, which are the most critical lines (weak lines), so they are eliminated from the system. The eliminated lines are $e\,(4, 9)$, $e\,(9, 8)$, and $e\,(5, 6)$,

Table 1: Initialized parameters for the IEEE bus system.

Parameters	IEEE 9-bus system	IEEE 39-bus system	IEEE 118-bus system
V^{BS}	$v1$, $v2$	$v33$, $v37$	$v31$, $v87$
V_1^{CR}	$v1$	$v30$, $v31$, $v32$, $v37$, $v39$	$v10$, $v12$, $v25$, $v26$, $v31$
V_2^{CR}	$v2$, $v3$	$v33$, $v34$, $v35$, $v36$, $v38$	$v46$, $v49$, $v54$, $v59$, $v61$, $v65$, $v66$, $v69$, $v80$, $v87$, $v89$, $v100$, $v103$, $v111$
V^{CL}	$v4$, $v6$, $v8$	$v4$, $v5$, $v7$, $v8$, $v12$, $v13$, $v14$	$v33$, $v43$, $v53$, $v72$, $v86$, $v87$, $v107$, $v111$, $v112$, $v117$
E_E	e_1, e_2, e_3	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)	e (5, 8), e (8, 9), e (9, 10), e (34, 43), e (37, 38), e (38, 65), e (40, 42)

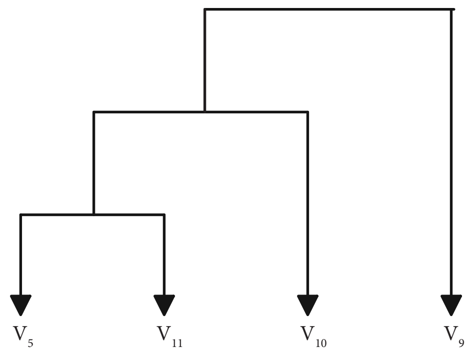

Figure 7: Dendrogram of the partitioning of the IEEE 9-bus system with reactive power balance.

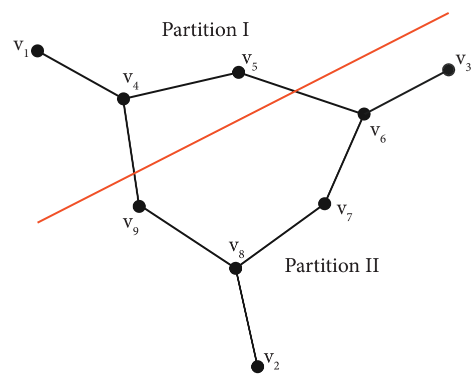

Figure 8: Graph of final partitions of the IEEE 9-bus system with reactive power balance.

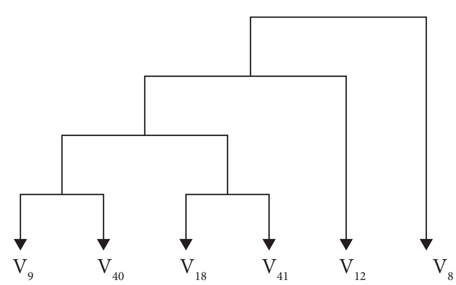

Figure 9: Dendrogram of the partitioning of the IEEE 39-bus system with reactive power balance.

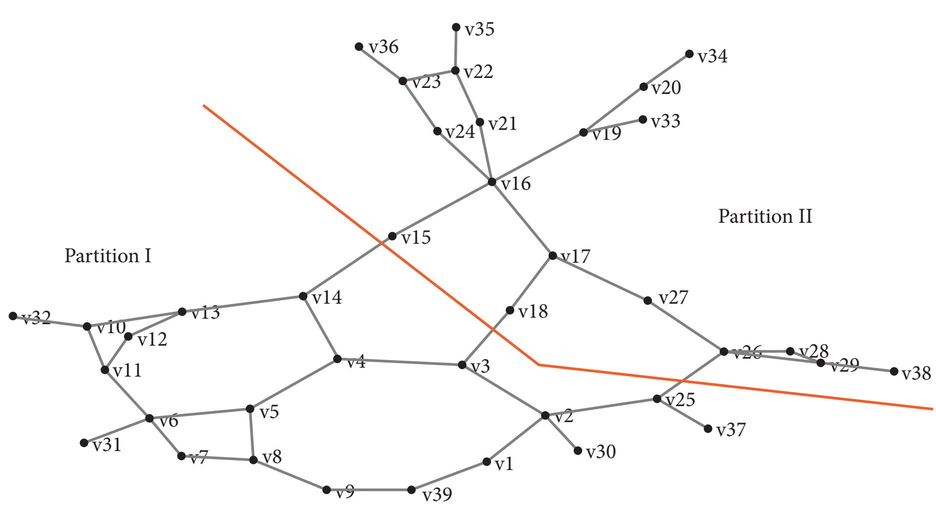

Figure 10: Graph of final partitions of the IEEE 39-bus system with reactive power balance.

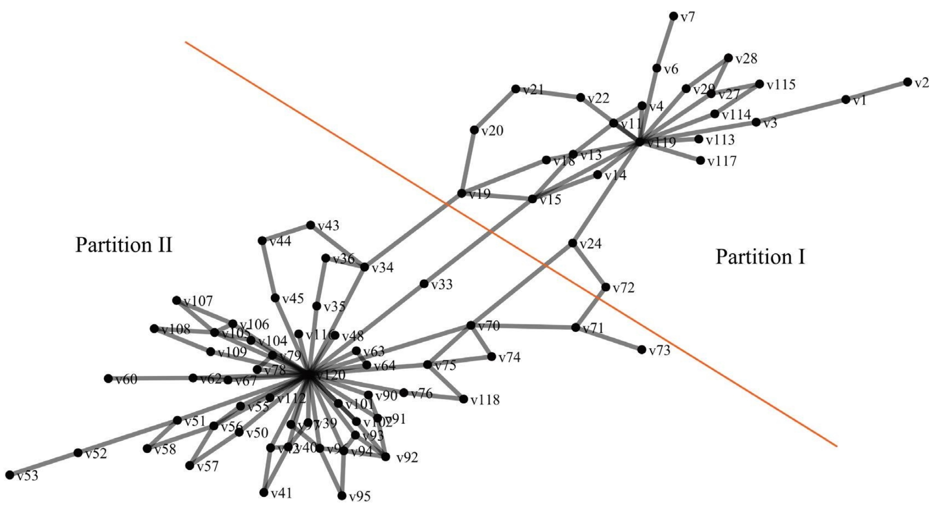

Figure 11: Graphical representation of final partitions of the IEEE 118-bus system with reactive power balance.

Table 2: LQPN ranking table for the IEEE 9-bus system.

Branch	From BUS	To BUS	LQPN	Rank
2	4	5	0.04116	1
4	3	6	0.045825	2
7	8	2	0.047741	3
5	6	7	0.05188	4
1	1	4	0.05306	5
6	7	8	0.06238	6
3	5	6	0.115203	7
9	9	4	0.140375	8
8	8	9	0.14602	9

which are shown using red colour in Figure 12. These lines defined the partition boundaries for the line stability factors for voltage stability analysis. As a result, using the respective partition boundaries, three partitions are formed, which are shown in Figure 12.

For the IEEE 39-bus system, the LQPN values of three lines are identified to be above the cutoff value, i.e., 0.1; these lines are set to be the most critical lines (weak lines) and are eliminated from the system. The eliminated lines are $e\,(3, 4)$, $e\,(8, 9)$, and $e\,(26, 29)$, which define the partition boundaries. However, these partition boundaries are unable to provide two or more partitions. The buses within the single partition formed are not found to be coherent. Then, 0.07 is chosen as the new cutoff value. Still, the buses in the partition are not coherent. Again, 0.05 is the new cutoff value after which the LQPN values of 12 lines are obtained above the cutoff value and thus eliminated from the system. The eliminated lines are represented in red colour, as shown in Figure 13. The line parameters required for the calculation have been taken from [36, 41]. Using the respective partition boundaries, 8 partitions are formed, which are shown in Figure 13.

For the IEEE 118-bus system, the cutoff value is taken to be 0.1, and all the LQPN values are compared with other cutoff values. The LQPN values of 34 lines are above the cutoff value, which is set to be the most critical lines (weak lines), and they are eliminated from the system. However, these partition boundaries are unable to provide two or more partitions, and the buses within the single partition formed are not found to be coherent. Then, 0.07 is chosen as the new cutoff value, but still, the buses in the partition are not coherent. Again, 0.05 is chosen as the new cutoff value. LQPN values of 87 lines are found above the cutoff value and are eliminated from the system. An overview of the IEEE 118-bus system and the eliminated lines (red-colored lines) are shown in Figure 14. After using the respective partition boundaries, 31 partitions are formed, which are shown in Figure 14.

4. Discussion

After analyzing the results of the proposed agglomerative hierarchical clustering method in three different IEEE test-bus systems, it is observed that two partitions are formed for all test bus systems. This method of clustering is mainly based on the generation-load difference of reactive power between the two buses. The two partitions are primarily formed because each system has two black start generators and based on those generators, two cranking groups are formed: forming the final two partitions.

The agglomerative clustering approach can quickly form the required number of stable clusters for reactive power, but it does not ensure the overall stability of the clusters. A voltage level of the system is directly related to reactive power; the change or disturbance in the flow of reactive

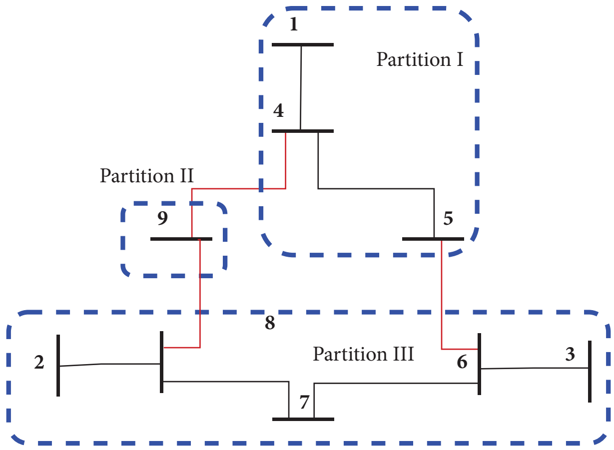

Figure 12: Single line diagram representing final partitions of the IEEE 9-bus system with the LQPN method of clustering.

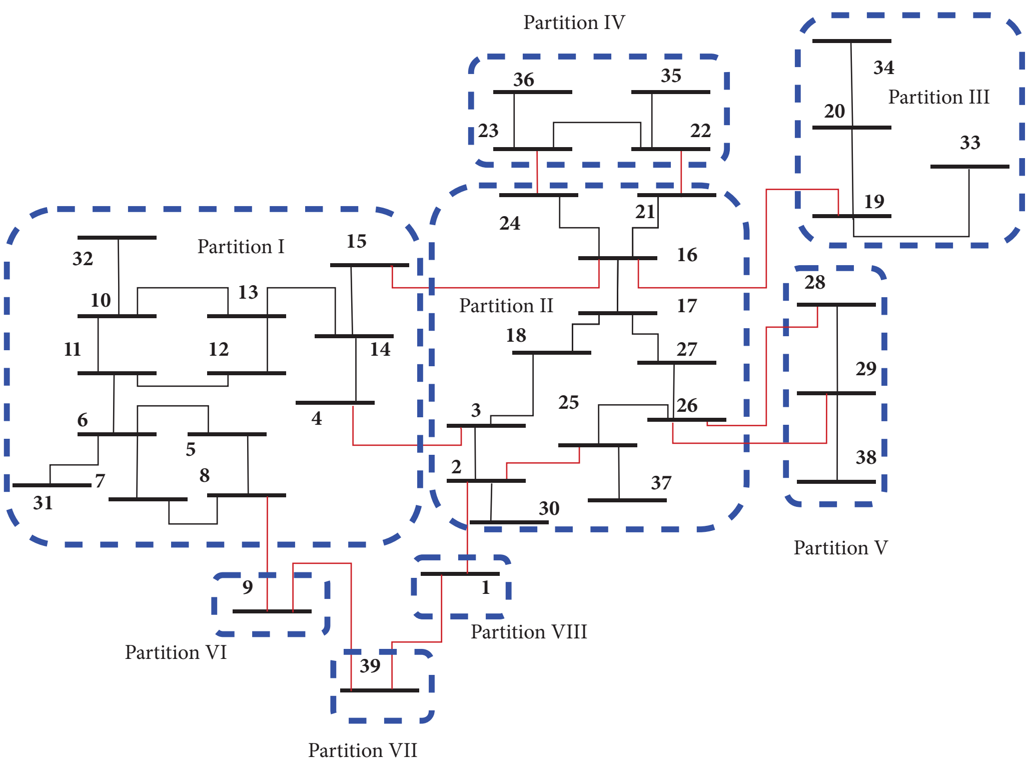

Figure 13: Single line diagram representing final partitions of the IEEE 39-bus system with the LQPN method of clustering.

power can cause high voltage fluctuation in the clusters. The voltage may rise or fall below the critical limit such that there will be high chances of voltage collapse. If voltage collapse occurs during the restoration phase, there is an increase in the chance of reoccurring blackouts. This might inflict further damage to the power system. Due to this reason, there is a high necessity for analysis of voltage stability in the clusters formed. In this study, the voltage stability of individual partitions is checked by performing a voltage stability analysis using the line stability factor.

Performing clustering using line stability factor, the weak and strong regions are identified for voltage stability level as the larger clusters indicate comparatively higher voltage stable regions than the smaller clusters. Here, larger clusters include a large number of stable buses; any voltage fluctuations in other buses or systems will not adversely affect the stability level of those buses. However, the smaller clusters include buses that are more critical and prone to voltage collapse. These regions can be used to compare the voltage stability of the agglomerative clusters. The lines with higher LQPN values are the more critical lines in the system. These lines are very much prone to failure if any disturbances occur in the system. The critical lines should avoid any overloading or disturbances and the critical buses should be synchronized first, and then, the stable clusters need to be synchronized. All these outputs and results shown

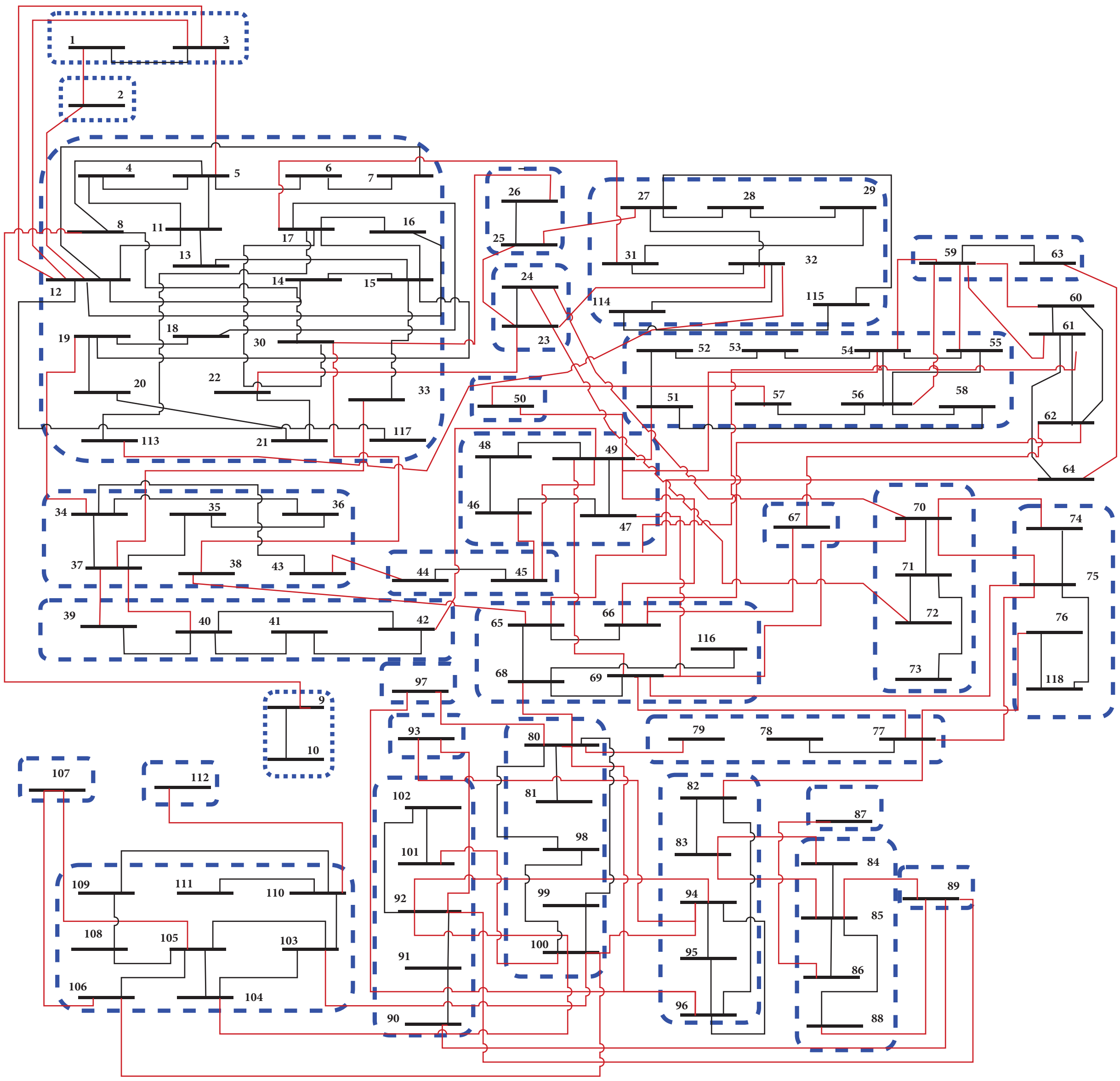

FIGURE 14: Single line diagram representing final partitions of the IEEE 118-bus system with the LQPN method of clustering.

by the cluster formed by the presented method of clustering by using line stability factor must be taken into consideration for smooth restoration of the power system.

The clusters formed by agglomerative clustering included both the strong and weak regions concerning voltage stability level (shown by the method of clustering using line stability factor). The agglomerative partitions balance the weaker regions by merging them with the stronger regions. Hence, the overall agglomerative partitions are stable concerning voltage stability. The cutting sets for the agglomerative clusters are not critical lines for $N-1$ contingency analysis, but some of the lines in the cutting sets (in agglomerative clusters) are shown as critical by the method of clustering using the line stability factor. This indicates that concerning active power flow, those lines are not critical, but concerning voltage stability, those lines are critical. These lines should be taken into consideration during the restoration process. In this case, they should be supplied with either inductive or capacitive reactive power (i.e., proper compensation should be carried out) as per the need to maintain the voltage level in the buses connecting those lines that reduce the chances of voltage collapse. Finally, for real-time restoration, the cluster shown by the agglomerative method can be used considering the repercussions shown by strong and weak regions formed by a method of clustering using the line stability factor.

5. Conclusion

This research paper introduces a novel methodology employing an agglomerative clustering approach to partition power systems, designed to create segments with balanced reactive power for efficient restoration following a blackout. This method enables the division of the system into several subsystems, facilitating parallel restoration processes. Central to this approach is the formation of clusters assuming the operational readiness of black-start generators to supply power to nonblack-start generators. While most partitions demonstrate stability and readiness for restoration, there are instances where some partitions with negative generation-load differences require additional support, possibly from VAR compensators. A key finding is the potential synergy when this strategy is integrated with the agglomerative hierarchical clustering approach focused on active power balance. Such integration could lead to a comprehensive strategy for real-time restoration, effectively balancing both active and reactive power, including voltage stability. This comprehensive approach could be vital for TSOs in control centres, enabling the efficient, synchronized restoration of the entire system with minimal time and losses.

However, this methodology is based on certain idealized assumptions, including the immediate availability of all lines and generators during restoration. The need for additional VAR compensators in some partitions could lead to significant costs. Moreover, the methodology's emphasis on line stability factors for voltage stability may not fully encompass other critical factors impacting system stability. The methodology also lacks empirical validation in combining strategies for active and reactive power balance with voltage stability. Its adaptability to diverse and integrated grid conditions, which are inherently stochastic, is yet to be tested. Future research should aim to adapt the methodology to dynamic grid conditions, addressing new complexities emerging in the modern power system. There is a need to develop control strategies for the practical application of this methodology and assess its feasibility under extreme conditions such as natural disasters or cascading events. Enhancing grid resilience in such extreme conditions remains a crucial area for future work. This study forms a foundation for a more resilient and efficient approach to power system restoration, but it also highlights the challenges and opportunities for innovation that require continued research and development in this essential field.

Nomenclature

Acronyms and Abbreviations

IEEE: Institute of Electrical and Electronics Engineer
MILP: Mixed integer linear programming
LPA: Label propagation algorithm
RES: Renewable energy sources
BS: Black start
nBS: Nonblack start
NR: Network reconfiguration
TSOs: Transmission system operators
GSUS: Generator startup sequencing
WAMS: Wide area measurement system
PPSR: Parallel power system restoration
DGs: Distributed generators
GRAs: Generic restoration actions

Sets

G: Set of nodes and edges in a graph
V: Set of nodes
E: Set of edges
V^{GN}: Set of nodes with generators
V^{BS}: Set of nodes with black start generators
V^{CR}: Set of cranking group
G^{SP}: Set of shortest path
V^{CL}: Set of critical loads
V^{CN}: Set of critical nodes
E_{CL}: Set of critical edges or lines
E_{NM}: Set of edges with no monitoring equipment
E_U: Set of edges which are unsuitable
E_{CS}: Set of edges which are cut sets
ϕ: Null set
E_E: Union set of edges with no monitoring equipment, unsuitable edges, and edges that are cut-sets
V_k: Nodes in the k^{th} partition

Parameters

V_1, V_2: Representation of node 1 and node 2
E_1, E_2: Representation of edge 1 and edge 2
$\varphi(V_k)$: Generation load difference of a k^{th} partition
$Q(v_i)$: Reactive generation load difference at node i
$Q_{MG}(v_i)$: Maximum reactive power generation capability at v_i
$\beta(v_i)$: Percentage of load that should be restored
$Q_{LD}(v_i)$: Expected reactive power consumption at v_i

Variables

M: Number of partitions to be formed
V_i: Voltage at node i
Q_i: Reactive power at node i
Q_r: Reactive power at node $i+1$
X: Reactance of the line
R: Resistance of the line
P_i: Active power at node i
P_r: Active power at node $i+1$
V_{i+1}: Voltage at node $i+1$.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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