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Clustering Nepalese power system into stable islands considering real power balance

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Abstract

Development of power system restoration strategies after a blackout carry major importance in today's power system. This work groups the different nodes of Integrated Nepal Power System (INPS) into several clusters taking active power flow in the line as major consideration. This clustering task is expected to simplify the restoration work and minimize the restoration time for INPS. Agglomerative hierarchical clustering algorithm has been used to create the node-groups which are termed as partitions or clusters in the paper. The clustering algorithm solves a constrained optimization problem modelled on the basis of active power generation and load difference. Utilizing this technique, two cases have been studied upon in the INPS. Case I has taken two black start generators and partitioned the system two clusters whose generation load difference was found to be 200.308 MW and 321.778 MW respectively. Similarly, case II has taken three black start generators and partitioned the system into three islands whose generation load difference was found to be 142.632 MW, 313.912 MW, and 118.788 MW. Positive load generation difference values indicate that the islands can be operated independently before synchronization even if the loads deviate from the forecasted value.

1. Introduction

Despite the availability of enhanced technology and control techniques, operating experiences in many countries show that blackouts are unavoidable and so the study of restoration strategies has vital importance for enhancing the robustness and reliability of our interconnected systems [1].

In the context of Nepal, the demand of electricity and consecutively the size and complexity of the power system is seen to be increasing day by day [2]. With this, the need for power system restoration plans and strategies after a blackout seem necessary be studied upon. This work attempts to separate the Nepalese power system into stable islands which are enabled to get restored independently and finally the islands can be connected via tie lines restoring the whole power system.

The major objective of restoration tasks may be stated as: restore the power system in minimum time with reduced complexity [3]. The preliminaries for the restoration process involves three major stages: preparation/black start, system restoration, and load restoration [3], [4], [5], [6], [7].

In the first stage, the black start (BS) generators are identified in the system. Also, the availability of black start generators, their generation capabilities, and all the information regarding the BS generators need to be collected [6]. Black start generators may be defined as the ones which can start when isolated, with no support from the grid, and can energize a bus [8]. Advantages of using hydropower as black start resources may be stated as quick availability and adequate ramp rates for craning other generators and is proven to be a better black start source as compared to other sources [9]. The characteristics like small station power requirements, quicker restart, enough watts and volt ampere reactive (VAr) capability, damping out of oscillations, capability to energize transmission lines and crank other generators makes hydropower plants as most suitable black start sources [9]. With these conclusions, the Nepalese power system seems to have enough black start resources as it

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is Hydropower dominated system.

Furthermore, few published works of literature about the restoration in the American and European power system state that even the substations which fulfill some requirements can be used for black start. The requirements include resilient site electricity supply, capability to remain in service with no external infeed i.e resilient battery backup for control, protection, and SCADA systems, and remote maintenance and controlling flexibility [10], [11]. This is commonly termed as 'substation black start resilience' [10].

In the second stage, we come up with the cranking task. The group of generators that are energized by a particular black start unit is termed as one cranking group[4]. Determination of cranking groups also involves different methods like mixed-integer programming techniques to maximize the generation capability, assessment of frequency and voltage balance while energizing the non-black start sources, grouping based on the distance of non-black start sources from the black start ones, and many similar techniques [3], [4], [12], [13]. The major factors to be considered are availability and connectivity of a minimum of a black start generator in every cranking group and whether the black start generator can fulfill start-up energy requirements of non-black start generators within their cranking time or not [12], [13]. Some methods directly implement sectionalizing strategies instead of determining only cranking groups and restoring the loads afterward [14], [15], [16], [17].

After the generators are grouped, all the generators in a particular group are connected using the shortest possible path joining them. This is usually achieved using shortest-path tree algorithms like Dijkstra's algorithm [12]. Then, the black start generator gradually energizes the generators which need external crank in its cranking group via the lines in shortest-path trees. Few specified loads are also energized during cranking to stabilize the frequency of operation [4]. This clarifies that the decentralized location of multiple black start generators eases the cranking task. In the third stage, a suitable partitioning strategy for the construction of islands is to be made and implemented. Clustering algorithms like spectral clustering, k-means clustering, hierarchical clustering, etc implemented constrained or unconstrained are found to be widely practiced for this purpose lately. Although clustering originally belongs to the data analysis sector, it has found significant application in the power system in recent researches [14], [17], [18], [19], [20], [21], [22].

To ensure the independent restoration and successful synchronization of each subsystem, the following are the major requirements to be fulfilled: [3]–[6], [12], [13], [16], [20]

(1) A minimum of one black start generator is required in every partition to restore it independently. Moreover, we need to make sure that the connection within the cranking groups is ensured.

(2) Voltage stability should be taken into account via sufficient voltage control resources.

(3) Tie lines with monitoring equipment's for the recording phase across the lines while synchronizing the islands.

(4) Sufficient power generation in each partition to maintain frequency balance.

Based on these three stages, similar works for restoration strategies have been performed worldwide, some of which are mentioned in the further text.

The power system is represented as a weighted graph with nodes showing the buses and edges showing the lines [22]. The electrical similarity which is the main basis for the formation of a cluster is quantified based on voltage fluctuation which in turn signifies the reactive power perturbation in those particular buses. In addition to this, studying the influence of fluctuation of active power and phase angles in a similar manner would have yielded more precise results for the same work. Similarly, hierarchical clustering methodology is used to reveal the internal connectivity and details of the power system and spectral clustering uses the Laplacian Eigenvalues and Eigenvectors of graph represented power system to cluster it [21]. Also, the same paper explains that clustering based on admittance will display the internal connectivity and details of the network, and clustering based on power flow will create the islands thereby disrupting the least possible power flow and enabling preventive islanding. The work predicts the number of clusters to be formulated beforehand from dendrogram which in many other works of literature seems to be taken as a limitation of spectral clustering [15]. The authors use hierarchical clustering based on intra and inter-cluster distances for zone formation and agglomerative hierarchical clustering for optimal DG placement planning in distribution networks [20],[21]. Agglomerative hierarchical clustering seems to yield more clear results just with the implementation of a simple algorithm and clearly pictured dendrogram in the field of restoration. This is why this paper has also used the this algorithm. Power flow disruption is minimized and spectral clustering is used for controlled islanding constrained on generator coherency which is implemented in two steps [18]. Here generator coherency determination is emphasized as it seems to be a major deciding factor for the island formation. Similarly, constrained spectral clustering is performed in the graph representation of Network, which uses physical and inherit properties like edge weights, cranking groups, strongly and weakly connected lines to give stable islands [17]. The major constraints to be satisfied are black start provision, voltage stability, consumption-generation balance, and monitoring the synchronism between islands which are similar to that in this paper [17] .

Furthermore, with these evolving techniques using clustering algorithms applied to power system restoration, a few terminologies are to be known about:

(i) Tie lines: A set of lines that interconnect the islands with each other. The tie lines so defined need to have monitoring equipment connected to them and should not be N-1 contingent lines.

(ii) Excluded edges: The set of lines or edges (as termed in graph theory) which cannot be used as tie lines. The lines which are N-1 contingent, or have a transformer directly connected to them, or lack the monitoring equipment's connected lie in the excluded set of edges [20]. These lines will be termed as critical lines in this paper from now onwards.

(iii) Critical nodes: The loads which are prioritized to be restored as soon as possible during power system restoration lie under critical loads. Example: Hospitals, National assembly buildings, control centers, etc Critical nodes are the set of nodes that supply critical loads [3].

The generator's power output and load power requirement must be made almost equal for the maintenance of system frequency in the confines of the desired range. Despite the availability of the highest generation capacities, actual power consumption in the partition remains uncertain before restoration. And so, the load restoration strategies are based on forecasted power consumption. Therefore, if the highest generation capacity of a partition is hardly able to supply the forecasted consumption requirements in that partition, the actual power requirements might be failed to be supplied because the loads can deviate up and down from the predicted consumption values. As a result, the partitions should be designed in such a way that each of them has sufficient generation capacity to keep the system stable. This work intends to propose a network partitioning method for parallel restoration of power system restoration that maximizes each partition's capability, ensuring that such a circumstance can be handled while addressing the constraints listed above.

Looking at the current scenario of INPS, each nodes are energized one by one while restoring the power system from a blackout. This makes the task of system operator vague and complicated for every restoration and also this kind of restoration takes longer time. Clustering those nodes into separate partitions with ensured stability while energizing them individually simplifies the restoration task and also restoring the whole cluster instead of a single node at a time minimizes restoration time.

2. Current Scenario of the study area

Integrated Nepalese Power System (INPS) is currently owned and operated by Nepal Electricity Authority (NEA). There are around 31 small and large NEA-owned hydropower plants connected to the grid and around 23 isolated small power plants. Similarly, Hetauda diesel plant, Duhabi multifuel, and solar power plants in Nuwakot, Gamgadhi, and simikot are also running under the ownership of NEA. In addition to this, around 108 IPP-owned hydropower plants are operating connected to INPS. With this, the installed capacity of INPS is 1451.335 MW [2]. Also, INPS is enabled to import the electricity as needed from India [2].

Transmission voltage in INPS comprises of 66 kV, 132 kV, 220 kV, and 400 kV. With sixteen 66 KV lines, forty-one 132 KV lines, and five 220 KV lines total length of transmission in INPS becomes around 3927 KM [2].

In this work, various small generators' substations and 33KV and below lines are lumped together into a single bus/node. So, we have modeled a system with 45 generators and 92 buses/nodes which only contain the portion of the grid above 66 KV representing INPS in the Electrical Transient Analyzer Program (ETAP) for this work.

3. Problem formulation and methodology

The methodology implemented in this work includes Network representation using graph theory, defining the generation load difference, and formulating it into an optimization problem.

3.1. Problem formulation

3.1.1. Network Representation using graph theory

Graph theory enables us to represent a power system using a directed or undirected graph which consists of a set of nodes(V) indicating buses in the grid and a set of edges(E) representing the lines connecting the nodes.

IEEE 9 bus system is represented as a graph in Figure 1.

The nodes are numerically represented as 1, 2, 3 up to the last one i.e 9, generalized as'vi', and the lines joining them represent the edges. Connectivity among the nodes is represented in the adjacency matrix each term of which is 1 if node I is connected to node j and zero otherwise, provided that i and j represent the index of the matrix which equals the number of nodes[16].

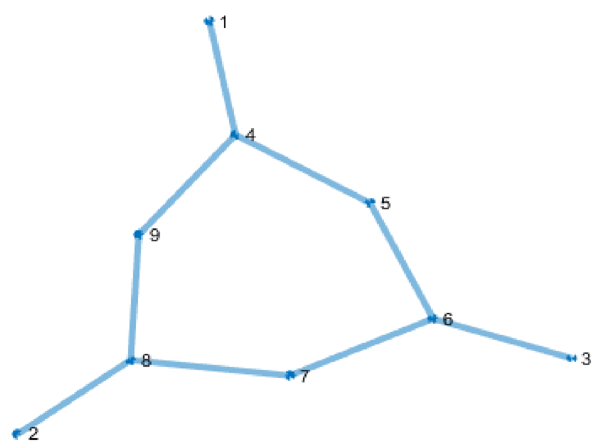

Figure 1: IEEE 9 bus system redrawn as a graph

Let a set representing the node be V. For the restoration procedure, the nodes in the set V are classified under many other subsets. The major subsets classification includes generation nodes VGN and black start nodes VBL which respectively represent the buses with generators connected to them and the generators with black start capability. Different groups are made using the generation nodes so that each group has at the minimum of one black start source. Furthermore, the buses which have critical loads connected to them are represented as V^{CL}.

3.1.2. Generation load difference

Individual islands must have the generation-load balance as one of the major criteria's to operate with stability. The difference between generated and consumed active power can be written as[17]:

$$\varphi(V_k) = \quad \Sigma P(v_i) \tag{1}$$

Where, V_k represents k^{th} partition, P(v_i) represents the generation-consumption difference at the node v_i which is calculated as [17]:

$$P(v_i)(V_k) = \quad \mathrm{P}_G(v_i) - \alpha(v_i)P_L(v_i) \tag{2}$$

Here, $P_G(v_i)$ and $P_L(v_i)$ indicate the maximum wattage generation capability and expected wattage consumption at node v_i. $\alpha(v_i)$ is a factor that represents the amount of percentage load at node v_i which needs to be restored before the islands are synchronized. The value of $\alpha(v_i)$ is taken to be one for the nodes in V^{CL}. For non-critical loads, the value of$\alpha(v_i)$ depends on the maximum generation capability of the partition. In practice, the value of $\alpha(v_i)$ is taken to vary from 0.4 to 0.75 [23]. Staying into the range, this paper has used $\alpha(v_i)$=0.7 for the nodes with non-critical loads.

3.1.3. Formulation of the optimization problem

Network partition aims to accomplish the simultaneous restoration of more than one independent partition to achieve the system restoration faster after a blackout. Network partitioning strategy cannot be defined as a simple mathematical problem because of the physical constraints it needs to satisfy. As a result, it is constructed as a constrained optimization problem that must satisfy all of the constraints outlined in the preceding sections. This section includes the graph notation representation of those requirements which enables us to get an objective function and a few constraints.

For M restoration processes assumed such that $2 \leq M \leq |V^{BS}|$, the network partitioning strategy should separate the network into M partitions satisfying the conditions in Equations 3 and 4[3]

$$V_i \cap V_j = \quad \phi \tag{3}$$

$$V_1 \cup V_2 \cup \ldots \ldots .V_M = \quad \mathrm{V} \tag{4}$$

For i,j $\in \{1, 2, \ldots \ldots ., M\}$ and $i \neq j$.

M disjoint cranking groups are required to restore each partition independently. Let the k^{th} cranking group be denoted by V_k^{CR}. To ensure the connectivity within the cranking groups, Equation 5[3] must be satisfied for all $k \in \{1, 2, \ldots \ldots ., M\}$.

$$V_k^{CR} \subseteq \quad \mathrm{V}_k \tag{5}$$

From 3 and 5, we can write $V_i^{CR} \cap V_j^{CR} = \phi$ for i, j belongs to $\{1, 2, \ldots \ldots ., M\}$ and i not equal to j.

Moreover, the generators with black start capacity need to supply the starting power to the generators which are not enabled to black start in a cranking group while restoring the system. Because of this, every cranking group should have at the minimum one black start source which is written mathematically in Equation 6 [3].

$$|V^{CR} \cap V^{BS}| \geq \quad 1 \tag{6}$$

For all $k \in \{1, 2, \dots \dots .., M\}$.

Let a set of lines, on the removal of which there is an adverse effect on the stability of power system be included under a set of critical lines denoted by $E_{CL}(\subset E)$. Therefore, these lines are mandatorily excluded from the set of tie lines which divide the blackout zone into sections or partitions. Also, these tie lines must have enough equipment to monitor the synchronization of clusters. Therefore, the lines which do not have the equipment to monitor represented in a set by $E_{NM}(\subset E)$ also must be excluded from the set of tie lines. If there are any other edges that cannot serve as tie lines, they are listed as unsuitable ones and denoted by $E_U(\subset E)$. The cut set or we may say the set containing suitable tie lines denoted by $E_{CS}(E)$ must satisfy Equation 7 [3].

$$(E_{CL} \cup E_{NM} \cup E_U) \cap E_{CS} = \quad \phi \tag{7}$$

To maintain power system stability with ongoing uncertainties and load fluctuations, the network segregation strategy should ensure enough reserve capacity in every island. Therefore, the objective function is to find the clusters which maximize the lowest load-generation difference of the islands and written as Equation 8[3].

$$\begin{aligned} \{V_1, V_2, \dots .., V_M\} = \quad & \text{argmax} \ \ (\min \varphi(V_k')) \\ & \{V_1', V_2', \dots\dots, V_M'\}, k \in \{1, 2, \dots \dots .., M\}. \end{aligned} \tag{8}$$

Subjected to Equations 3 to 7.

3.2. Illustration using IEEE 9 bus system

In a post-blackout scenario, it is required to collect details about the condition of different components in the power system. Some of the important components like black start generators and critical loads which might be deciding factors for the development of network partitioning strategy must be looked upon in particular This work assumes all such information to be available and executes the network partitioning strategy by solving the optimization problem defined. The problem is solved in three steps: initialization, initial partitioning, and agglomerative clustering which are illustrated in IEEE 9 bus system for easy demonstration. The output for the IEEE 9 bus system compared to the published works of literature even validates this work in INPS. The data for IEEE 9 bus system is taken from matpower.

3.2.1. Initialization

An undirected graph represents the power system after the blackout area is identified. For a clearer picture of the graph representation and to work further, defining different distinct nodes and edges becomes necessary in this step. The task is performed in reference to already practiced methods in power system engineering.

First of all, a set of black start generators must be identified. Usually, the information about the generators with black (self) start capability is already obtainable before restoration. Taking an example of North American power system, generators with black (self) start capacity are found to be bound by contracts with independent system operators to enable black start after a probable blackout [24]. For IEEE 9 bus system, $V^{BS} = \{v_1, v_2\}$ i.e, M=2.

After that, we distinguish the cranking groups making sure that it satisfies Equation 6. It is mandatory for each cranking group to have minimally one black start generator in it so that it could provide starting power to non-black start ones in that group. Furthermore, the speed of the cranking task will even be the deciding factor for the duration of restoration. In IEEE 9 bus system, the cranking groups are taken from [13], which groups the generators to t accelerate the cranking task. In IEEE 9-bus system, cranking groups are $V_1^{CR} = \{v_1\}$ and $V_2^{CR} = \{v_2, v_3\}$ [13].

Also, critical nodes are identified based on the priority in restoration mainly. It is taken that $V_{CL} = \{v_7, v_9\}$ in IEEE 9-bus r system.

And lastly, we need to define a set of lines that cannot be operated as tie lines during restoration. This set is also called the set of excluded edges and is given by $E_E = E_{CL} \cup E_{NM} \cup E_U$. In IEEE 9 bus system, $E_{NM} = E_U = \phi$, i.e $E_E = E_{CL}$ is assumed. The tie lines are not energized while restoring the power system parallelly and are only connected back at the last. The lines which violate the voltage and contingency criteria i.e critical ones can be distinguished using N-1 studies for respective parameters in ETAP. For IEEE 9 bus system, $E_{CL} = \{1-4, 2-8, 3-6\}$, where the numbers denote nodes, the element 1-4 represents the line joining node 1 to node 4, and so on.

3.2.2. Initial partitioning

Initial partitioning primarily requires the satisfaction of those constraints mentioned in previous sections. A path connecting the generator with black start to each generator with no black start within a cranking group is necessary. This is found with the help of shortest-path tree algorithms and routed using Dijkstra's algorithm[25]. Now, the nodes that come under a

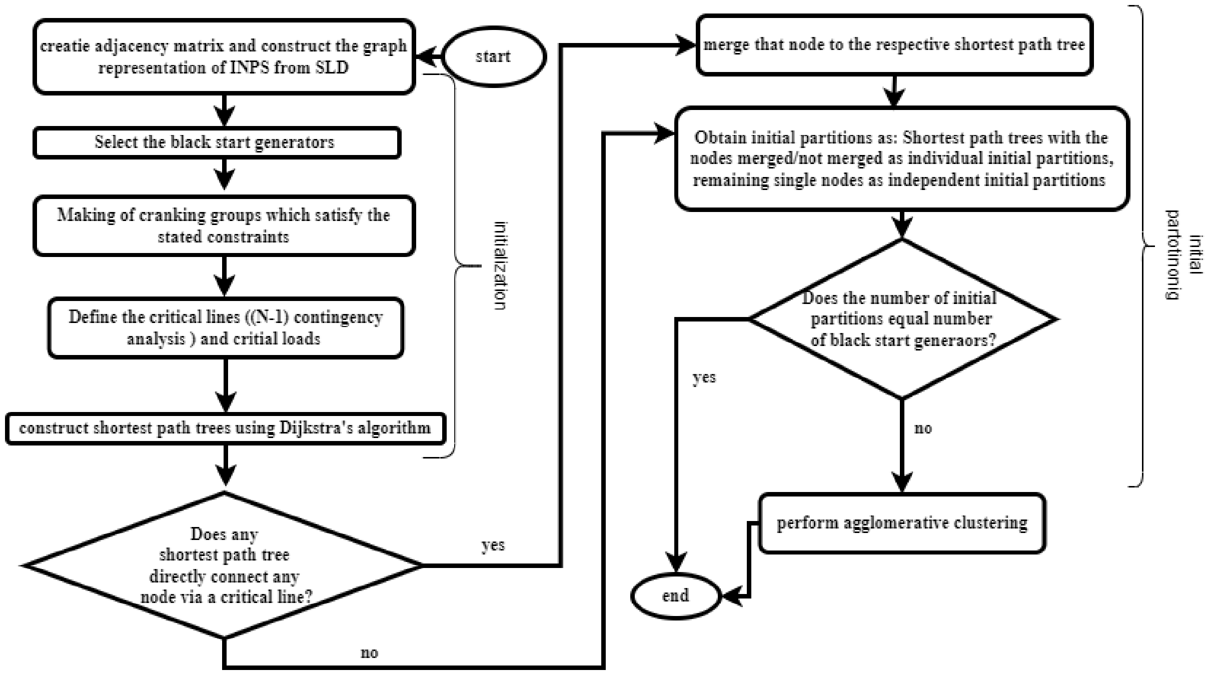

Figure 2: Workflow diagram for Illustration of methodology

shortest-path tree are separated as individual partitions. As V_1^{CR} has only one black-start node, so the respective tree is written as $TR_1 = \{v_1\}$. However, V_2^{CR} consists of both nodes i.e nodes with black start as well as nodes without black start. Therefore, we guarantee a path to supply cranking power from v_2 to v_3. Dijkstra's algorithm finds the corresponding shortest-path tree to be $TR_2 = \{v_2, v_3, v_6, v_7, v_8\}$ and the lines joining the nodes in TR_2 also lie in TR_2 itself.

After the shortest-path trees are obtained, the graph is divided into a set of partitions such that criteria's in Equation 5 - 7 are met, and each and every node lying in a particular tree are placed in a partition. For example, every node in TR_2 i.e. v_2, v_3, v_6, v_7, and v_8, belong to one partition. Furthermore, if any remaining node is connected to a tree by a critical line, that node is merged to the partition containing the shortest path tree considering it to lie in the same partition. Also, if any remaining nodes are connected to each other via any lines in E_E, the nodes are grouped to be counted as separate independent partitions. And, the nodes which remain single after this process are individually counted as initial partitions. For the IEEE 9-bus system, nodes v_5 and v_9 make two individual partitions, giving four initial partitions. The four initial partitions are indicated in Figure 2 using different node colors. The red-colored nodes indicate partition 1, the yellow nodes indicate partition 2, and the remaining blue nodes i.e. 9 and 5 are independent individual partitions. If there are M initial partitions by now, the proposed strategy completes here. Else, agglomerative clustering algorithm needs to be implemented.

3.2.3. Agglomerative Clustering

Now, in this step, the initial partitions are categorized as black start partitions (the ones which have black start generators in them) and non-black start partitions (the ones which don't have black start generators in them). M black start partitions are recorded by now. Then, a non-black start partition that is connected to a particular black start partition is temporarily merged with the black start one and the generation load difference of the merged group is calculated for the instant. This is done for every non-black start partition. The merged partition pair that produces minimum load-generation difference is saved for future use. This process is continued iteratively for all black start and non-black start partitions. In the end, we shall have M partition pairs options each of which contains at least one black start partition. The pair among those M pairs which has maximum load-generation difference is merged permanently now forming a new black start partition. And this process continues the same way until all the non-black start individual partitions get merged to the black-start ones.

The result showing the order in which the partitions are merged is in the form of a dendrogram as shown in Figure 4.

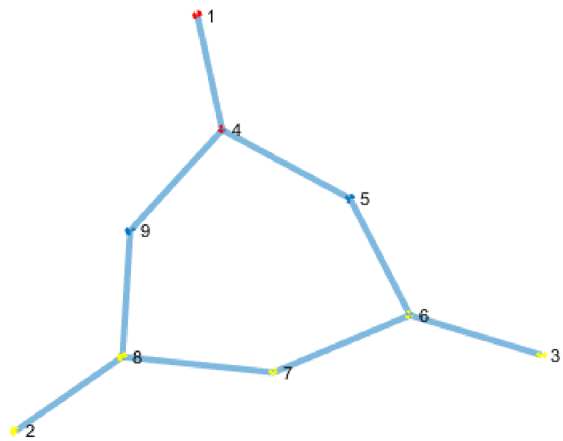

Figure 3: Initial partitions in form of colored nodes in IEEE 9 bus system

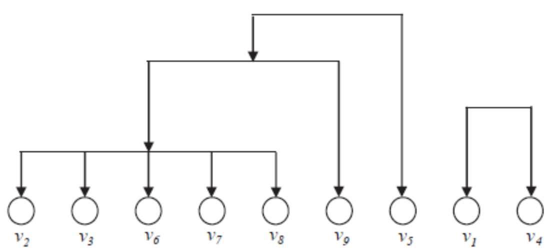

Figure 4: A dendrogram showing the hierarchical clustering in IEEE 9 bus network

And, Figure 5 shows the final two partitions for IEEE 9 bus network. Let the nodes above the black line be termed as partition 1 and the nodes below it be termed as partition 2. The Generation load difference in partition 1 is found to be 250 MW and that of partition 2 is found to be 275 MW. The surplus value of generation in each partition or island indicates that the islands can be operated independently during restoration. After these partitions get energized and start operating independently, they can be synchronized by energizing the lines 4-9 and 4-5, which are the tie lines here.

4. Case Study and results

Two cases have been studied for this work based on black start practice in Nepal. In case I, Kulekhani I and Dhalkebar substation have been taken as black start sources. Similarly, in case II, Kulekhani I, Dhalkebar Substation and Kaligandaki have been taken as black start sources. These two particular cases have been studied because these sources have been used as black start generators during restoration of INPS in the past.

4.1. Case I

4.1.1. Black Start Generators:

Although, it is recommended to have more than one black start generator in Nepalese or any other power system, this work is concerned with analyzing the current scenario of the grid, so this paper has taken Dhalkebar and Kulekhani I as black start generators as practiced in real-time for case I. Therefore, V^{BS}= {KulekhaniI, Dhalkebar Substation}

4.1.2. Critical Lines:

After modeling of Nepalese Power system and contingency analysis in it, the system was studied for finding n-1 contingent lines.

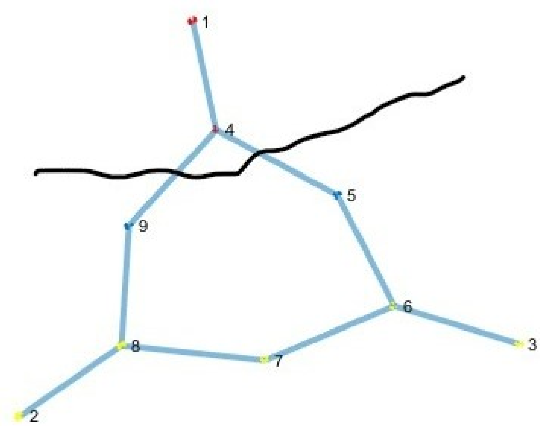

Figure 5: Final clusters for IEEE 9 bus system

Modeling and analysis has been done using ETAP software. The most critical lines were evaluated based on the performance indices given by the software. The one with the highest performance index is termed to be the one severely affected by the contingency event. But there were some lines, on the removal of which the base case load flow could not converge. So, these lines seem to be more critical than those with high performance indices. The lines, on the removal of which the base case load flow could not converge, are tabulated in Table 1.

Critical lines are the lines that cannot be down during any stage of the restoration. If they are used to interconnect the islands, they will have to be down during the initial phase of the restoration process represented using node numbers in the graph. The respective nodes represented by specific node numbers are tabulated in the appendix.

4.1.3. Cranking groups:

The cranking task is one of the most crucial tasks in restoration. Two cranking groups have been assumed for this case considering the geographical location of

Table 1: List of critical lines on the removal of which the base case load flow does not converge

Line ID in single line diagram	Starts from (substation)	Ends at (substation)
Line 12	New Chabel	Lainchaur
Line 32	Indrawati	Panchkhal
Line 36	Suichatar	Matathirtha
line 58	Bharatpur	Kawaswati
Line 63	Chanauta	Butuwal
Line 72	Lamahi	Chanauta
Line 103	Marshyangdi s/s	Dumre
Line 108	Devighat	Trishuli
Line 172	Chapali s/s	Bhaktapur
Line 184	Syaule	Attaria
Line 193	Dhalkebar	Chapur
Line 213	Buruwal	Parasi
Line 225	Parasi	Aadhikhola
Line 241	Lekhnath	Madi
Line 242	Parwanipur	Raxaul

the generators with black start and their capacity. The cranking groups are stated as buses here, may be written as:

V_1^{CR} = {Anarmani, Bhotekoshi,Bus 97, Hewa, Indrawati, Kabeli Amarpur, Khimti, Dhalkebar s/s, Kushaha, Lamosagu, Multifuel, Raxaul, Singati, Sunkoshi}

V_2^{CR} = {Bhulbhule, Bus 113, Bus 138, Bus 90 (Lower modi), Butwal, Chilime s/s, Damauli, Devighat, Gandak, Kaligandaki, Kulekhani, Kulekhani, Lamahi, Madi, Mahendranagar, Dumre, Marshyangdi, Middle Marshyangdi, Syanga, Modikhola, Pokhara, Syaule, Trishuli 3B hub, Trishuli}

Figure 6 shows the graph representation of the Nepalese grid with the shortest path connecting V1CR and V2CR highlighted in yellow and red colors respectively. This shortest path is set up with the help of Dijkstra's algorithm. The nodes are represented using node numbers in the graph. The respective nodes represented by specific node numbers are tabulated in the appendix.

4.1.4. Initial Partitions:

Now, we search for the critical edges in the graph. All other lines in Table 1 except the ones connecting Chapali (node 23) substation to Bhaktapur (node 10) and New Chabel (node 69) substation to Lainachour (54) lie inside either yellow region or red region in the graph shown in Figure 6. But, the node representing Bhaktapur substation (node 10) lies in the yellow region. So, we merge node 23 with the yellow region as it is connected via a critical line yellow region i.e one of the shortest path trees to consider it as an initial partition.

Furthermore, the New Chabel (node 69) to Lainachour (54) line is considered as an independent separate initial partition as it does not lie inside any of the shortest path trees.

And finally, the remaining nodes which are not involved in any of the shortest path trees and critical edges are separately considered as individual partitions. So, we tabulate initial partitions as shown in Table 2.

Table 2: Initial partitions for the case I

Initial Partition number	Buses
1	Initial partition 1
2	Initial partition 2
3	Initial partition 3
4	Amlekhjung
5	Balaju s/s
6	Baneshwor
7	Birgunj
8	Bus 48
9	Chapali
10	Ghorahi
11	Hapure
12	Hetauda(LV) 132
13	Hetauda(HV)220
14	Hetauda corridor
15	K3
16	Kamane
17	Matatirtha s/s
18	New khimti
19	Okhaltar
20	Parwanipr 2
21	Patan
22	Simera
23	Teku

Where,

Initial partition 1 = {Anarmani, Banepa, Bhaktapur Bhaktapur 2, Bhotekoshi, Bus 97, Chapur, Damak, Dhalkebar (220 KV), Dhalkebar (132 KV), Duhabi, Godak Illam, Hewa, Indrawati s/s, Kabeli Amarpur, Khimti s/s, Kushaha, Lahan, Lamosagu, Mirchalya, Multifuel, Panchkhal, Parwanipur, Phidim, Raxaul, Rupni, Singati, Sunkoshi s/s, Chapali s/s}

Initial partition 2 = {Attaria, Balaju s/s, Bardaghat, Bharatpur, Bhulbhule, Burigau, Bus 113, Bus 138, Bus 90, Butwal, Chilime s/s, Damauli, Devighat, Gandak s/s, Hetauda diesel plant s/s, Kaligandaki, Kawaswati, Kohalpur, Kulekhani (132 KV), Kulekhani (66 KV), Kusum, Lamahi, Lamki, Lekhnath, Madi, Mahendranagar, Dumre, Marshyangdi, Matatirtha, Middle marshyangdi,Modikhola, Phalamnpur,Pokhara, Shivapur/Chanauta, Syuchatar (132 KV), Syuchatar (66KV), Syanga, Syaule, Trishuli 3B hub, Trishuli s/s}

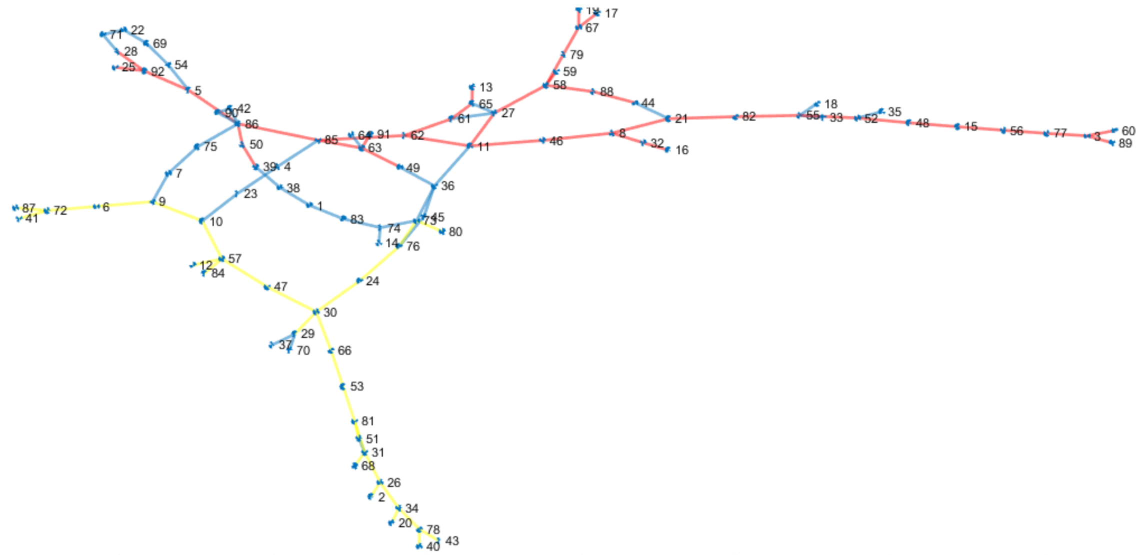

Figure 6: Graph representation of INPS with shortest path trees connecting the cranking groups highlighted for case I

Initial partition 3 = {New Chabel, Lainachour}

4.1.5. Agglomerative Clustering:

Figure 7 shows the order in which the initial partitions mentioned in previous sections are merged one after another. All the generators are confined within initial partition 1 and initial partition 2 and so, the nodes in these two partitions are energized firstly. The amount of load pickup in each node of initial partitions 1 and 2 is decided based on whether they are critical nodes or not.

Kulekhani I in initial partition 2 and Dhalkebar in the initial partition I are expected to start cranking at the same time.

After all the generators in the initial partition I have been cranked, it will firstly energize the group containing Kamane, Hetauda 132 KV substation, patan, baneshwor, and balaju substation since these are located nearest based on the distance which is assumed to be load generation differences. After that, initial partition along with the few nearest substations supplied, runs with a good margin of stability limit pickup more load and will further supply Birjung, Simera, Parwanipur 2, Hetauda corridor, and Amlekhjung. After that, hetauda and New Khimti will be energized at the same time.

Similarly, after all the generators in partition II have been cranked, it will firstly energize Okhaltar, Chapali, and Initial partition 3, i.e New Chabel and Lainachour. After that, the next nearest group will be searched and energized i.e Teku, K3 will be energized. And finally, since matatirtha s/s, Hapure, Ghorahi, and Bus 48 are the almost same distance away from initial partition 2, they will be energized at the last.

In Figure 8, the black line separates the graph representation of INPS in two major clusters. The clusters are restored as independent islands first and then the tie lines interconnecting them are energized. The tie lines interconnecting them are shown in Table 3.

Table 3: Tie lines for the case I

From	To
Patan (Node num 75)	Syuchatar 66 KV (Node num 86)
Hetauda diesel plant (Node num 39)	Hetauda corridor (Node num 38)
Balaju s/s (Node num 4)	Syuchatar 132 KV (Node num 85)
Kulekhani 132 KV (Node num 49)	Hetauda 132 KV (Node num 36)
Bharatpur (Node num 11)	Hetauda 132 KV (Node num 36)

The generation load difference of the finally partitioned islands are 200.308 MW and 321.778 MW. The positive value of generation load difference further assures the stability of the islands when operated independently as they can supply the load even if it slightly deviates from the predicted value.

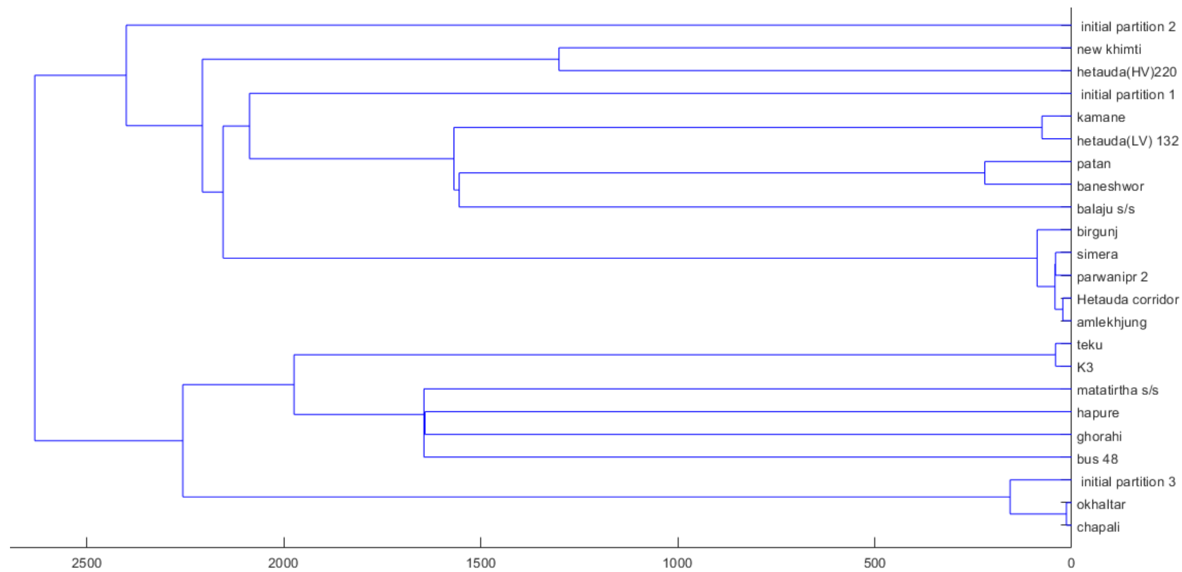

Figure 7: Dendrogram showing the hierarchy of merging the initial partitions for the case I in INPS

4.2. Case II

4.2.1. Black start generators:

Kaligandaki hydropower station along with the ones taken in the previous case are taken as black start generators for this case. Therefore, V^{BS} = {KulekhaniI, Dhalkebar Substation, Kaligandaki}

4.2.2. Critical Lines:

The critical lines taken are the same as that in Case I.

4.2.3. Cranking groups:

The three black start generators are respectively cranking the non-black start generators in three groups. The groups are again based on geographical locations. They may be stated as :

V_1^{CR} = {Anarmani, Bhotekoshi, Bus 97, Hewa Bus, Indrawati, Kabeli/Amarpur, Khimti bus, Kushaha Bus, Lamosagu, Multifuel, Singati, Sunkoshi}.

V_2^{CR} = {Chilime, Devighat, Hetauda DP, Kulekhani II, Raxaul, Trishuli 3B hub, Trishuli} and

V_3^{CR} = {Bus 138 (ThapaKhola), Bus 90(Lower Modi), Butwal bus(Aadhikhola), Damauli IPP, Lamahi, Madi(Upper Madi), Mahendranagar, Middle Marshyangdi, Marshyangdi, dumre, Modikhola,Pokhara, Syanga, Syaule, Bus 113(Ramnagar), Bhulbhule (Upper marshyangdi), Gandak}.

V_1^{CR} is cranked by the Dhalkebar substation, V_2^{CR} is cranked by Kulekhani I, and V_3^{CR} is cranked by Kaligandaki in this case.

4.2.4. Initial partitions:

Now we again search for the critical edges in the graph. All other lines in Table 1 except New chabel (node 69)-Lainachour(node 54), Chapali s/s(node 23)-Bhaktapur (node 10), Dhalkebar(node 30)-Chapur (node 24), and Marshyangdi (node 62)-Dumre (node 61) lie in any one of the shortest path trees (red, yellow or green region in Figure 8).

But Bhaktapur (node 10) lies in yellow region and so, Chapali s/s (node 23) is to be merged to yellow region. Similarly, Dhalkebar (node 30) lies in the yellow region, so Chapur (node 24) is to be merged to the yellow region again.

The edge joining Marshyangdi (node 62)-Dumre (node 61) doesn't lie in any of the shortest path trees but both these nodes lie in green region. Therefore, this edge is also included in the green region.

The nodes New chabel (node 69), Lainachour (node 54) don't lie in any of the shortest path trees but they are connected by a critical edge. So, they are considered to be separate partitions And finally, the remaining nodes which are not included in any of the shortest path trees and neither do connect the critical edges are considered to be individual partitions for now. And we tabulate the initial partitions for case II are shown in Table 4.

Where,

Initial partition 1 = {Chapur, Chapali s/s, Sunkoshi s/s, Indrawati s/s, Panchkhal, Banepa, Bhaktapur (66 KV), Bhaktapur 2(132 KV), Bhotekoshi, Singati, Lamosagu, Khimti s/s, Dhalkebar (132 KV), Dhalkebar (220

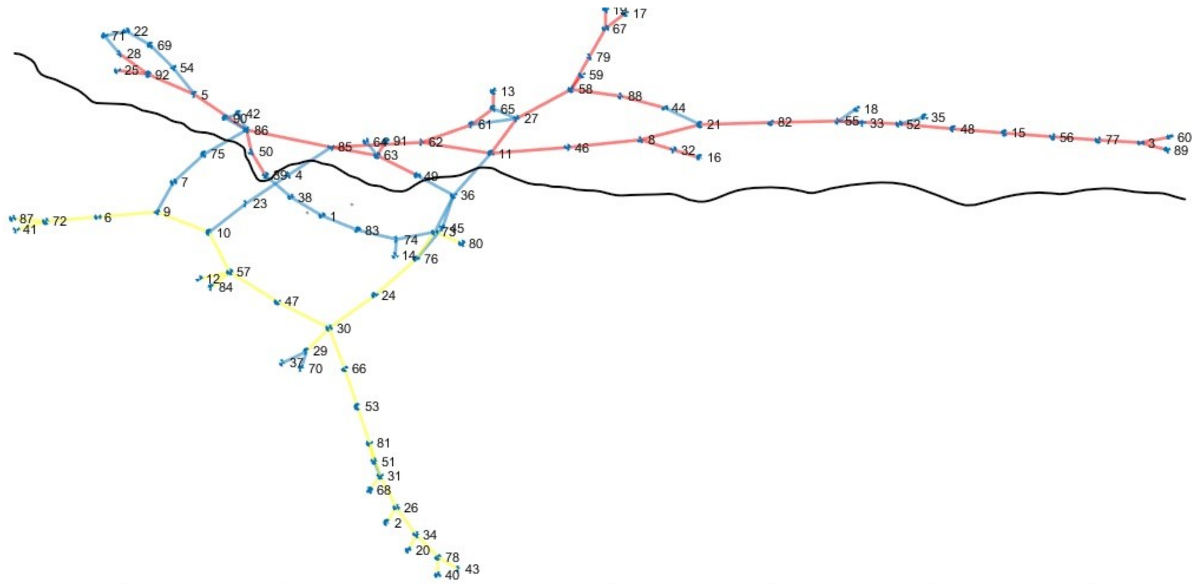

Figure 8: Cluster (islands) separated for the case I

Table 4: Initial Partitions for case II

Initial Partition number	Buses
1	Initial partition 1
2	Initial partition 2
3	Initial partition 3
4	Initial partition 4
5	Balaju S/S
6	Baneshwor
7	Birjung
8	Bus 48
9	Chapali
10	Ghorahi
11	Hapure
12	Hetauda (132 KV)
13	Hetauda (220 KV)
14	K3
15	Kamane
16	Matatirtha(220)
17	New Khimti
18	Okhaltar
19	Patan
20	Pathlaya
21	Teku

KV), Mirchalya, Lahan, Rupni, Kushaha, Duhabi, Multi-fuel, Damak, Anarmni, Godak Ilam, Bus 97 (Maikhola), Phidim, Hewa, Kabeli/Amarpur}

Initial partition 2= {Chilime, Devighat, Trishuli s/s, Balaju s/s (66 KV), Suichatar (66 KV), Kulekhani (66 KV),Hetauds D/P s/s, Hetauda Corridor, Amlekhjung, Simera, Parwanipur 2 (66 KV), Parwanipur (132 KV), Raxaul, Suichatar (132 KV), Trishuli 3B hub, Matatirtha (220 KV), Kulekhani (132 KV)}

initial partition 3 = {Bhulbhule, Middle Marshyangdi, Damauli, Dumre, Lekhnath, Madi, Pokhara, Modikhola, Bus 138 (IPP, Thapakhola), Bus 90 (Lower modi), Syanga s/s, Kali, Marshyangdi s/s, Bharatpur, kawaswati, Bardaghat, Bus 113 (Ramnagar Import), Gandak s/s, Butwal, Shivapur/chanauta, Lamahi, Kusum, Kohalpur, Burigau, Lamki, Phalamnpur, Attaria, Mahendranagar, Syaule}

Initial partition 4 = {New Chabel, Lainachour}

4.2.5. Agglomerative clustering:

Figure 10 shows the dendrogram which illustrates the sequence of merging the initial partitions with one another to form independently operating islands.

Firstly the three black start generators in initial partition 1, initial partition 2, and initial partition 3 are started at the same time. Then, they respectively crank their allocated non-black start generators one after another energizing the lines traced in the shortest path trees.

Initial partition 2 is designed to energize Teku, K3, Matatirtha (220 KV), Birjung, nodes in initial partition 4, and finally Okhaltar and chapali. This connection will be operated as an independent island for a while.

Initial partition 1 will energize Pathlaya, Kamane, and hetauda (220 KV) in one step. After that Patan, Baneshwor, and Balaju will be energized gradually to make another independently operating island.

And, initial partition 3 will gradually energize bus 48, Ghorahi, Hetauda (132 KV) and New Khimti making

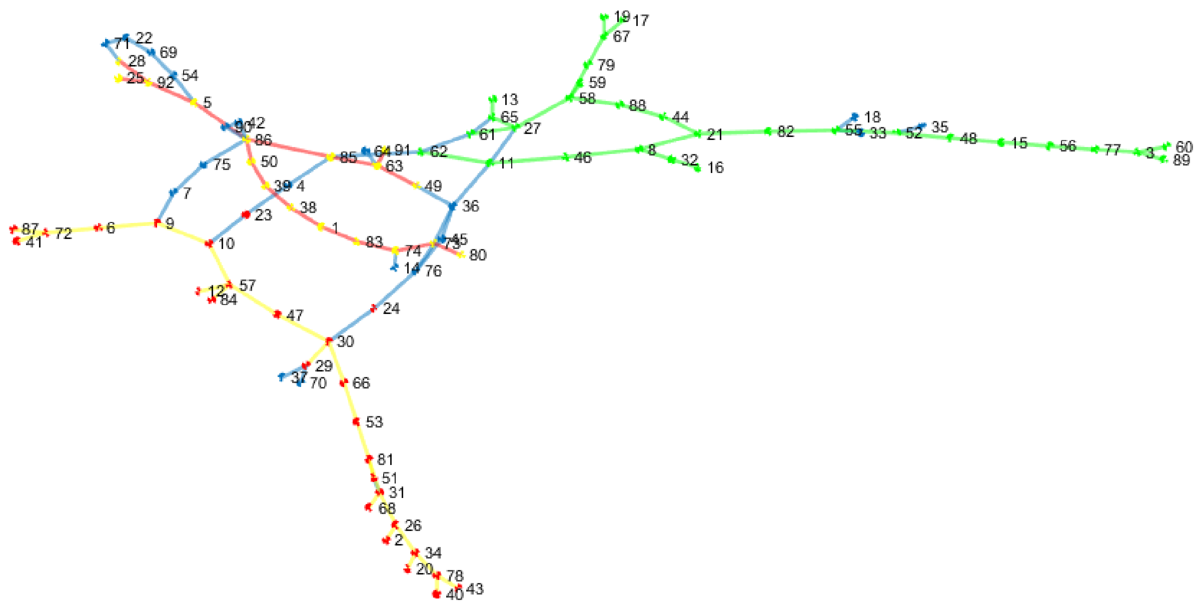

Figure 9: Graph representation of INPS with shortest path trees connecting the cranking groups highlighted for case II

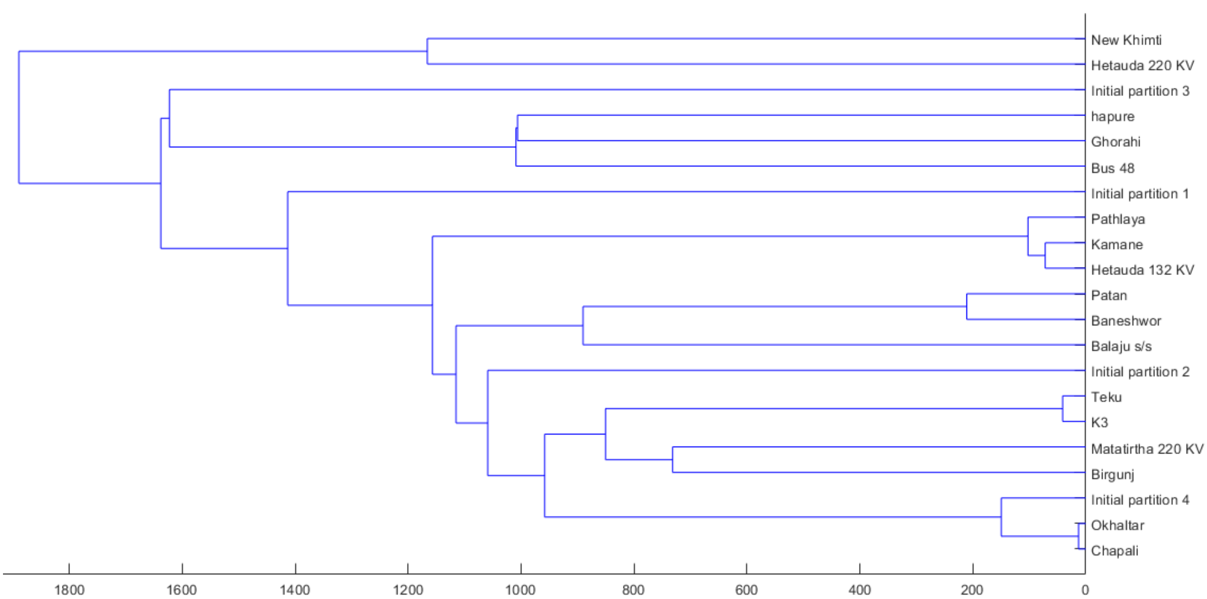

Figure 10: Dendrogram showing the hierarchy of merging the initial partitions for case II in INPS.

this combination the third independent island.

In Figure 11, the black line separates the graph representation of INPS in three major clusters. The clusters are restored as independent islands first and then the tie lines interconnecting them are energized. The tie lines interconnecting them are tabulated in Table 5.

The generation load difference of finally parted islands are 142.632 MW, 313.912 MW, and 118.788 MW respectively. The positive value of generation load difference further assures the stability of the islands when operated independently as they can supply the load even if it slightly deviates from the predicted value.

Table 5: Tie lines for case II

From	To
Matatirtha (Node num 64)	Marshyangdi (Node num 62)
Kulekhani (Node num 49)	Hetauda 132 KV (Node num 36)
Hetauda 132 KV (Node num 36)	Parwanipur (Node num 73)
Patan (Node num 75)	Syuchatar 66 KV (Node num 86)
Bajalu s/s (Node num 4)	Chapali (Node num 23)
Parwanipur (Node num 73)	Pathlaya (Node num 76)

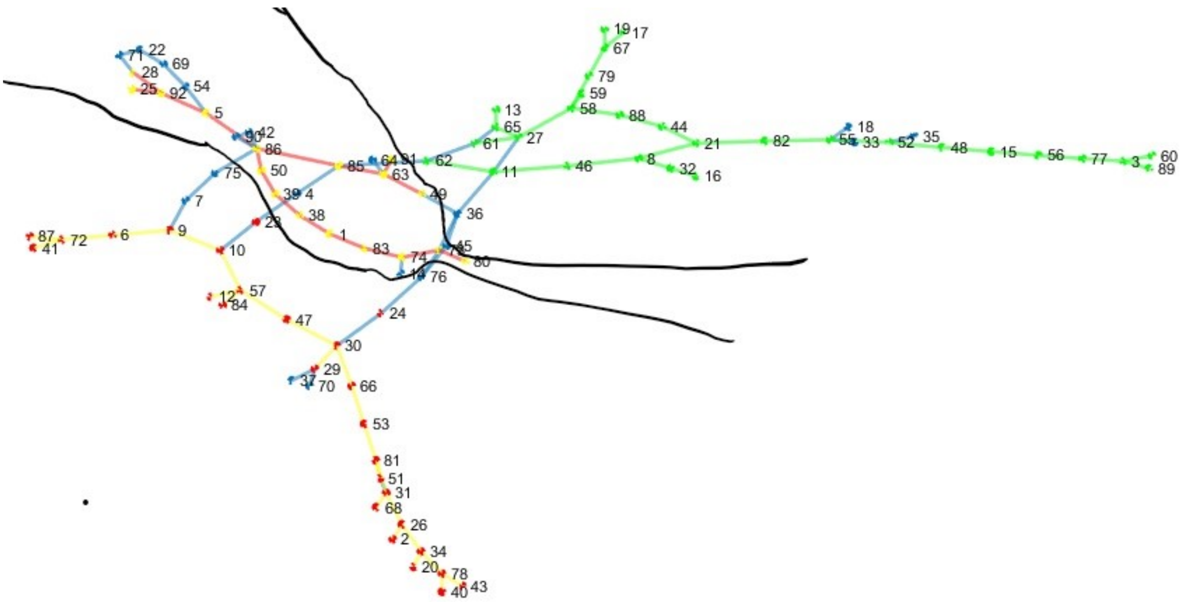

Figure 11: Clusters (islands) separated for case II.

5. Conclusion

In this paper, we implemented agglomerative clustering strategy for clustering INPS into multiple islands looking into two different black start scenarios. The first case considered the restoration of the grid via two black start resources only i.e. Kulekhani I hydropower station and Dhalkebar substation which is the point of import of power from the Indian grid for Nepal. In this case, two stable islands were formed which ensured their stability with a positive generation load difference of 200.308 MW and 321.778 MW respectively at last. The dendrogram shows the order of restoration of initial partitions which projects the complete step by step strategy for restoration. Also, in the second case, the Kaligandaki power station was added to the set of black start generators which was designed to crank the generators located in the western region of INPS. The second case resulted in three islands that could be restored independently and operated with positive generation load difference of 142.632 MW, 313.912 MW, and 118.788 MW. And also, dendrogram reflects the order of merging the initial partitions. These formed islands, after being restored independently, can be synchronized to each other via tie lines as mentioned. Thus, this paper finds the applicability of the network partitioning plan in INPS which could make the restoration task easier in real-time.

Conflict of interest

No conflict of interest

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