

PLANNING OF GRID AND SUPPLY RESTORATION IN THE DISTRIBUTION GRID WITH A HIGH PROPORTION OF RENEWABLE ENERGIES AND DISTRIBUTED GENERATION

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Abstract: The high proportion of supply-dependent, regionally concentrated RE leads to the need to build more extensive grids and targeted controllability to avoid grid restrictions. Based on build-up grid and supply restoration strategy, a restoration approach coupled with an optimization algorithm originally designed and implemented for transmission network has been modified to cater the challenges and complexities of distribution grid. The algorithm is programmed in MATLAB and includes load flow calculation and evaluation of the system's dynamic behavior during the restoration. Moreover, K-shortest algorithm and heuristic technique are implemented to identify optimal power system restoration paths.

In this paper, a parallel restoration approach is presented using exemplary transmission grids. The analysis of simulation results is utilized for adaptation of the restoration plan for distribution system operators (DSOs). The starting point is a parallel construction of several grid islands, which is favorable for minimum resupply times and made possible by the existence of several potentially black start-capable generation units, whose limits are optimally determined.

Keywords: Power system restoration, decentralized generation, heuristic initialization, discrete evolutionary programming

1 Introduction

In the event of a blackout, the network operators are responsible for rebuilding the grid with the help of black-start capable generation units. The transmission system operators (TSOs) as central coordinators have planned processes which are regularly tested in simulations, training sessions and, regarding black start and grid restoration, also in real tests. Two classical approaches to system restoration are adopted. In the worst-case scenario, these processes are based on the requirement to rebuild the own grid without external support (bottom-up), whereby a distinction is made with respect to the top-down strategy of rebuilding under voltage specification from a neighboring grid [1, 2]. In view of the energy transition, the gradual decommissioning of conventional generation and a decentralized shift of generation to the distribution grids leads to a decrease in the available balancing energy in the TSO grid [3]. This leads to the need for more intensive cooperation between TSOs and DSOs in the future in addition to the successive resupply of consumers. Regarding active power management, a mutual exchange between TSOs and DSOs must be planned and defined in processes. For this reason, research on the classic bottom-up strategy as a description of the relationship

between TSOs and DSOs with advanced combination concepts of build-up and build-together describes the necessary contribution of the DSOs in new strategies [2]. Furthermore, decision aid tools implemented for TSOs need to be extended to the DSOs with the necessary adaptations to assist with the grid and supply restoration planning. However, the decentral existence of generation motivates the building of restoration islands already on the DSO level, also following a bottom-up strategy for each island.

This paper is organized as follows: Section 2 describes the methodology of the presented restoration approach. Section 3 discusses the implications for grid and supply restoration for DSO. A description of the network model and evaluation of simulation results are given in section 4.

2 Methodology

One of the key responsibilities of a grid operator is power system restoration planning during a blackout event. Reducing the amount of time needed to return the system to the normal and stable operating state is the main goal of restoration. Furthermore, quick and organized corrective measures should be implemented to minimize the possibility of a system collapse which could lead to a further blackout. When operating staff expertise, computer simulations and real system physical and operational knowledge are integrated, the system restoration planning might be greatly enhanced [4]. There are two popular approaches for restoration planning:

1. Bulk power restoration: Successive Restoration of affected areas starting at predefined core network parts using distributed power sources.
2. Sectionalized power restoration: Parallel Island restoration through sub-division of the system with reduced switching operations.

As the emerging approach, parallel restoration of a power system involves three steps which are illustrated as follows [5]:

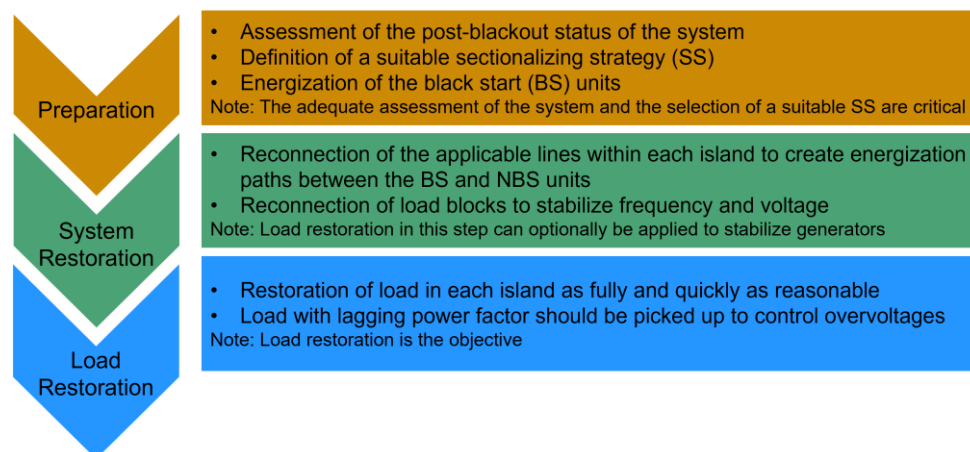


Figure 1: The three primary steps to restore the power system in parallel [14]

This study elaborates the methodical approach of the proposed planning algorithm for the first two steps of parallel restoration. Firstly, based on the build-together strategy, a parallel restoration between TSO and DSO is envisioned with the focus on TSO side. Afterwards, the build-up strategy is taken into consideration with independent grid and supply restoration by

DSOs and a suitable plan is proposed and developed. Based on this plan, tools and corresponding algorithms are to be adapted and tested for Central European grids. This is summarized and elaborated in the next section exclusively for the distribution networks, but utilize strategies and tools applied for transmission networks.

2.1 Sectionalization planning

To accomplish parallel restoration of a power system in the least amount of time, sectionalization planning is required. The formation of several islands determines which lines should not be restored. From the TSO perspective, these transmission lines are referred to as "cut sets" and are of great significance for the proposed optimization algorithm. This study utilizes graph theory to accurately represent the actual structure of the system and determine the restoration path. Heuristic initialization provides the initial cut sets which are adopted by the discrete evolutionary programming (DEP) optimization method to finally yield the optimal cut sets [4].

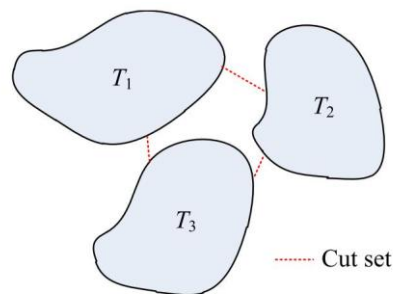


Figure 2: Islanded power system [4]

Figure 2 illustrates a system that is sectionalized into three islands (T_1, T_2 & T_3) with comparable restoration times. The cut set is determined to consist of three lines. To speed up system resynchronization, the common restoration time across all the islands is selected as the primary factor in this study. The system resynchronization time can be found as $\max(T_1, T_2, T_3)$ and an objective function (ΔT) is proposed to produce 'n' islands with similar restoration time and small number of cut sets [4].

$$\Delta T = (\max\{T_1, T_2, \dots, T_n\} - \min\{T_1, T_2, \dots, T_n\}) + t_{tl}(z) \rightarrow \min \quad (1)$$

where z is the cut set number.; t_{tl} is the cut-set time to connect.

2.1.1 Network modeling using graph theory

The application of graph theory provides a simplified representation of the network which allows it to be captured in an optimization problem with the objective function defined above. In the event of a blackout, an undirected network is established and denoted as $G = (V, E, W)$, where V is the collection of nodes of major electrical components (buses, generators, and loads), interconnected by a set of edges (lines), E , each associated with a weight factor, W . The weight factor denotes the level of connection exhibited by edges. The connection status of the edges is represented by a binary value, where 1 and 0 indicate a connected and disconnected edge respectively.

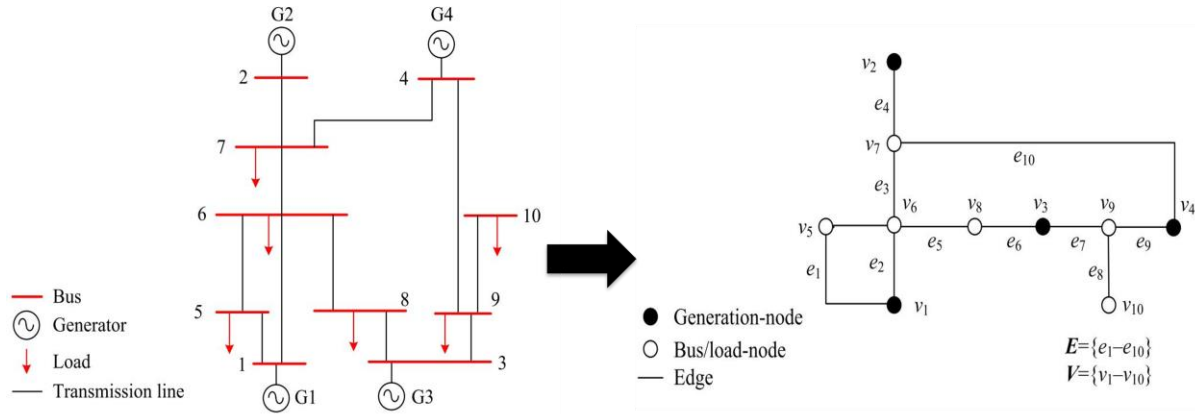


Figure 3: Network modelling using graph theory [4]

2.1.2 k-shortest algorithm

After network modelling, the shortest path algorithm is applied to determine the shortest resupply path for the critical grid elements, i.e., the secured loads and the secured generation. To determine the transmission path for restarting a generating unit, a weighting factor is provided to the charging current of each line. This is done to prevent the occurrence of excessive charging currents, which corresponds to overvoltage risks and especially the need of provision of reactive power.

The shortest restoration path P is defined as an alternating sequence of different nodes and edges [6, 7]. The overall length of the path P , denoted as $w(P)$ is defined as the sum of the symmetric lengths included within P , representing the distance between the starting point s and the endpoint t [8].

$$w(P) = \sum_{i \in P} w_i \quad (2)$$

Additionally, it is possible to compute the overall electrical distance between the two nodes. Hence a new subset $Z \subset G$ is introduced with components z_i belonging to Z .

$$z(P) = \sum_{i \in P} z_i \quad (3)$$

2.2 Heuristic initialization

This approach uses the knowledge and experience of the network operator to identify sensible network areas that initially need to be separated [4]. Heuristic strategies require knowledge of restoration constraints, operation procedures and minimal restoration times to find the best solution. As they affect the overall parallel restoration time, the restorative times for each of the primary system elements must be considered. The restoration constraints which include the black start (BS) unit's availability, load-generation balance, voltage profile and the lines' capacity to carry out the synchronous equipment connections process need to be considered [9]. With the help of this information, a realistic initial cut set is determined that approaches the ideal solution.

Two fundamental steps need to be taken into consideration to find the original cut set. These include putting the generators in order based on how many BS generators are in the system. Based on the balance of total active power generation, the generators are then grouped together. A heuristic technique based on the generator's skeleton is suggested to find the initial cut set. A detailed elaboration of both steps with a simplified example is provided in section 2.2.1-2.2.2.

To account for the electrical distance between them, generator units are categorized into r groups (r being the number of islands) based on similar capacities. The balance of total power generation and the generator skeleton size gap are calculated in each potential set and the group with the lowest power balance and gap size is chosen for the following stage [9]. Here, gap size or skeleton size is the number of edges covering the path between generator units in a group and is defined as follows:

$$\Delta s = \max\{S_{G1}, S_{G2} \dots S_{Gr}\} - \min\{S_{G1}, S_{G2} \dots S_{Gr}\} \quad (4)$$

All relevant steps are depicted in Figure 4 where each incremental advancement ensures that the overall active power generation surpasses the total load consumption, hence fulfilling the necessity to restore the balance between generation and load [4].

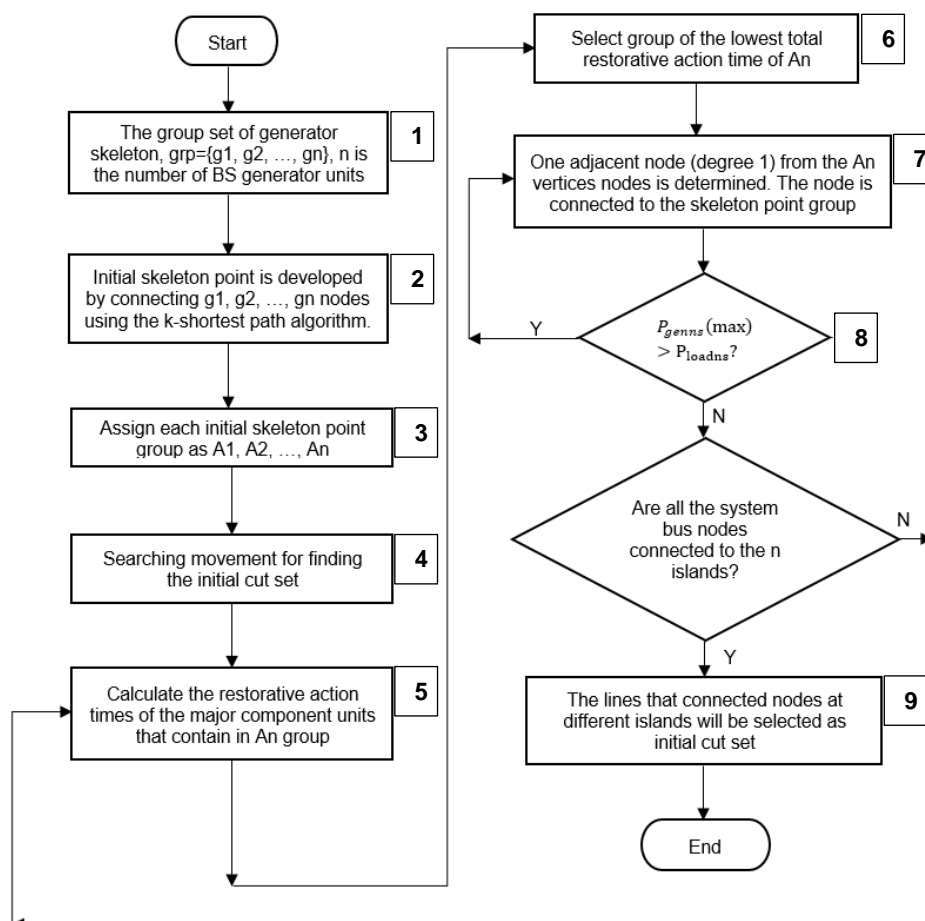


Figure 4: Flow chart of heuristic initialization method [4]

2.2.1 Generator grouping

The single line diagram presented in Figure 3 is considered to explain the selection process of for the initial cut set. The network consists of four generators at nodes 1, 2, 3, and 4 with

different generations i.e., $P_1 = 40MW, P_2 = 20MW, P_3 = 40MW$ and $P_4 = 20MW$. The black start units are situated at nodes 2 and 3 whereas the load buses have a 20MW rating with critical loads at nodes 6 and 10 respectively. This yields two generator groups in accordance with Figure 4 (step 1).

Figure 5 and Table 1 show the result of applying the generator's skeletal group identification method Figure 4 (steps 2 & 3). The skeleton points are grouped in accordance with the overall load generation balance and the group set with the lowest load generation balance is used, thus the first group in this case.

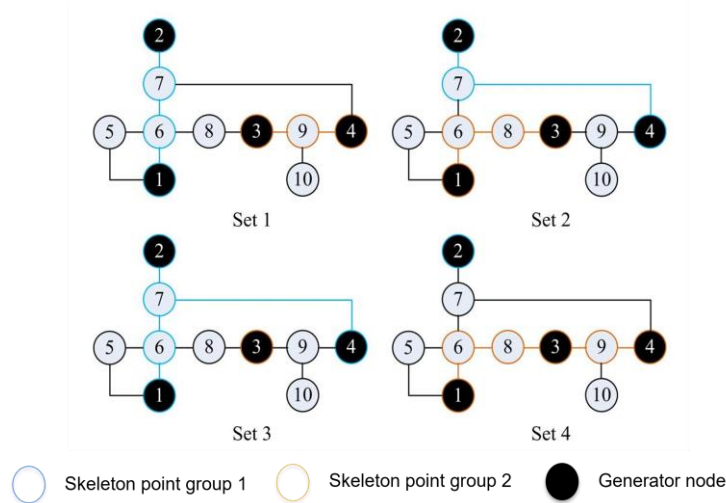


Figure 5: Determine generator's skeleton [4]

Table 1: Generator groupings

Set of groups	Generator node (Group 1)	Generator node (Group 2)	$P_1(MW)$	$P_2(MW)$	$\Delta P(MW)$
1	1, 2	3, 4	60	60	0
2	2, 4	1, 3	40	80	40
3	1, 2, 4	3	80	40	40
4	2	1, 3, 4	20	100	80

2.2.2 Initial cut set

Starting with the skeleton points resulting from the minimal connections to build the generator groups using k-shortest path, a search strategy will be implemented to determine the initial cut set as per Figure 4 (step 4). While maintaining the load generation balance, the points will be increased by looking for a nearby node. Additionally, it must guarantee that the new points do not cross over into existing groups. To find a new node to join their group, the group with the shortest restoration time is chosen. The principal power units in each group are used to calculate the restorative action time. The process is repeated until every node is attached to one of the groups that have been created [4]. The resulting generator skeletons from Figure 5 (Set 1) are nodes 1, 2, 6, 7 (group 1) and nodes 3, 4, 9 (group 2).

Since group 2 has the lower restoration time compared to group 1, it will search and connect neighboring nodes which are 8 and 10 thereby yielding a higher restoration time. Finally, group 1 will add node 5 to the group [4]. The resulting initial cut set obtained by following the actions summarized in Figure 4 (steps 5-9) is illustrated in Figure 6.

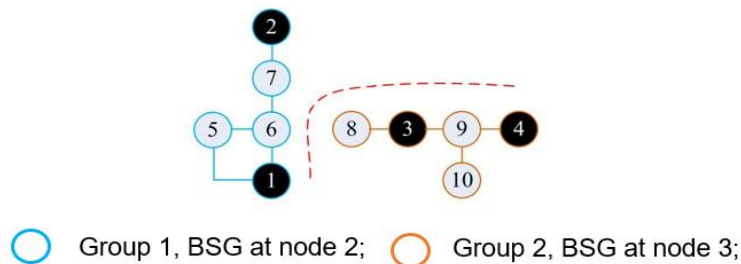


Figure 6: Application of heuristic initialization to find the initial cut set [4]

2.3 Discrete Evolutionary Programming (DEP)

The initial cut sets obtained from the heuristic initialization are then utilized by DEP optimization algorithm to achieve the desired optimal results in an iterative process. The result is the limits of grid islands to be set up separately (optimal cut sets). Since the associated switching operations must be carried out in the short time window after the blackout, in which battery storage in the stations still enables remote-controlled switching operations, a predefined plan is required here. The optimization's goal is for the islands with the fewest cut set members to have comparable restoration times. Figure 7 shows the flowchart of the general DEP algorithm [4].

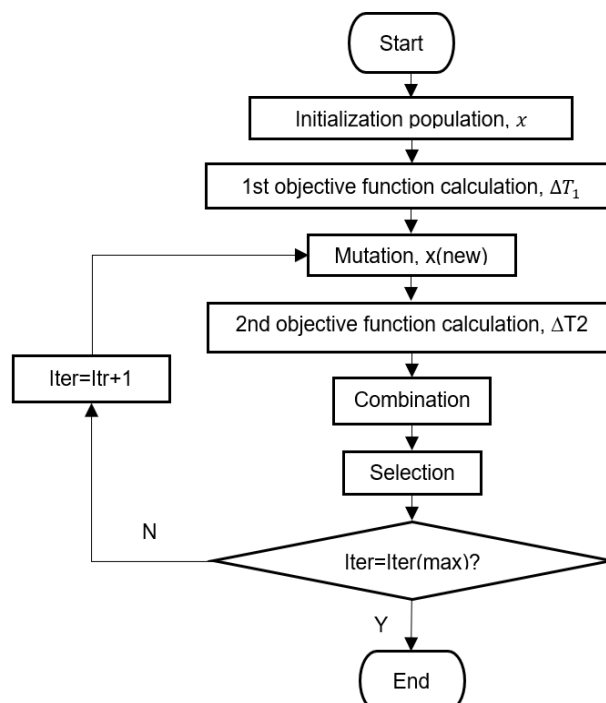


Figure 7: DEP optimization method [4]

Optimization begins with the calculation of the first objective function using heuristic initialization population. This is followed by the mutation process to obtain a new set of

particles. The second objective function is then calculated followed by the combination of initial and mutated populations with their corresponding fitness in array form. Finally, the best populations are selected based on their fitness value, which is the objective function according to equation (1). The process is repeated until maximum iteration is reached [10].

3 Implications for grid and supply restoration for DSOs

In particular, the DSO is responsible for the secure establishment of grid areas suitable for reconnection, the allocation of secure loads in accordance with the requirements of the TSO [3], as well as the connection of sufficiently predictable consumption power. However, the intermixing with distributed energy resources in its distribution grid introduces additional complexities which need to be addressed as follows:

- Extended forecasting and control procedures to comply with specified power bands with regards to the stability of the still weak overall system.
- Additional restoration constraints related to the DG dynamics and safety operational procedures for islanded configurations are to be introduced [11].
- Time dependency of available generation with the need to quickly calculate optimal islands for the cut sets is critical.
- DG start-up processes and cold load pick-up dynamics must also be considered [12].
- Location of the remote controllable stations must be taken into account for the creation of islands and the resulting cut sets.
- For islanding in medium voltage networks, aspects of neutral point handling are just as important, so that no limits for residual currents are exceeded in the islands with single-pole faults.

In view of these complexities, the proposed restoration plan is to be adapted for implementation in the distribution grid. This is catered in the case of devising a build-up strategy, i.e., the formation of island grids from the distribution grid itself, which is currently only envisaged as an exception in regulatory terms. The DSO requires the same capabilities and tools as a TSO which can result in speed advantages in grid and supply restoration not only for the individual DSO, but also for the overall system, hence proving beneficial to combat the increased penetration of renewables in the system. The DSO can initially develop several grid islands and thus achieve a speed advantage in the restoration of supply due to the necessary switching operations.

The aim of this study is to address these potential challenges encountered during the DSO restoration process, specifically the unavailability of branches and intermittency of renewable generation. To tackle these issues, the research proposes the modification of the implemented algorithm to address the above-mentioned complexities. One such proposed adaptation is the modification of k-shortest algorithm. In cases when the absolute shortest path is not feasible for implementation in the restoration process, alternative options such as the second or third shortest simple paths can be considered as substitutes. Moreover, by the identification of several shortest simple pathways, it becomes feasible to see any alterations in $w(P)$ and $z(P)$ as defined in section 2.1.2 for each path after the restoration of a branch. A possibility is present for the alteration of the second or third shortest simple paths, initially identified, when updating the list of shortest paths from the BS unit to the NBS units or critical loads (CLs). This is due

to possible changes in the required number of connections and the electrical distance to elements that remain disconnected during the restoration process [8].

4 Results and discussion

The proposed methodology is implemented and simulated in MATLAB/Simulink environment with the IEEE 39 bus system and the results are presented and discussed as follows:

Using graph theory, the IEEE 39 bus system is first sectionalized in MATLAB, as shown in Figure 8. Each island is formed based on the balance between power generation and the total predicted load. All significant equipment in the system is assumed to be physically isolated, and the circuit breakers are left open.

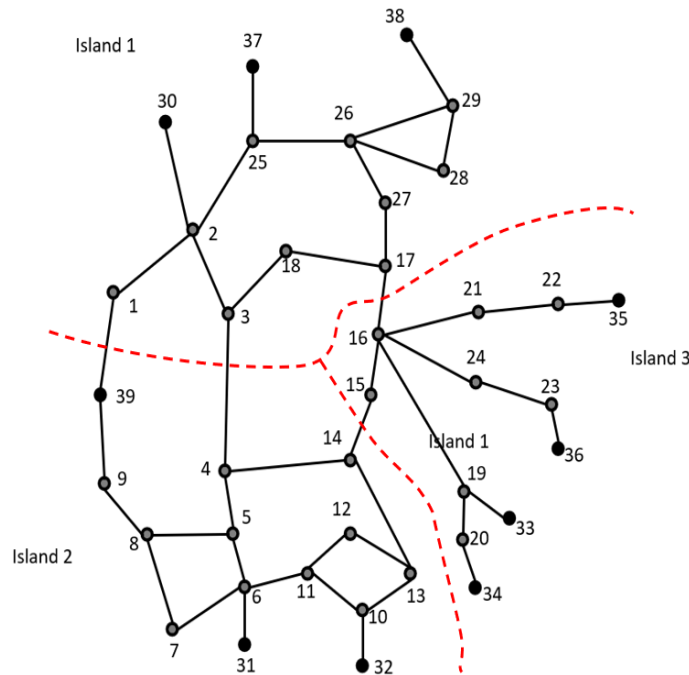


Figure 8: Three islands comprised the New England 39-bus test system's sectionalization strategy

Based on the analysis of the IEEE 39 test system data, there are a total of 10 generators and 46 transmission lines. The total generation capacity is 6193 MW, while the total load is 5939 MW. There are 3 BS units i.e., G3, G4 and G8 located at buses 32, 33 and 37 respectively. The remaining generators are classified as NBS units. Nodes 7, 18, 21, 23, and 26 contain CLs, while the remaining are termed non-critical loads (NCLs). The shortest electrical distance between the BS and NBS units for the generator bus 32 are shown in Table 2 as an example. The highlighted paths are more clearly elaborated in Figure 9 for the entire system.

Table 2: Shortest paths from BS generator to other generators

Generator Bus (BS)	Shortest path	No. of Edges	Edges Electrical distances (p.u.)
32	(32, 10, 11, 6, 31)	4	0.0479
	(32, 10, 11, 6, 5, 8, 9, 39)	7	0.0897
	(32, 10, 13, 14, 15, 16, 19, 20, 34)	8	0.0973

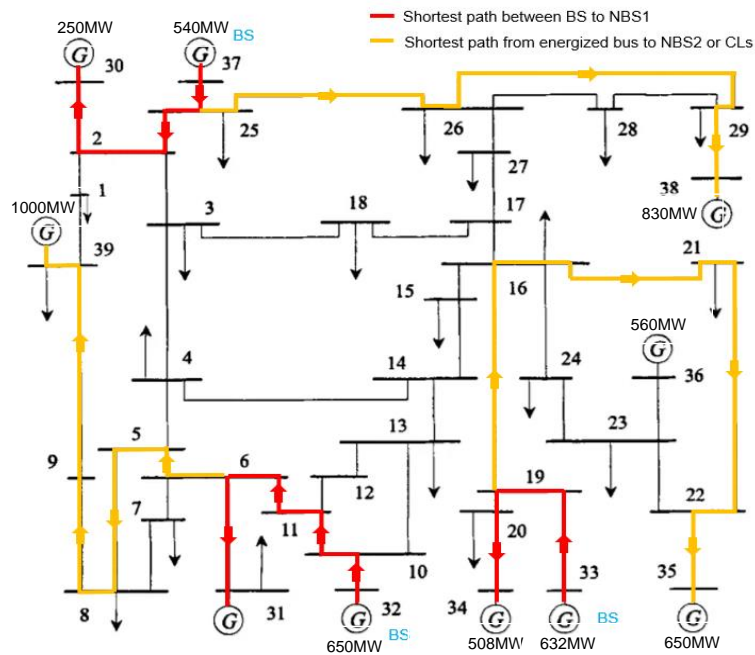


Figure 9: Shortest path from BS unit to NBS units in IEEE 39 bus system

The heuristic initialization is then implemented to obtain the generator groups and consequent initial cut sets (refer Figure 4: steps 1 to 3). The yielded generator groups constitute of (30, 37, 38); (31, 32, 39); and (33, 34, 35, 36) with a minimal use of active load-generation to achieve a balanced power distribution across all islands which is 253.8 MW (6193MW – 5939MW). The skeleton size gap ΔS is calculated using equation (4) and equates to 3 with R3 and R1 having max and min values of 9 and 6 respectively. Table 3 provides the detailed results while, the restoration time for the main equipment of each island is given in Table 4.

Table 3: Heuristic initialization of IEEE 39 bus test system

Set of groups	Group Island	Generator bus	Balanced Generation of Power ΔP (MW)	Size gap of skeleton ΔS	Initial cut set
1	R1 R2 R3	30 37 38 31 32 39 33 34 35 36	253.8	3	1-39, 3-4, 14-15, 17-18, 17-27

Table 4: Time to complete an action during power system restoration [4]

Action	Action type	Time required (min)
A1	Restart BS unit	15
A2	Energize a bus from BS unit	5
A3	Connect tie line	25
A4	Crank power to a NBS unit from a Bus	15
A5	Synchronize subsystems	20
A6	Pick up load	10

Figure 10 shows the initial generator architecture for groups R1, R2, and R3. The restorative time of each power unit in every skeletal group are calculated with example of region R1 shown in Table 4. With R1 yielding the shortest energizing time of 125 minutes, it extends the search

and connect strategy for neighboring buses (refer Figure 4: steps 4 to 8). The initial cut set after the searching movement (refer Figure 4: step 9) is shown in Figure 10.

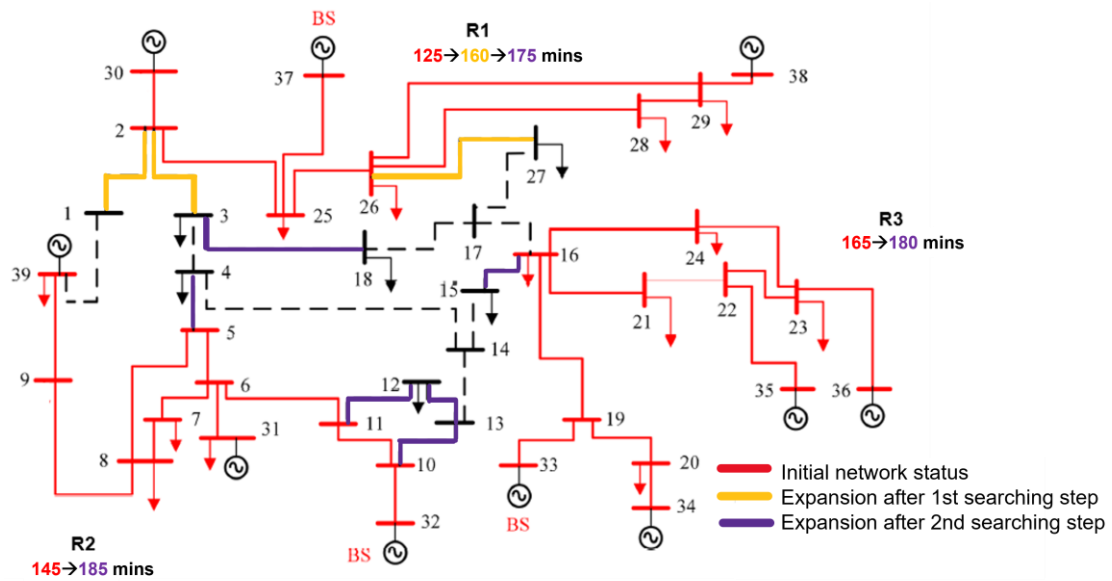


Figure 10: Initial cut set after heuristic initialization

Table 5: Restoration time for region R1

Path	Restored elements	Actions	Time(min)
-	BS unit at node 37	A1	15
37-25-2-30	NBS unit at node 30	A2+A2+A2+A4	30
25-26	CL at node 26	A2+A6	15
-	NCL at node 25	A6	10
26-29-38	NBS unit at node 38 & NCL at node 29	A2+A2+A4+A6	35
26-28-29	NCL at node 28	A2+A2+A6	20
Total restoration time R1 region			125

Finally, DEP algorithm determines the optimal cut set (z) by utilizing the initial cut set finalized with reduced search space. Implementation of DEP algorithm as illustrated in Figure 7 results in the optimized cut set {1-39, 3-4, 14-15, 16-17}, as shown in Figure 11. This cut set is smaller than the initial cut set presented in Table 3.

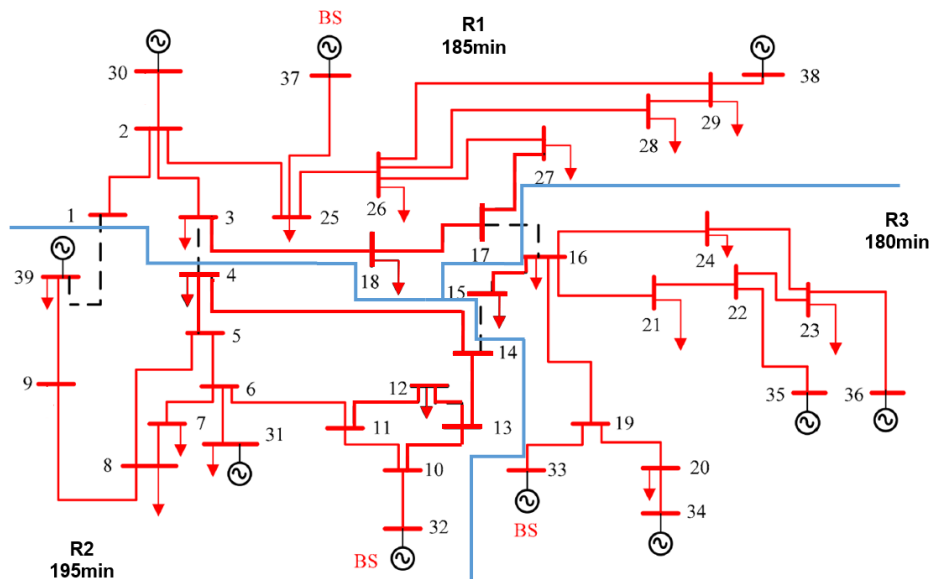


Figure 11: Final cut set with each island restored

5 Conclusion and future work

A modified restoration approach based on the parallel restoration of power systems is presented in this paper. Heuristic techniques and DEP optimization algorithms are deployed to find out the optimal system restoration approach. Moreover, the potential challenges in the distribution grid are also addressed and adaptations are proposed as a framework for further research. Simulation results show the efficacy of the proposed algorithm for optimal system restoration.

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