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An Optimization-Based Intentional Islanding Scheme for Service Restoration in Distribution Systems Considering Anti-Parallel Operation of Distributed Generations

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Abstract: An islanding operation of distributed generations (DGs) in emergencies due to a fault in distribution systems can be a means of power supply for important loads in outage areas by facilitating the self-sufficient capability of DGs forming microgrids. This paper presents an optimization-based intentional islanding scheme to derive a near-optimal service restoration (SR) plan. The anti-parallel operation of DGs is considered a new constraint that avoids more than two DGs in an island thereby, enabling simpler control and operation of the distribution system in an emergency. Each island is created by an island partitioning scheme based on the tree representation of the network and fast searching scheme for the tree structure considering load importance, and a genetic algorithm (GA) is utilized to explore possible SR solutions. Case studies on IEEE 69-bus distribution system according to various fault locations are conducted, and the simulation results show that the proposed scheme can restore more loads with higher priority in outage areas by the intentional islanding of DGs. Furthermore, the time for deriving the optimal solution can be reduced since the evaluations for infeasible solutions are not performed.

Keywords: anti-parallel operation; distributed generation; distribution system; intentional islanding; islanding partitioning; optimization



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1. Introduction

Distribution systems play a very important role as the final link between power utilities and customers and have been operated in a radial structure that aims for low cost and simple design. Due to the radial operation of distribution systems, a failure of components in the distribution system causes outages for the customers, which requires a fast and efficient service restoration (SR) plan for the outage loads in order to improve system reliability [1–3].

When a fault occurs in a distribution system, it is detected and located by utilizing distribution automatic equipment such as feeder remote terminal units (FRTUs) that sends the fault information to the distribution automation system (DAS) through communication links [4,5]. Then, the fault is isolated from the main source by opening the upstream and downstream automatic switches of the fault. Restoration plans for outage loads are established by SR application in DAS considering various objectives (e.g., amount of load restored, network losses after changing system topology, number of switching required for the new topology), and constraints (e.g., voltage and line loading limits) according to the operation philosophy of a distribution system [6–8]. The SR can be regarded as a multi-objective non-linear problem of topology reconfiguration under a fault situation and optimization of switches (branches) in a distribution system [9].

Normally, distributed generations (DGs) are considered to be disconnected from a distribution system under a fault situation since islanding operations by DGs cause higher uncertainties and complexities in the operation under emergency conditions. However,

intentional islanding schemes based on island partitioning have been studied to facilitate the self-sufficient capability of DGs for SR problems by forming microgrids since the islanding operation of DGs could be a means of power supply for important loads in outage areas [10–13]. By utilizing the intentional islanding of DGs, benefits such as system reliability and outage cost can be achieved. The power balance, the difference between DG capacities and loads in an island, as well as normal constraints in distribution system operation, should be taken into account when a distribution system under faults is partitioned into several islands [14,15].

The intentional islanding method of DGs using island partitioning has been studied by several researchers in recent years. The method in [16] uses minimum spanning tree and dynamic programming methods to quickly achieve distribution network island separation under the constraints. In [17], an energy-risk-evaluation-based island partition strategy considering the power supply and demand balance is proposed. The research [18] proposes a dynamic islanding planning method based on strong search capability under Dijkstra Algorithm optimizing controllable loads in the system. The study [19] presents the islanding strategy using a systematic reduction of tertiary loads and expanding the external supply capacity of the microgrid to include an islanding assessment metric for the reliability of the obtained strategy. In [20], an island partition scheme considering the importance of loads and their controllability is proposed based on the established mathematical model. Another research [21] presents a multi-objective reconfiguration optimization method to improve the minimum node voltage and reduce network loss. The islanding configuration is determined in [21] by a centralized controller that performs a load forecast to evaluate the probability of successful operation of any possible islanding. A procedure for autonomous partitions of a microgrid without connections to the main source is proposed in [22]. The study [23] proposes the improved leapfrog algorithm to solve the tree backpack island partition optimization model with a DG. In [24], a two-stage solution procedure for an optimal systematic strategy to restore the post-contingency distribution grid after the occurrence of severe disturbances causing an outage is presented.

The previous research in [16–24] reveals that the intentional islanding operation can be an effective scheme for power supply under fault situations by providing alternative energy sources using DGs. However, the result of island partitioning using schemes presented in the previous works should deal with complex parallel operations under emergencies since multiple DGs are included in a single island. As the parallel operation requires more complex control and protection schemes of the system, the increased uncertainties and complexities make the operation during an emergency difficult for operators and introduce additional equipment and costs for reliable control strategies [25,26]. To avoid complex operations under an emergency due to a fault, this paper proposes an anti-parallel intentional islanding scheme for SR in distribution systems. Furthermore, an optimization-based approach using a meta-heuristic scheme is presented to explore possible SR plans and achieve optimality in SR considering the importance and controllability of loads.

This paper is organized as follows: Section 2 describes the general SR process as well as the objectives and constraints of the SR problem considered in this paper. Section 3 presents the proposed optimization-based intentional islanding scheme considering the anti-parallel operation of DGs. Simulation results considering various conditions are discussed in Section 4, and finally, the conclusion is in Section 5.

2. Service Restoration Problem Statements

2.1. Service Restoration Process

To improve the reliability of distribution systems, SR is performed by distribution system operators to restore outage loads by finding proper backup feeders that can provide power supply for the out-of-service loads under a fault situation until the fault is eliminated [27]. For the SR, a series of switching operations is required to transfer the outage loads to the alternative feeders. Therefore, the SR results in a new network topology of

the distribution system, and the number of possible topologies is exponentially increased according to the number of controllable switches in the system.

Figure 1 illustrates the general SR process in distribution systems. When a fault occurs in a distribution system feeder, a proper protective device, such as a circuit breaker (CB), operates to cut off the power supply from a main source to the fault location. The DAS recognizes the fault through alarms that inform whether the CB operates or not. Then, fault information, such as fault indicators (FIs), received through communication from FRTUs is utilized to identify a fault location. Once the fault location is determined, the faulty section is isolated from the main source by opening the upstream and downstream automatic switches of the fault, and the power supply to the upstream loads is resumed by reclosing the CB. The SR is performed to restore the downstream outage loads by multiple switching operations causing a new system topology. If the fault is eliminated, then the system returns to the original topology before the fault.

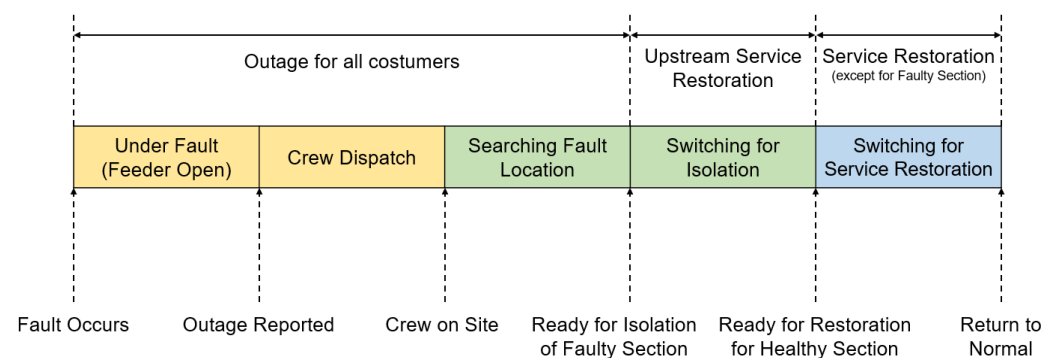


Figure 1. General service restoration process in distribution systems.

An example of the service restoration process is depicted in Figure 2. Suppose that the fault occurs in the section between S1 and S2 switches. The CB is tripped by a protection relay such as overcurrent relays (OCRs) and overcurrent ground relays (OCGRs), and FRTUs on CB and S1 experience fault currents exceeding a predetermined value for generating FIs. Due to the tripping of the CB, all the loads in the faulty feeder are out-of-service as shown in Figure 2a. The DAS determines the fault location using the FI information and performs the fault section isolation by opening S1 and S2. Then, CB is reclosed to restore loads in the section between CB and S1. To restore the downstream loads of S2, an SR is performed by closing a candidate switch such as S3, S4, and S5.

2.2. Objectives and Constraints

The SR can be regarded as a nonlinear multi-objective problem since SR plans are established by considering various objectives such as the outage loads, power losses, and the number of switching operations required to achieve a new topology. In this paper, minimizing outage loads in a distribution system is considered an objective since it is a more important factor than others, especially in emergencies that do not last for a long time. In order to emphasize load importance in an emergency, load importance coefficients are applied to ensure that the SR scheme restores as many critical loads as possible despite the disconnection of controllable loads within an island. The objective function considering a load importance index can be expressed as Equation (1).

$$\min F = \sum_{i=1}^l \left(\alpha_{C1} \left(1 - \frac{PRE_{C1i}}{P_{C1}} \right) + \alpha_{C2} \left(1 - \frac{PRE_{C2i}}{P_{C2}} \right) + \alpha_{C3} \left(1 - \frac{PRE_{C3i}}{P_{C3}} \right) \right) \quad (1)$$

where, l is the number of islands in a distribution system; α_{C1} , α_{C2} , and α_{C3} are coefficients of load importance for load classes 1, 2, and 3, respectively; PRE and P are the sum of loads restored in an island and the total load in a distribution system, respectively.

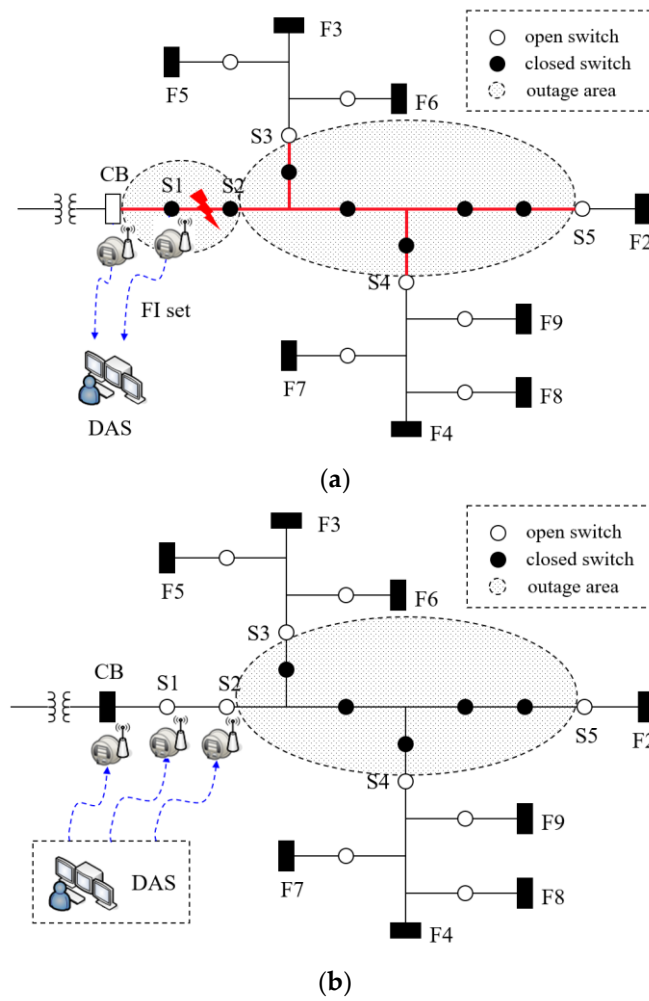


Figure 2. An example of the service restoration process: (a) Before the fault section isolation; (b) After the fault section isolation.

The topology derived by the SR scheme needs to satisfy distribution system operating constraints. The following constraints are applied to check whether an SR plan derived is feasible or not.

- Power balance;
- Bus voltage;
- Branch capacity;
- Anti-parallel operation.

The DG capacity in an island should be greater than all loads in the island to meet the power balance constraint, and bus voltages and branch capacities should be within the allowable range. The constraints applied to the SR problem can be expressed by Equations (2)–(4).

$$P_{DG} \geq \sum_{i=1}^N P_{Li} \quad (2)$$

$$S_{max,i} \geq S_i \quad (3)$$

$$V_{lower} \leq V_i \leq V_{upper} \quad (4)$$

where, N is the number of loads in an island; P_{DG} , P_L are active power capacity of DG and load, respectively; and S_{max} is the branch capacity limit; V_{lower} and V_{upper} are the lower and upper limits for bus voltages, respectively.

It is noted that the anti-parallel operation is introduced as a constraint in this paper. An island with more than two DGs imposes complexity in system operation since the parallel operation requires an improved control system that reflects the different dynamics of DGs. Protection-related challenges are also expected due to multiple fault current sources and the resulting reverse power flows. Furthermore, a tool or control center for the automatic management of various DGs should be introduced, which causes additional equipment and costs for reliable control strategies [25,26]. For example, in the case of inverter-based DGs, a communication-based control scheme collecting the operating information of each DG should be introduced to deal with the parallel-connected mode control [28].

3. Proposed Service Restoration Scheme

3.1. Island Partitioning Method

Intentional islanding operation of DGs can provide a distribution system in an emergency with the self-sufficient capability by supplying power to important loads in outage areas. To restore the outage loads and achieve minimal generation–load imbalance, outage parts within the distribution system isolated from the main source should be divided into multiple islands making them self-sufficient areas. Figure 3 shows the overall procedure of the island partitioning method used in this paper.

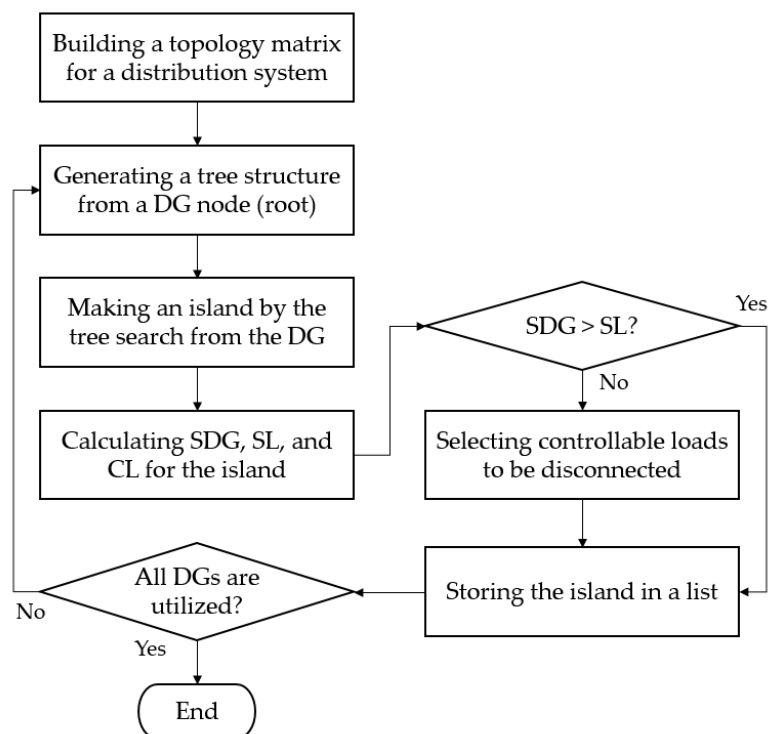


Figure 3. The overall procedure of the island partitioning method.

As indicated in Figure 3, firstly, a topology matrix containing information on connection relationships between all buses (nodes) in a distribution system is generated according to the current switch status. Elements in the matrix are encoded with 1 for ‘connected’ and 0 for ‘disconnected’ so that network searches can be performed by tracking all the ‘connected’ paths. Once the topology matrix is built, then a tree is created where the root is a DG-connected bus, and an initial island is built according to the path in the tree. Three quantities in the island are calculated to evaluate whether the initial island is feasible considering the power balance: (1) the total DG capacity (SDG), (2) the total

amount of loads (SL), and (3) the total amount of loads that can be disconnected for load sheddings (CL).

For the initial island, the power balance constraint is satisfied if the SDG is greater than the SL. Therefore, the information on the initial island can be stored in a list without any changes since the island can be considered a feasible one satisfying the power balance constraint. Otherwise, controllable loads to be disconnected should be selected for meeting the constraint. To select which controllable loads in the island should be disconnected, all possible combinations considering the controllable loads are examined, and the one resulting in the minimum generation–load imbalance is chosen as the best one. The procedure of island partitioning is conducted until all DGs in the system are exploited to make islands. The islanding partitioning is performed by the number of DGs because the proposed scheme does not allow parallel operation of DGs meaning that there is only one DG within an island.

Figure 4 illustrates an example of island partitioning for a simple system with 11 buses, two DGs, and two controllable loads. As shown in Figure 4a, two branches are disconnected to make islands in the system, and the corresponding system topology matrix is created by Equation (5). Based on the matrix, a subtree with one DG as a root node is generated as indicated in Figure 4b. By using the tree search and load information shown in Table 1, the SDG and SL for the DG1 are calculated as 100 kW and 90 kW. Since the SDG is greater than the SL, the island with DG1 is stored without any load shedding by controllable loads. For the DG2, the SDG and SL are derived as 200 kW and 240 kW and it needs to make use of load sheddings to restore more important loads in the island. Three combinations are available because there are two controllable loads, and the load at bus 8 is chosen to be disconnected to make the least generation–load imbalance. For the sample system, two islands are generated with one load shedding, and the island with DG1 contains buses 4, 5, 6, and 7 whereas the island with DG2 includes buses 2, 3, 8, 9, 10, and 11.

$$\text{topology matrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \quad (5)$$

Table 1. Active power and class of loads in the sample system.

Bus No.	Active Power [kW]	Load Class	DG Capacity [kW]
1	70	3	100
2	50	2	0
3	50	1	0
4	20	3	0
5	30 (controllable)	2	0
6	30	1	0
7	10	3	0
8	100 (controllable)	3	0
9	10	3	200
10	60 (controllable)	3	0
11	30	1	0

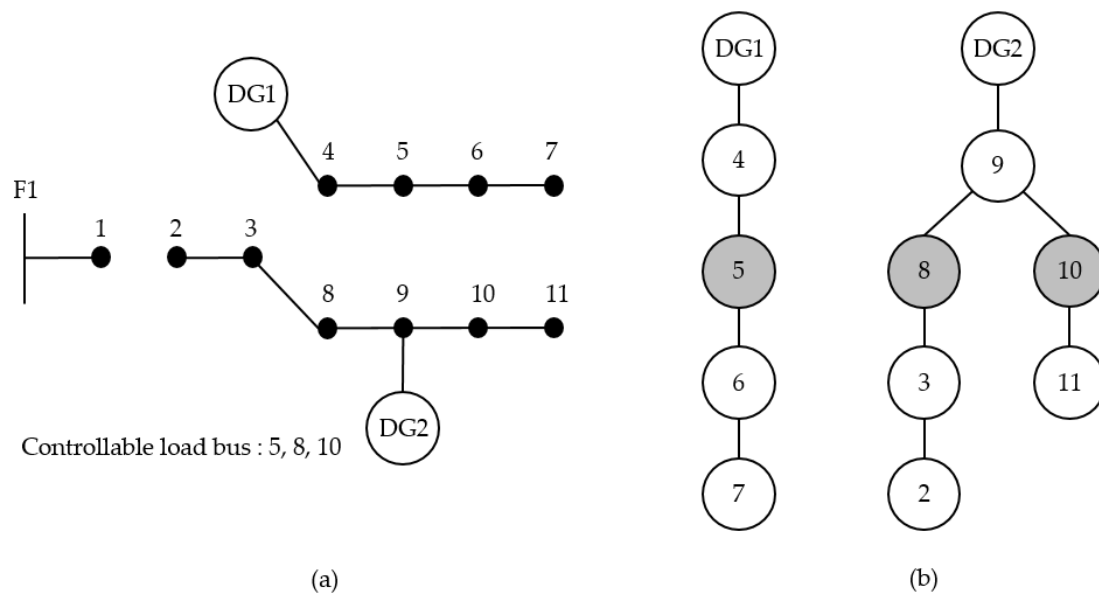


Figure 4. An example of island partitioning for a simple system: (a) sample system configuration; (b) tree representation of the sample system.

3.2. Optimization-Based Intentional Islanding Scheme

The proposed intentional islanding scheme utilizes an optimization technique based on genetic algorithm (GA), which is one of the meta-heuristic algorithms inspired by natural selection in order to derive a near-optimal topology of a distribution system. GA is commonly used to find optimal or near-optimal solutions to the problems from the search space which otherwise would have taken a significant amount to solve. It uses crossover and mutation operations to achieve exploration of the search space by creating new solutions. Furthermore, the selection operation is utilized to promote exploitation by identifying good solutions in the population. As a result of iterative GA operations, a wide range of solutions have been reasonably explored, and the near-optimal solution can be derived. The binary-coded GA is utilized since the status of switches (branches) in a distribution system can be easily represented by binary values such as 0 (open) and 1 (closed). Therefore, a single control variable corresponds to the status of one switch, and the number of GA control variables is the same as the number of controllable switching devices in a distribution system. The GA plays the role of searching possible topology candidates in a significantly wide search space due to the large number of controllable switches in a distribution system. Figure 5 shows the flowchart of binary-coded GA, and the details of the algorithm are provided in [29,30].

Figure 6 shows the flowchart of the proposed optimization-based SR algorithm. First of all, populations representing distribution system topologies are initialized as depicted in Figure 6. The number of variables in a population equals the number of branches, and the variables are randomly encoded by 0 (open) or 1 (closed) except for a faulty section which should be regarded as an open one. Once the populations are created, the proposed algorithm performs the island partitioning process as described in Section 3.1. If an island contains more than two DGs, the penalty is imposed on the corresponding population because it is considered an infeasible solution violating the anti-parallel operation constraint. Otherwise, the load flow analysis is conducted to calculate distribution network quantities such as the magnitude of bus voltages and power losses in an island. Then, the constraints regarding the operational limits of the distribution network shown in Equations (2)–(4) are checked, and the penalty is imposed on the corresponding population in case there is any network constraint violation. If the population satisfies all the constraints, the objective function (F) is calculated by using Equation (1). The process is iteratively performed for all the populations and terminated after reporting the best SR result when it reaches the

maximum iteration. If the termination condition is not met, the populations are updated by using processes of GA to search for other topology candidates for SR plans.

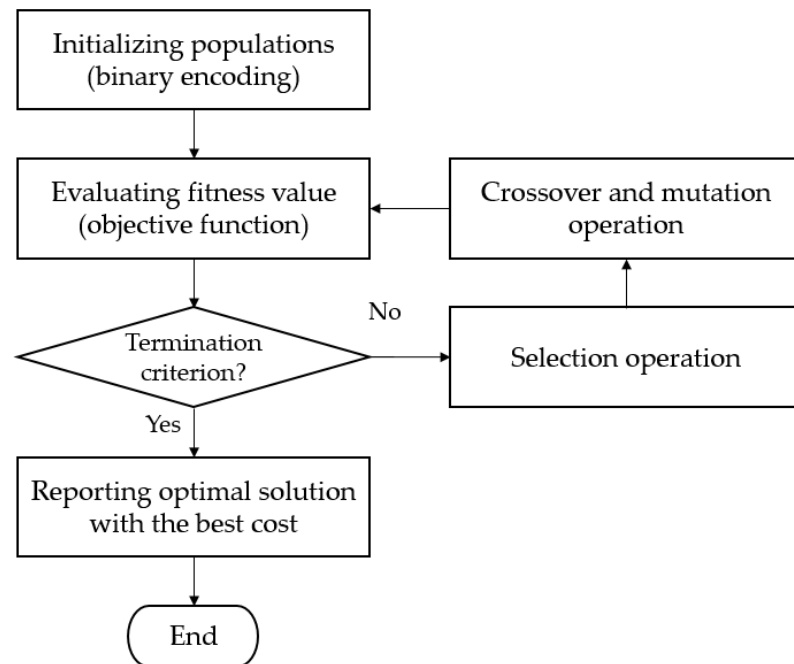


Figure 5. Flowchart of the binary-coded genetic algorithm.

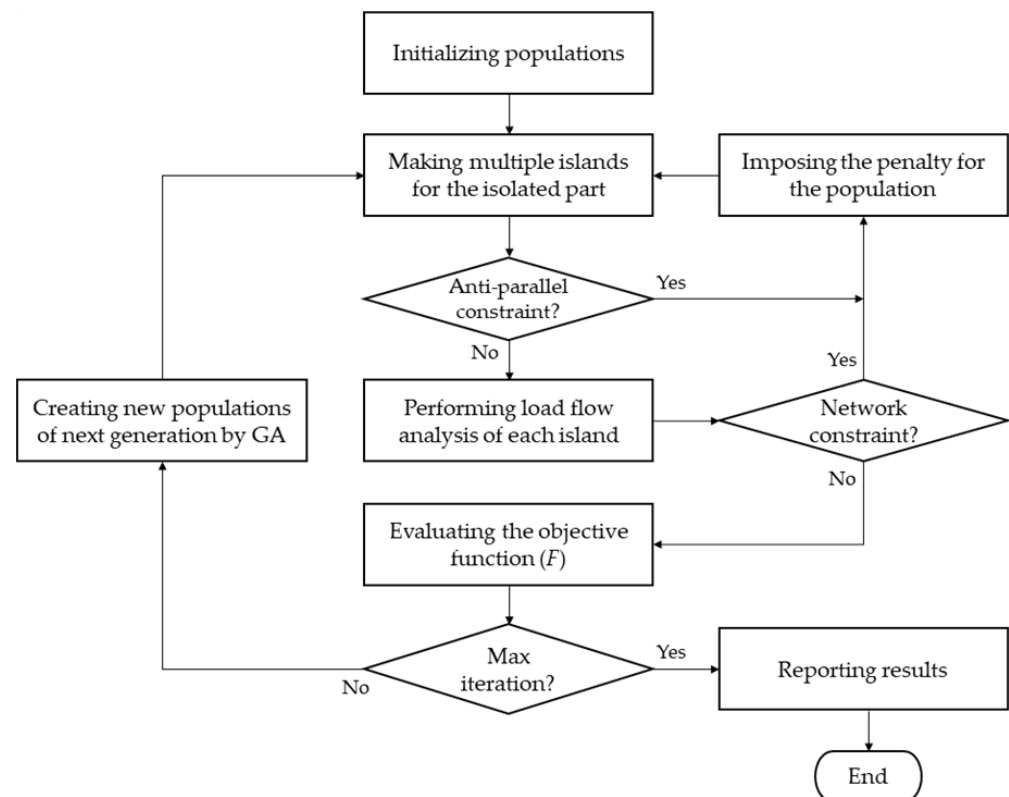


Figure 6. Flowchart of the proposed optimization-based SR algorithm.

The proposed SR algorithm can derive a near-optimal SR plan with the help of the optimization-based approach using a meta-heuristic algorithm so that the SR solution is regarded as a reliable one concerning optimality. Furthermore, it can significantly improve

the time required to derive an optimal SR plan as it takes advantage of the anti-parallel operation constraint that narrows down the search space thereby reducing the time to perform load flow analysis and evaluate all candidate topologies.

Figure 7 depicts the structure of the SR application using the proposed algorithm in the DAS environment. Three fundamental functions are implemented in the SR application: (1) binary-coded GA, (2) island partitioning scheme, and (3) load flow calculation module. When a fault occurs in a distribution system, the faulty section is identified by utilizing FI information transmitted from the field devices (e.g., FRTUs) through DNP 3.0 communication protocol, and the isolation of the fault section is conducted by opening upstream and downstream switches of the fault location. To restore outage loads and derive an optimal SR plan, the SR application executes the GA-based optimization function. The application generates a network topology and its tree structure by using the status of switching devices transmitted from FRTUs through the front-end processor (FEP). Then, the island partitioning function in the SR application is executed to make multiple islands through the tree search, and the load flow analysis is performed to check the network constraints. In the DAS environment, online load flow or state estimation applications are available to provide the SR application with network analysis results. To facilitate communication between relevant applications, middleware (e.g., memory database, message queue) can be used. Otherwise, network analysis functions such as load flow should be implemented in the SR application as illustrated in Figure 7.

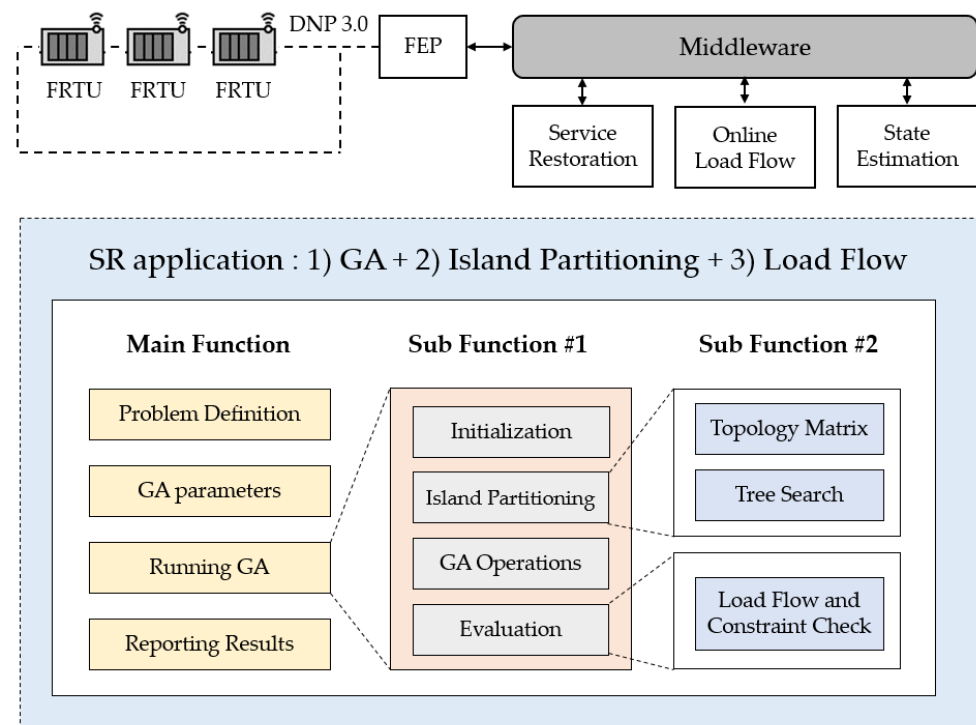


Figure 7. Structure of the SR application using the proposed algorithm in the DAS environment.

4. Case Studies

The modified IEEE 69-bus test system shown in Figure 8 with two tie lines is used to evaluate the performance of the proposed SR scheme. The test system is a 12.66 kW distribution system with a total load of 3.8 MW and 2.69 MVAR, and the details on the test system, such as the network configuration and line parameters, are provided in [31]. The data of DG used in the simulations are indicated in Table 2. Five DGs with a total capacity of 980 kW are installed so that five islands should be created to avoid the parallel operation of DGs, and all the DGs are modeled by constant active power and voltage (PV) type to enable an island can be operated with a reliable voltage source. The maximum iteration of

100 in the GA process is applied, and 100 populations are created for each iteration. The probabilities of crossover and mutation are set to 0.8 and 0.2, respectively. The lower and upper limits for bus voltages regarding the constraint shown in Equation (4) are chosen as a value of 0.95 p.u. and 1.05 p.u., respectively. MATLAB R2021b is utilized to implement the proposed SR scheme including data structure generation, GA processes, and load flow calculation, and the case studies are performed in an Intel Core i7-8700 K CPU@3.70 GHz PC.

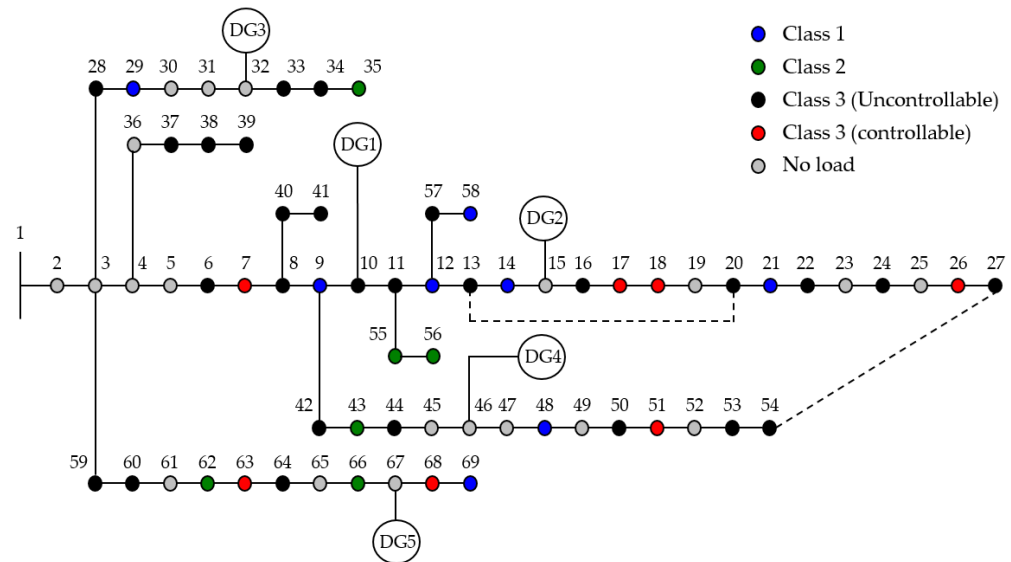


Figure 8. Modified IEEE 69-bus test system.

Table 2. Data of DGs in the test system.

DG No.	Bus Connected	Capacity [kW]	DG Type
1	10	240	PV
2	15	300	PV
3	32	70	PV
4	46	250	PV
5	67	120	PV

Tables 3 and 4 show the data of controllable loads and the importance of each load, respectively. Six controllable loads with the lowest importance coefficient are chosen to be disconnected for restoring more important loads thereby minimizing the objective function in Equation (1). All loads in the test system are grouped into three classes, and different coefficients (α_{C1} , α_{C2} , and α_{C3}) are imposed according to the importance of each load.

Table 3. Data of controllable load.

No.	Type	Location (@Bus)
1	Controllable	7, 17, 18, 26, 51, 63
2	Uncontrollable	others

Table 4. Group of loads according to load importance.

Load Class	Coefficient	Location (@Bus)
1	100	9, 12, 14, 21, 29, 48, 58, 69
2	10	35, 43, 55, 56, 62, 66
3	1	others

4.1. Case 1: A Fault on Bus 2–3

In case 1, a fault on the branch between bus 2 and bus 3 is considered. To isolate the fault from the main source, the switches on bus 2 and bus 3 are opened, resulting in severe outages on most of the loads in the system. Initial populations are randomly generated by the proposed algorithm except for a variable for the faulty branch, and the variable holds a value of '0' representing the open branch.

Table 5 shows the simulation result for case 1. The best SR plan derived by the proposed algorithm divides the isolated part of a distribution system into five islands. According to the anti-parallel constraint, each island has one DG as a power source for feeding the loads in the island. Since the total capacity of DGs is less than the total amount of loads in the outage area, islands are created to restore the maximum possible loads considering the importance of each load. As indicated in Table 5, loads of 850.19 kW that are 86.7% of the total capacity of DGs are restored by the intentional islanding scheme, and three controllable loads at buses 17, 18, and 63 are disconnected to restore more important loads.

Table 5. Simulation result for case 1.

Island No.	Bus	Restored Load [kW]			Load Shedding [kW]
		Class 1	Class 2	Class 3	
1	10 (DG), 11, 55, 56	0	36	173	0
2	12, 13, 14, 15 (DG), 17, 18, 19, 20, 21, 22	267	0	14.3	120 (@ bus 17, 18)
3	29, 30, 31, 32 (DG), 33, 34, 35	26	6	33.5	0
4	9, 42, 43, 44, 45, 46 (DG), 47, 48	130	26.4	28.35	0
5	62, 63, 64, 65, 66, 67 (DG), 68, 69	39.22	30	40.42	24 (@ bus 63)
Total			850.19		144

Figure 9 depicts the best cost of the objective function according to the iteration for case 1, and the best cost converges to a value of 6.6216 to minimize the objective function as the iteration of the GA-related process repeats. The graphical representation of the islanding partitioning result for case 1 is provided in Figure 10. As shown in the figure, most of the important loads, such as class 1 and 2 loads, are restored by the proposed algorithm although the class 1 load at bus 58 is still in the outage area due to the lack of capacity of DGs. Figure 11 illustrates the voltage profiles of each island created by the proposed algorithm for case 1. The maximum and minimum voltages are calculated as 1.010 p.u. corresponding to each DG bus and 0.963 p.u. at bus 12, respectively. The voltage magnitude of all the buses in the islands is within the allowable range, 0.95 p.u.–1.05 p.u., as the populations with voltages outside the acceptable range are eliminated due to the penalty value in the network constraint check. The algorithm takes about 8 s to derive the optimal solution, and it can be considered acceptable to provide a distribution network operator with service restoration solutions.

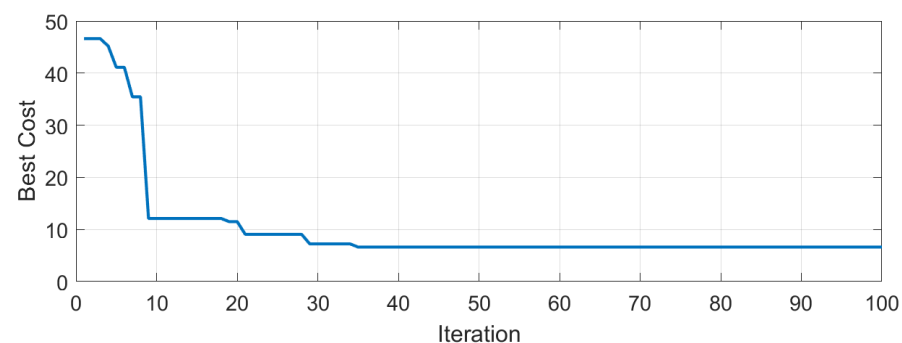


Figure 9. Best cost of the objective function according to the iteration for case 1.

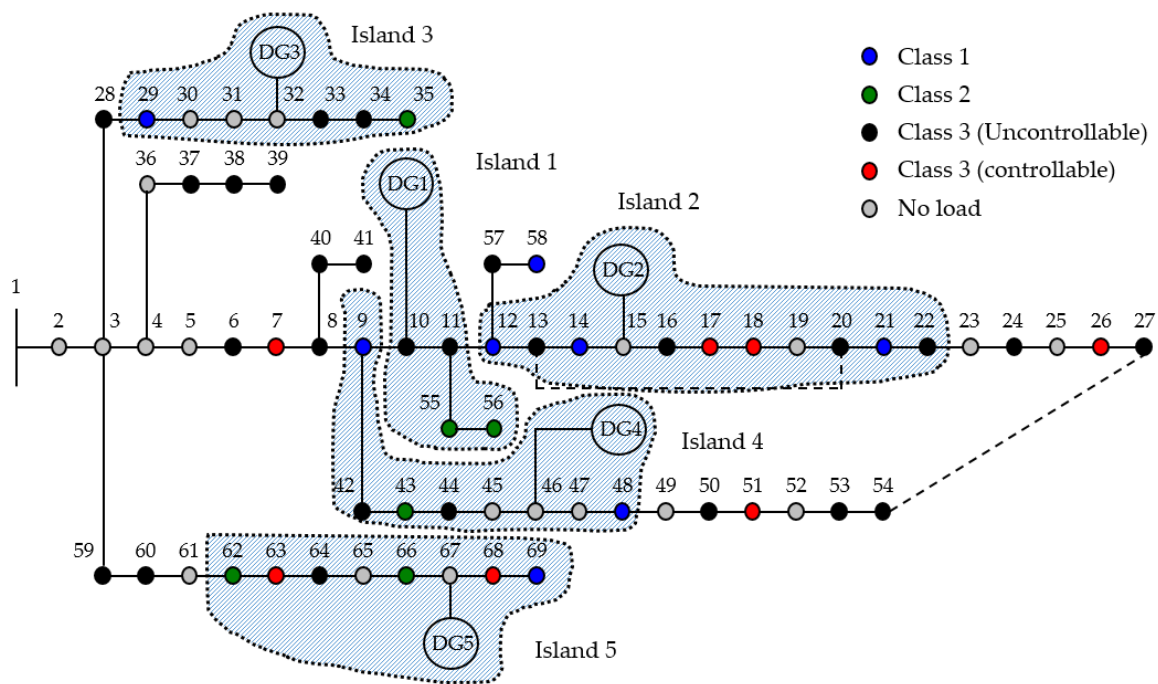


Figure 10. Island partitioning result for case 1.

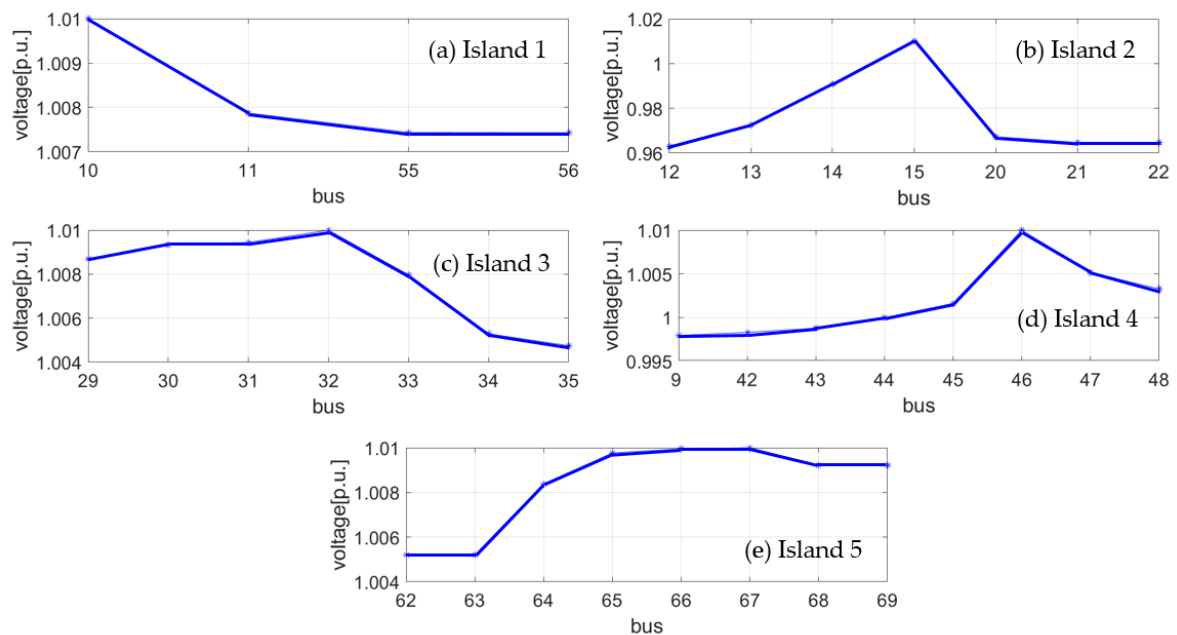


Figure 11. Voltage profiles of each island for case 1: (a) island 1; (b) island 2; (c) island 3; (d) island 4; (e) island 5.

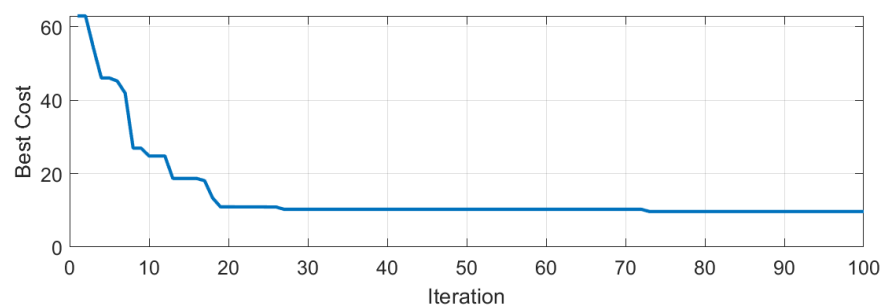
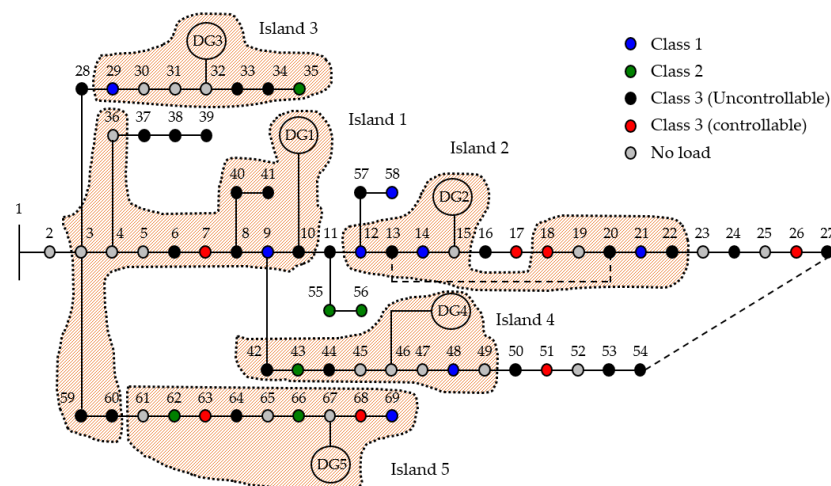
4.2. Case 2: Double Fault on Bus 2–3 and Bus 10–11

Two faults on buses 2–3 and buses 10–11 are assumed in case 2 to consider two branches out at the same time resulting in severe outages on most of the loads in the system. Table 6 indicates the simulation result for case 2, and loads of 842.89 kW, which are 86.0% of the total capacity of DGs are restored by the best SR plan. Three controllable loads at buses 7, 18, and 63 are disconnected to restore more important loads. It can be seen that the same amount of class 1 loads is restored by the SR algorithm compared to case 1 with the help of the self-sufficient capability of DGs in the distribution system despite more open branches.

Table 6. Simulation result for case 2.

Island No.	Bus	Restored Load [kW]			Load Shedding [kW]
		Class 1	Class 2	Class 3	
1	3, 4, 5, 6, 7, 8, 9, 10 (DG), 36, 40, 41, 59, 60	30	0	201.7	40.4 (@ bus 7)
2	12, 13, 14, 15 (DG), 18, 19, 20, 21, 22	267	0	14.3	60 (@ bus 18)
3	29, 30, 31, 32 (DG), 33, 34, 35	26	6	33.5	0
4	42, 43, 44, 45, 46 (DG), 47, 48, 49	100	26.4	28.35	0
5	61, 62, 63, 64, 65, 66, 67 (DG), 68, 69	39.22	30	40.42	24 (@ bus 63)
Total			842.89		124.4

Figure 12 depicts the best cost of the objective function according to the iteration for case 2. The best cost converges to a value of 10.2712, which is less than the value for case 1 since class 2 loads are not fully recovered although almost the same amount of loads are restored compared to case 1. Figure 13 depicts the graphical representation of the islanding partitioning result for case 2. Compared to the result of case 1, the class 2 loads (at buses 55 and 56) are not fully recovered by DG1 due to the open branch between buses 10 and 11. However, the class 3 loads at buses 6, 8, 40, 41, 59, and 60 are restored by DG1 instead of feeding the loads at buses 55 and 56. The voltage profiles of each island created by the proposed algorithm for case 2 are shown in Figure 14. The maximum and minimum voltages are calculated as 1.010 p.u. corresponding to each DG bus and 0.955 p.u. at bus 18, respectively. As in case 1, the voltage magnitude of all the buses in the islands for case 2 is within the allowable range implying that the derived SR plan does not violate the network constraint regarding bus voltage.

**Figure 12.** Best cost of the objective function according to the iteration for case 2.**Figure 13.** Voltage profiles of each island for case 2.

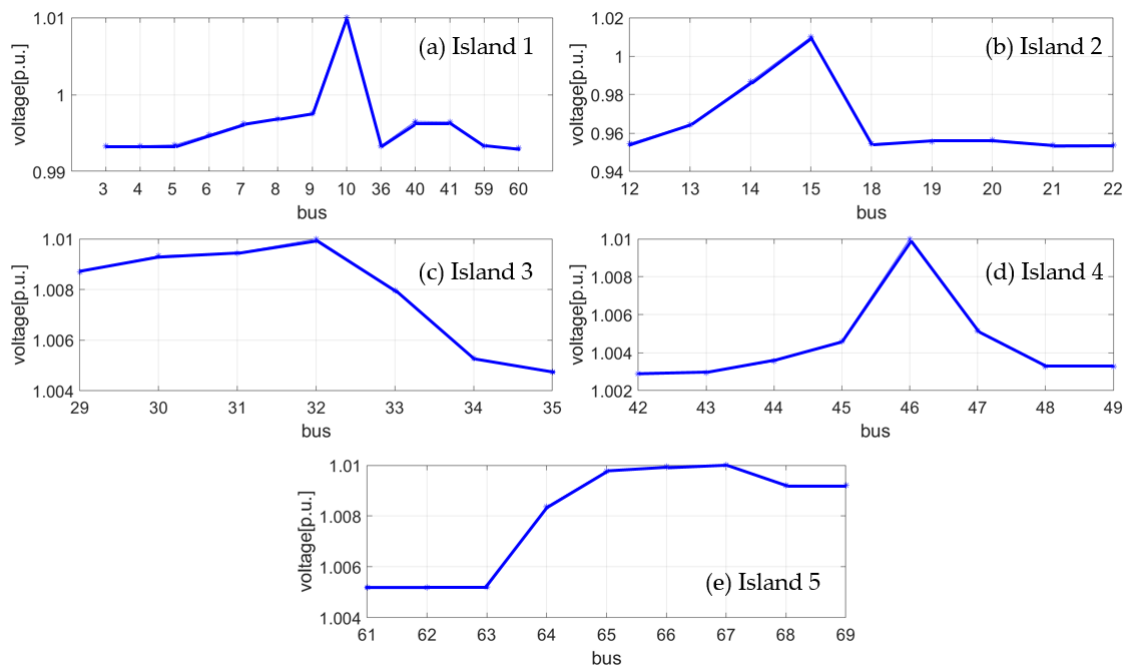


Figure 14. Voltage profiles of each island for case 2: (a) island 1; (b) island 2; (c) island 3; (d) island 4; (e) island 5.

It can be concluded from the simulation results that the proposed intentional islanding scheme for SR can derive a near-optimal solution to restore outage loads in a distribution system by utilizing an optimization-based approach using a meta-heuristic algorithm. Furthermore, simple control and operation are achieved since the derived SR plan guarantees the anti-parallel operation of DGs. In addition, the time required for obtaining the best SR plan can be significantly reduced by applying the anti-parallel operation constraint to the searching process.

5. Conclusions

This paper presents an optimization-based intentional islanding scheme for service restoration in distribution systems. Island partitioning is performed by network search, and load importance is considered to determine a solution that can restore more important loads in a distribution system. In addition, GA is utilized to explore possible SR solutions, and anti-parallel operation constraint is imposed to not only narrow down the search space but derive a solution for more efficient operation of a distribution system in emergencies. The proposed scheme can provide a near-optimal SR plan by utilizing a searching process of GA, and it is expected that simple control and operation can be achieved through the derived SR plan with the help of the anti-parallel operation of DGs. Furthermore, it can be regarded as feasible to be implemented since the SR application based on the proposed scheme can be applied to the DAS environment by employing conventional communication infrastructure and field devices that are already installed in distribution systems. Switching sequences for reaching the final system topology derived from the proposed scheme can be further researched as future work, and other objectives regarding the switching sequences should be considered.

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Abbreviations

Notation	Description
SR	Service Restoration
FRTU	Feeder Remote Terminal Unit
DAS	Distribution Automation System
DG	Distributed Generation
CB	Circuit Breaker
FI	Fault Indicator
OCR	Overcurrent Relay
OCGR	Overcurrent Ground Relay
SDG	Total DG capacity
SL	Total amount of loads
CL	Total amount of disconnectable loads
GA	Genetic Algorithm
FEP	Front-End Processor
α_{CX}	Load importance coefficient for load class X
PRE	Sum of loads restored in an island
P	Total load in a distribution system
P_{DG}	Active power capacity of DG
P_L	Active power capacity of load
N	Number of loads in an island
S_{max}	Branch capacity limit
V_{lower}	Lower limit of bus voltage
V_{upper}	Upper limit of bus voltage

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