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Directed graph-based distribution network reconfiguration for operation mode adjustment and service restoration considering distributed generation

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Abstract We present a directed graph-based method for distribution network reconfiguration considering distributed generation. Two reconfiguration situations are considered: operation mode adjustment with the objective of minimizing active power loss (situation I) and service restoration with the objective of maximizing loads restored (situation II). These two situations are modeled as a mixed integer quadratic programming problem and a mixed integer linear programming problem, respectively. The properties of the distribution network with distributed generation considered are reflected as the structure model and the constraints described by directed graph. More specifically, the concepts of "in-degree" and "out-degree" are presented to ensure the radial structure of the distribution network, and the concepts of "virtual node" and "virtual demand" are developed to ensure the connectivity of charged nodes in every independent power supply area. The validity and effectiveness of the proposed method are verified by test results of an IEEE 33-bus system and a 5-feeder system.

Keywords Distribution network, Distributed generation, Network reconfiguration, Directed graph, Operation mode adjustment, Service restoration

1 Introduction

Distributed generation (DG) is being increasingly deployed into the distribution network, enabling the network to be more flexible in addressing changing market conditions. DG is typically defined by small generators of less than 10 MW, which are commonly powered by renewable energy sources that are connected to transmission or distribution systems [1]. Installing DGs at optimal locations in the distribution network may yield many benefits to the electric utilities, including reduced active power loss, improved voltage profiles, enhanced electric service reliability and increased energy efficiency. Additional benefits include reduced peak power demand, distribution line overloading relief, reduced environmental impacts and deferred investment in existing power network upgrade projects. Distribution networks with DG have the capability of intended island operation and higher self-healing [2]. However, the installation of DG will affect the power flow distribution of the network, and reconfiguration can enable further reductions in power loss and further improvements in voltage profiles. There are two types of switches in the distribution network, namely sectionalizing switches (normally closed) and tie switches (normally open), the closed/open states of which can be altered under

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permissible circumstances to reconfigure the network topological structure to achieve particular objectives.

There are two main situations for distribution network reconfiguration, which are based on different purposes. Situation I is operation mode adjustment, where the network topology is optimized by altering the states of switches according to the loads, thus achieving particular aims such as active power loss minimization. DG typically operates in the grid-connect mode. Situation II is service restoration. When part of the distribution network suffers from power outage due to certain fault, power supply for the non-fault outage area should be restored by standby power sources as much as possible. If there is no standby power source or the capacity of the standby power source is inadequate and there are DGs in the non-fault outage area, then the area can be divided into islands to ensure restoration for important loads powered by DGs.

Network reconfiguration is a complex combinational optimization problem [3], and many approaches have been proposed for power loss minimization in the literature. Treating DGs as negative loads, Cui et al. [4] applied a genetic algorithm (GA) to address the network reconfiguration problem to achieve power loss minimization. The results showed that network reconfiguration with DGs reduces active power loss and improves the voltage profile over feeders. Dai et al. [5] reconfigured the distribution network based on a refined branch-exchange technique. This method can decrease the number of necessary switch combinations and quickly determine the distribution network topological structure to reduce active power loss. With regard to topology adjustment, this algorithm switches off the branch that has a current closest to the ideal transfer current and obtains a near-optimal solution relatively quickly. Rao et al. [6] proposed a new approach for reconfiguring and installing DGs simultaneously in the distribution network. A metaheuristic harmony search algorithm (HSA) was used to reconfigure and identify the optimal placement of DGs. The results showed that the simultaneous network reconfiguration and DG installation method is more effective in reducing power loss and improving the voltage profile. Numerous studies have considered network reconfiguration for service restoration. Li et al. [7] proposed a service restoration model for reconfiguration in which the minimization of both active power loss and the possible number of switch operations are considered simultaneously, and a new approach based on the tabu search was used to solve this model. Gholami et al. [8] proposed two heuristic methods to solve the service restoration problem considering load shedding based on two important indices and a graph-based method. Li et al. [9] formulated a heuristic algorithm for service restoration of the distribution network with DG to determine the closing order of tie switches by calculating the optimal cut point. The capacity of the standby power source can be well utilized, and the effects of uncertainty on loads and DG outputs on service restoration can be included.

Overall, current approaches for distribution network reconfiguration are divided into heuristic methods and intelligent algorithms. Heuristic methods are easy to implement and have high searching efficiency but generally cannot converge to the global optimal solution in a large-scale distribution network. Regarding intelligent algorithms, the global optimal solution can be achieved theoretically, but the disadvantage is that the actual results are greatly influenced by their parameter settings, which lack common criteria. A large value of the iteration number will increase the computational time, whereas a small value may not ensure an optimal solution. The majority of previous studies did not provide approaches to ensure the radial structure for the distribution network. Therefore, in this paper a structural model based on the directed graph and the concepts of “virtual node” and “virtual demand” are developed to solve the reconfiguration problem of the distribution network with DG for two different situations: operation mode adjustment and service restoration. The model is tested on an IEEE 33-bus system and a 5-feeder system, and the results verify its feasibility and effectiveness.

The rest of this paper is organized as follows. Section 2 establishes a structural model of the distribution network. Section 3 formulates the two reconfiguration problems and describes them as a mixed integer quadratic programming problem and a mixed integer linear programming problem, respectively. Section 4 presents the results from two test systems, and Section 5 presents the conclusions.

2 Structural model of the distribution network

This paper considers two reconfiguration situations, as listed below.

> Situation I: reconfiguration for operation mode adjustment.
>
> Situation II: reconfiguration for service restoration, in which electrical islands may be divided to ensure the power supplied for loads as much as possible.

To improve the power supply reliability of the distribution network and ensure the simplicity and efficiency of relay protection devices, the distribution network is typically designed in a meshed structure and operated in a radial structure [10]. Using the concept of “directed graph” in graph theory [11], this section proposes a structural model to guarantee the connectivity and radial structure of the distribution network or electrical islands.

2.1 Connectivity constraints

First, the tree model is applied to describe the structure of the distribution network. The buses are considered as branch nodes or leaf nodes. Power supply branches are considered as edges that connect branch nodes and leaf nodes. Buses with DG installed are considered as DG nodes and buses carrying only loads are considered as load nodes. As such, the distribution network can be depicted as a tree $T(V,E)$, with nodes representing buses and edges representing power supply branches. $V=\{v_0, v_1, \cdots, v_n\}$ is the set of nodes, and E is the set of edges.

In situation I, all load nodes should be charged. In situation II, when a particular failure occurs, power supply for outage areas may not be restored through a standby power source or tie switches. Under this circumstance, electrical islands are divided to restore as much power supply as possible by DGs. In both situations, the structure of the network or each electrical island should satisfy the radial structure and ensure the connectivity of charged nodes. This paper defines two concepts that can be implemented to ensure the connectivity of charged nodes and power source nodes (including substation nodes and DG nodes): “virtual node” and “virtual demand”. The virtual node, which is represented by v_0 in this paper, has the following properties:

1) The virtual node is different from all other nodes in the distribution network. In situation I, the virtual node is connected to all substation nodes, whereas in situation II, the virtual node is connected to all substation nodes and DG nodes. The virtual node can only be connected with power source nodes through the openable virtual branch e'_{ij}, which also has two directional edges.
2) It does not generate, consume or transmit electric power; specifically, the virtual branch connecting the virtual node to the power source node does not transfer electric power.

Note that in both situations, the virtual node is regarded as the root node in the structural model. Virtual branches that are connected by substation nodes are not allowed to be disconnected, whereas those connected by DG nodes are allowed to be disconnected.

The properties of the virtual demand are as follows:

1) Every charged node (including the power source node) has one unit of virtual demand.
2) The virtual demand is only provided by the virtual node.
3) The transmission path of the virtual demand is composed of power supply branches and virtual branches.

The introduction of “virtual node” and “virtual demand” only increases the virtual demand property of charged nodes. The virtual branch only transmits the virtual demand and does not change the tree structure or operational status of the network. In Fig. 1, the transmission path of the virtual demand is indicated by the blue flow lines.

Because a power supply branch is part of the path that transmits the virtual demand, all charged nodes are connected in every isolated power supply area to ensure the transmission path of the virtual demand. As the only node that provides the virtual demand, the virtual node is located in the same connected graph with the power supply areas and all charged nodes are connected to the virtual node, as shown in Fig. 2. Thus, the virtual node can be considered as the root node of the entire system. The power supply areas are considered as subtrees of the entire rooted tree.

2.2 Radial structure constraints

Relevant concepts of the directed graph are introduced here to describe the radial structure of the distribution network. The directed graph has two indices: in-degree and out-degree, represented by $\lambda^{\text{in}}(v_i)$ and $\lambda^{\text{out}}(v_i)$, respectively. As a special case of the directed graph, the rooted tree can describe the open-loop structure of the distribution network [12]. However, loops may occur in the network when tie switches come into use, which causes the in-degrees of some nodes to exceed 1. In this case, other branches must be disconnected to guarantee the radial operational structure.

This paper presents the following properties based on the concept of directed graph:

1) Every branch (including tie switch branches) has two directional edges: the forward and backward edges.

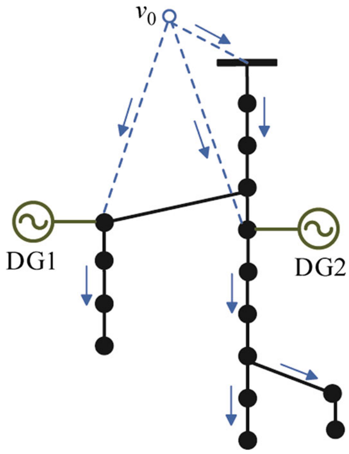

Fig. 1 Distribution network model with the virtual node and the virtual demand considered

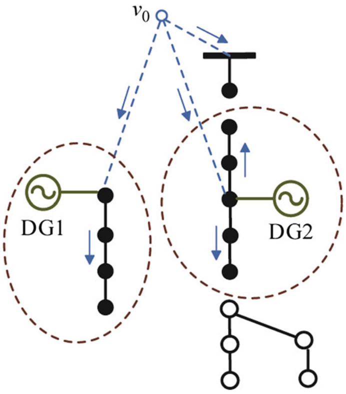

Fig. 2 Path of virtual demand in islanding mode

The edge direction that is from a smaller numbered node to another larger numbered node is defined as the forward edge, and the opposite applies for the backward edge. The binary variables s_{ij}^{d} and s_{ji}^{r} $(i<j)$ represent the selected states of the forward and backward edges, respectively, where 1 denotes selected and 0 denotes unselected. The binary variable $s_{ij}(i<j)$ represents the open or closed state of every branch, where 1 denotes closed and 0 denotes open. Only one directional edge of any branch can be selected at most to guarantee the radial structure of a connected graph:

$$s_{ij} = s_{ij}^{\mathrm{d}} + s_{ji}^{\mathrm{r}} \le 1 \tag{1}$$

2) The in-degree of the virtual node and charged nodes is 0 and 1, respectively. But as for uncharged nodes, the in-degree could be 0 or 1:

$$\lambda^{\mathrm{in}}(v_0) = 0 \tag{2}$$

$$x_i \le \lambda^{\mathrm{in}}(v_i) \le 1\ ,\quad i = 1, 2, \ldots, n \tag{3}$$

3 Problem formulation

This section establishes two respective models for the two network reconfiguration situations. Situation I represents operation mode adjustment, and situation II represents service restoration.

3.1 Model for operation mode adjustment

3.1.1 *Objective function*

The main purpose of network reconfiguration regarding operation mode adjustment is to minimize active power loss. The objective function can be formulated as follows:

$$\min \sum_{e_{ij}\in E} \frac{P_{ij}^2 + Q_{ij}^2}{U_j^2} r_{ij} \tag{4}$$

where P_{ij}, Q_{ij} are the active power and reactive power of branch e_{ij}, respectively; U_j the end node voltage of branch e_{ij}; r_{ij} the resistance of branch e_{ij}; and i, j the start and end node numbers of branch e_{ij}, respectively. In addition, U_j is assumed to be approximately 1 because the reactive power compensation in the real distribution network can typically hold the bus voltage nominally.

3.1.2 *Operational constraints*

Before and after reconfiguration, the distribution network must satisfy all of the operational constraints, which are formulated as follows:

1) Branch capacity constraints

$$-s_{ij}\overline{P}_{ij} \le P_{ij} \le s_{ij}\overline{P}_{ij} \tag{5}$$

$$-s_{ij}\overline{Q}_{ij} \le Q_{ij} \le s_{ij}\overline{Q}_{ij} \tag{6}$$

where $\overline{P}_{ij}$,$\overline{Q}_{ij}$ are the maximum permitted active and reactive power transmission capacity of branch e_{ij}, respectively; and the positive direction for P_{ij}, Q_{ij} from a smaller numbered node to another larger numbered node.

2) Power equilibrium constraints

The active power loss and reactive power loss caused by resistances and reactances are neglected to simplify the network reconfiguration model.

For the m^{th} substation node:

$$P_{\mathrm{G}m} - P_{\mathrm{L}m} = \sum_{j\in v_m} P_{mj} \tag{7}$$

$$Q_{\mathrm{G}m} - Q_{\mathrm{L}m} = \sum_{j\in v_m} Q_{mj} \tag{8}$$

where $m \in \Lambda$, Λ is the set of substation nodes; $j \in v_m$ represents all nodes connected to the m^{th} node; $P_{\mathrm{G}m}$, $Q_{\mathrm{G}m}$ the active and reactive power outputs of the m^{th} substation node, respectively; and $P_{\mathrm{L}m}$, $Q_{\mathrm{L}m}$ the active and reactive loads absorbed from the m^{th} node, respectively.

For the n^{th} DG node:

$$P_{\mathrm{DG}n} - P_{\mathrm{L}n} = \sum_{j\in v_n} P_{nj} \tag{9}$$

$$Q_{\mathrm{DG}n} - Q_{\mathrm{L}n} = \sum_{j\in v_n} Q_{nj} \tag{10}$$

where $n \in \Omega$, Ω is the set of DG nodes; and $P_{\mathrm{DG}n}$, $Q_{\mathrm{DG}n}$ the active and reactive power outputs of the n^{th} DG, respectively.

For other non-power source nodes:

$$-P_{\mathrm{L}i} = \sum_{j\in v_i} P_{ij}\ ,\quad i \neq m,n \tag{11}$$

$$-Q_{\mathrm{L}i} = \sum_{j\in v_i} Q_{ij}\ ,\quad i \neq m,n \tag{12}$$

3) DG output constraints

$$\underline{P}_{\mathrm{DG}n} \le P_{\mathrm{DG}n} \le \overline{P}_{\mathrm{DG}n} \tag{13}$$

$$\underline{Q}_{\mathrm{DG}n} \le Q_{\mathrm{DG}n} \le \overline{Q}_{\mathrm{DG}n} \tag{14}$$

where $\underline{P}_{\mathrm{DG}n}$, $\overline{P}_{\mathrm{DG}n}$ are the lower and upper bounds of the active power output of the n^{th} DG, respectively; and $\underline{Q}_{\mathrm{DG}n}$, $\overline{Q}_{\mathrm{DG}n}$ the lower and upper bounds of the reactive power output of the n^{th} DG, respectively.

4) Connectivity constraints

$$-f_{\mathrm{L}i} = \sum_{j\in v_i} f_{ij}\ ,\quad i \neq 0 \tag{15}$$

$$-s_{ij}N \le f_{ij} \le s_{ij}N \tag{16}$$

where $f_{\mathrm{L}i}$ is the virtual demand of the i^{th} node and $f_{\mathrm{L}i} = 1$; f_{ij} the virtual demand transmitted on branch e_{ij}; and N the total number of nodes in the distribution network.

5) Radial structure constraints

Except the virtual node, the in-degree of any other node is 1:

$$\sum_{i\in v_k} s_{ik}^{\mathrm{d}} + \sum_{j\in v_k} s_{jk}^{\mathrm{r}} = 1\ ,\quad k \neq 0 \tag{17}$$

The in-degree of the root node is 0 and the out-degree is equal or greater than 1:

$$\sum_{j\in v_0} s_{j0}^{\mathrm{r}} = 0 \tag{18}$$

$$\sum_{j\in v_0} s_{0j}^{\mathrm{d}} \ge 1 \tag{19}$$

The state of every branch should be equal or less than 1:

$$s_{ij} = s_{ij}^{\mathrm{d}} + s_{ji}^{\mathrm{r}} \le 1 \tag{20}$$

In general, (4)–(20) constitute the network reconfiguration model for operation mode adjustment, which is a mixed integer quadratic programming (MIQP) problem.

As noted above, this network reconfiguration model is simplified, and the optimal solution for this model can be obtained. However, the solution of the objective function obtained is an approximate solution because the active power loss and reactive power loss caused by resistances and reactances are neglected. For a practical system, the proposed method is likely to provide the global optimal solution or a near-optimal solution, which can be treated as the initial solution for other reconfiguration methods.

3.2 Model for service restoration

In this situation, assume that there may be nodes that lose power after reconfiguration. Thus, a binary variable x_i is introduced to represent the charge state of the i^{th} node. 1 denotes charged, whereas 0 denotes uncharged.

3.2.1 *Objective function*

Regarding network reconfiguration for service restoration, the objective is to maximize the total loads restored.

$$\max \sum_{i\in V} P_{\mathrm{L}i} \tag{21}$$

3.2.2 *Operational constraints*

1) Power equilibrium constraints

$$-s_{ij}\overline{P}_{ij} \le P_{ij} \le s_{ij}\overline{P}_{ij} \tag{22}$$

$$P_{\mathrm{G}m} - P_{\mathrm{L}m} = \sum_{j\in v_m} P_{mj} \tag{23}$$

$$P_{\mathrm{DG}n} - P_{\mathrm{L}n} = \sum_{j\in v_n} P_{nj} \tag{24}$$

$$P_{\mathrm{L}i} = x_i \bar{P}_{\mathrm{L}i} \tag{25}$$

$$x_n \underline{P}_{\mathrm{DG}n} \le P_{\mathrm{DG}n} \le x_n \overline{P}_{\mathrm{DG}n} \tag{26}$$

In (25), $\bar{P}_{\mathrm{L}i}$ is the active load of the i^{th} node. Considering that wind generation and photovoltaic generation without electrical energy storage cannot provide steady power because they are incapable of regulating the frequency, they are unable to power the island individually and should operate synergistically with the DGs that are capable of regulating the frequency [13]. Thus, virtual branches between the virtual node and the DG nodes that are incapable of regulating the frequency should be removed.

2) Connectivity constraints

Apart from (15) and (16), (27) is added to describe the relationship between virtual demand and charge state of the i^{th} node.

$$f_{\mathrm{L}i} = x_i \times 1\ ,\quad i \neq 0 \tag{27}$$

3) Radial structure constraints

Equations are similar to (17)–(20). Note that since there may be uncharged nodes after dividing electrical islands, (17) should be modified as:

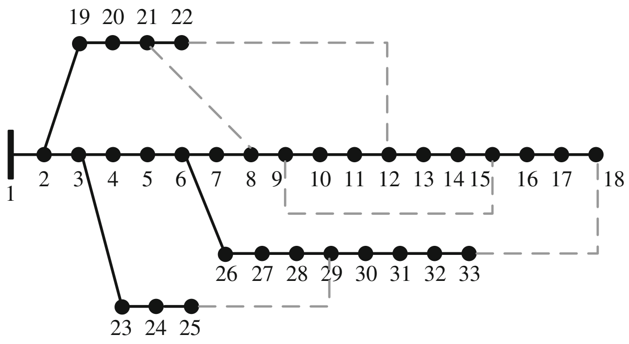

Fig. 3 IEEE 33-bus system

$$x_k \leq \sum_{i \in v_k} s_{ik}^{\mathrm{d}} + \sum_{j \in v_k} s_{jk}^{\mathrm{r}} \leq 1, \quad k \neq 0 \tag{28}$$

4) Node status consistency constraints

$$s_{ij} - 1 \leq x_i - x_j \leq 1 - s_{ij} \tag{29}$$

which shows the relevance between branch status and charge status of the two nodes connected by the branch.

In summary, (15), (16), (18)–(29) constitute the network reconfiguration model for service restoration, which is a mixed integer linear programming (MILP) problem.

4 Case studies

In this paper, models are established on the AMPL platform [14] and solved using CPLEX. To demonstrate the effectiveness and superiority of the proposed method, it is applied to two systems: an IEEE 33-bus system and a 5-feeder system. Network reconfiguration for operation mode adjustment is tested in the IEEE 33-bus system (case 1), and network reconfiguration for service restoration is tested in the 5-feeder system (case 2).

4.1 Case 1: IEEE 33-bus system reconfiguration for operation mode adjustment

This test system is a radial distribution system with thirty-two sectionalizing switches and five tie switches, as shown in Fig. 3. The system is a three-phase 12.66 kV system, and the line and load data are obtained from [15]. The total active and reactive power loads of the system are 3715 kW and 2300 kvar, respectively. For the initial network, the total active power loss is 202.68 kW and the minimum voltage is 0.9131 p.u.

Consider two reconfiguration scenarios:

Scenario 1: Without DG in the network.
Scenario 2: Four DGs are installed at nodes 4, 7, 25 and 30, with capacities of 50, 100, 200 and 100 kW, respectively, and power factors of 0.8, 0.9, 0.9 and 1.0, respectively [16].

The test results of the proposed method are shown in Table 1. After reconfiguration, for scenario 1, the total active power loss is reduced to 139.55 kW and the minimum voltage rises to 0.9378 p.u. For scenario 2, the total active power loss is reduced to 112.19 kW and the minimum voltage rises to 0.9465 p.u. Compared with the results in [15] and [17], the proposed method is more effective in reducing power loss and increasing the minimum voltage, thereby demonstrating the superiority of the proposed method over the other methods.

The voltage profile curves of the above scenarios for the IEEE 33-bus system are shown in Fig. 4.

Fig. 4 shows that the voltage profile is improved after network reconfiguration.

4.2 Case 2: 5-feeder system reconfiguration for service restoration

The system is shown in Fig. 5. DG1 is a photovoltaic power generation system with electrical energy storage.

Table 1 Comparison of simulation results for the IEEE 33-bus system

	Base case	[15]	[17]	Scenario 1	Scenario 2
Open switches	8–21	8–21	8–21	7–8	7–8
	9–15	9–15	9–10	9–10	9–10
	12–22	11–12	9–15	14–15	14–15
	18–33	28–29	28–29	25–29	18–33
	25–29	31–32	18–33	32–33	28–29
Power loss (kW)	202.68	146.83	141.60	139.55	112.19
Loss reduction (%)	–	27.55	30.14	31.15	44.65
Minimum voltage (p.u.)	0.9131	0.9233	0.9310	0.9378	0.9465

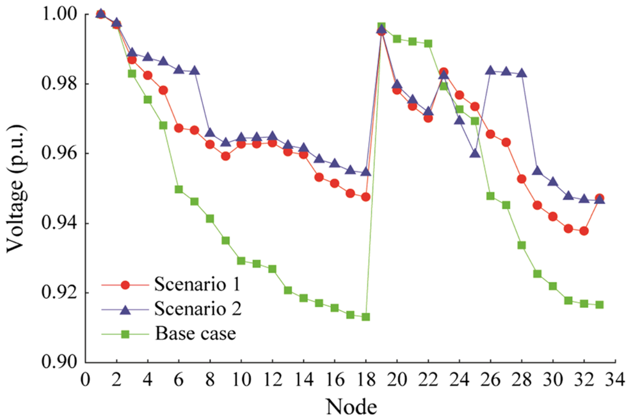

Fig. 4 Voltage profile curves of different reconfiguration scenarios for the IEEE 33-bus system

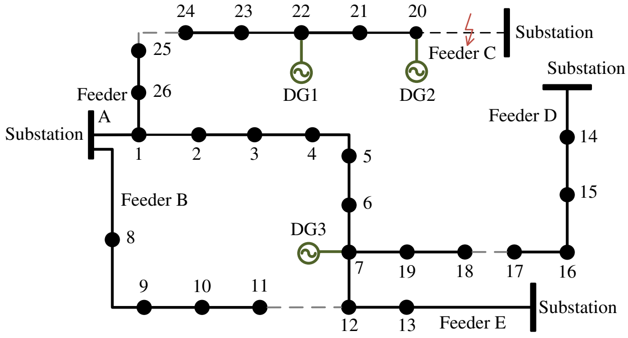

Fig. 5 5-feeder system

DG2 is a micro-turbine. DG3 is a wind power generation system without electrical energy storage, and thus it cannot supply power for the island individually. The rated capacities of DG1, DG2 and DG3 are 200, 600 and 200 kW, respectively, and the rated transmission capacity of each line is 2000 kW. Initially, the open switches are 5–6, 11–12, 17–18 and 24–25. Refer to [18] for specific parameters of the system.

Assume that a fault occurs at the export of feeder C such that loads powered by feeder C suffer from power outage. The network is reconfigured through the proposed model to restore power supply.

As shown in Fig. 6, open switches are 1–2, 11–12, 17–18, 20–21 and 22–23 after reconfiguration. In this situation, the active loads of feeders A, B, D and E are 1748, 359, 1457 and 1905 kW, respectively. If feeder A supplies power for node 22, which has an active load of 574 kW, then the active load of feeder A will increase to 2322 kW, which exceeds its rated transmission capacity. If DG1 and feeder A supply power for node 22 simultaneously, then the active load of feeder A is 2122 kW, which exceeds its capacity. Thus, switch 22–23 should be disconnected. The active loads of nodes 20, 21 and 22 are 419, 492 and 574 kW, respectively. Because DG1 can only provide an active power output of 200 kW and DG2 can only ensure the power demand of node 20, to meet the power equilibrium constraints, DG2 and node 20 constitute an island, switch 20–21 is disconnected and DG1 is out of service. Thus, nodes 21 and 22 are powered off. The CPU time to solve this case is approximately 0.056 s, which can meet the requirements of practical engineering.

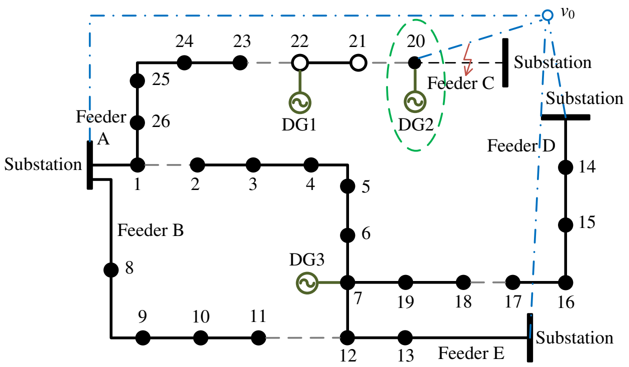

Fig. 6 Network reconfiguration result with island division

5 Conclusions

This paper studies reconfiguration of the distribution network with DG in two situations with different purposes. One situation is for operation mode adjustment and the other is for service restoration. A structural model based on the directed graph is developed to describe the radial operational structure of the distribution network. In this method, the connectivity of charged nodes in every electrical island is ensured through the "virtual node" and the "virtual demand". Models are established for these two situations, described as MIQP and MILP, respectively, and are solved using CPLEX on the AMPL platform. Test results of these two cases verify the effectiveness and superiority of the proposed two models.

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