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A Distribution Network Reconfiguration and Islanding Strategy

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A DISTRIBUTION NETWORK RECONFIGURATION AND ISLANDING STRATEGY

by

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ABSTRACT

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Under the Supervision of Dr. Lingfeng Wang

With the development of Smart Grid, the reliability and stability of the power system are significantly improved. However, a large-scale outage still possibly occurs when the power system is exposed to extreme conditions. Power system blackstart, the restoration after a complete or partial outage is a key issue needed to be studied for the safety of power system. Network reconfiguration is one of the most important steps when crews try to rapidly restore the network. Therefore, planning an optimal network reconfiguration scheme with the most efficient restoration target at the primary stage of system restoration is necessary and it also builds the foundation to the following restoration process. Besides, the utilization of distributed generators (DGs) has risen sharply in the power system and it plays a critical role in the future Smart Grid to modernize the power grid. The emerging Smart Grid technology, which enables self-sufficient power systems with DGs, provides further opportunities to enhance self-healing capability. The introduction of DGs makes a quick and efficient restoration of power system possible.

In this thesis, based on the topological characteristics of scale-free networks and the Discrete Particle Swarm Optimization (DPSO) algorithm, a network reconfiguration scheme is proposed. A power system structure can be converted into a system consisting of nodes and edges. Indices that reflect the nodes' and edges' topological characteristics in Graph Theory can be utilized to describe the importance of loads and transmission lines in the power system. Therefore, indices like node importance degree, line betweenness centrality and clustering coefficient are introduced to weigh the importance of loads and transmission lines. Based on these indices, an objective function which aims to restore as many important loads and transmission lines as possible and also subjected to constraints is formulated. The effectiveness of potential reconfiguration scheme is verified by Depth First Search (DFS) algorithm. Finally, DPSO algorithm is employed to obtain the optimal reconfiguration scheme. The comprehensive reconfiguration scheme proposed by my thesis can be the theoretical basis for the power grid dispatchers.

Besides, DGs are introduced in this thesis to enhance the restoration efficiency and success rate at the primary stage of network restoration. Firstly, the selection and classification principle of DGs are introduced in my thesis. In addition, the start sequence principle of DGs is presented as a foundation for the following stability analysis of network restoration with DGs. Then, the objective function subjected to constraints that aims to restore as many important loads as possible is formulated. Based on the restoration objective, islands that include part of important and restorable loads are formed because the DGs' capacity cannot ensure an entire restoration of the outage areas. Finally, DPSO is used to obtain the optimal solution of islanding strategy and the state sequence matrix is utilized to represent the solution space.

It is believed that this work will provide some useful insight into improving the power system resiliency in the face of extreme events such as natural or man-made disasters.

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Chapter 1 Introduction

1.1 Research Background

With the development of the power grid, configuration of the power system becomes more and more complicated. Furthermore, the large-scale application of long distance power transmission, increasing of impact load and natural disasters pose a huge challenge to the stability and security of the power system. Contemporary society's development relies on the continuity of power supply and the requirement for a stable and reliable power supply is becoming intensive. Although the stability of power system operation has hugely improved, it is still hard to avoid widespread blackouts when the power system suffers severe faults. Since the 1960s, several extensive blackout incidents have occurred worldwide, including the well-known 8.14 blackout of 2003 in parts of U.S. and Canada which involved the whole eastern power grid of North America. Over 20 power stations sunk into a 29-hour outage [1]. In the same year, a blackout accident in Moscow contributed to a large-scale outage in Southwest of Russia which leads to a complete power loss of public facilities [2]. In 2005, a whole island blackout occurred in Hainan that resulted in a splitting of all power stations and a complete power loss happened after 4 minutes [3]. All these power system accidents reminded people about the importance of a safe and reliable power system. Lots of reasons may lead to a widespread blackout and most blackout accidents cannot be predicted. So it is significant to propose a reasonable plan for power system restoration and effective measures must be taken to restore the power system as soon as possible.

1.1.1 **Power system blackstart processes**

1. Preparation stage

1) The dispatcher should confirm that power system has totally blacked out. When a blackout happens, the dispatcher must locate the fault point and isolate it. Based on feedback information, the dispatcher must estimate accurately if the power system has a widespread outage and confirm the relative outage area. After that, the power system enters a preparation stage. The criteria for estimating if the power system is in a widespread outage stage and confirming the system has totally blacked out is shown in table 1-1:

Executive Department	Starting Condition
Blackstart power station	Power station output falls to zero or all operation units are split
Dispatching station	(1) Total power of system decreases rapidly (2) Switch trip (3) Power flow of transmission lines decrease to zero (4) Loss of bus voltage (5) Abnormal decrease of system frequency
Transformer substation	(1) Power flow of transmission lines decrease to zero (2) Loss of bus voltage

Table 1- 1 Criteria of entire outage

2) Initial operation

After confirming the blackout scale, the dispatcher should operate based on a pre-defined scheme. A general scheme is that after a total blackout, the dispatcher keeps the asynchronous breaker closed, splits all blackstart units and opens line switches of substations. For a faster restoration and more simplified network configuration, power switches of no-voltage power stations are recommended to be opened. Breakers are retained on bus for a possible power restoration.

3) The crews start the backup power of power plants in order to guarantee the safety of main engines, communication devices and monitoring devices.

2. Selection of blackstart sources

Blackstart sources are the key to power grid blackstart. To restore power supply as soon as possible, it is recommended to find at least one generator with blackstart capability as the start generator in each outage area. After blackstart generators are started successfully in outage areas, power units with larger capacities are restored gradually and the regional power grid can be sectionally restored.

Power units like hydro turbine generators (especially pumped storage generator) and gas turbines are good choices for being blackstart sources. Power of pumped storage units can be transferred to electric energy rapidly. After a widespread blackout, the dispatcher can utilize small hydroelectric, gas turbine or power stations in island operation to restore important loads in system progressively.

3. Regional restoration

According to the proposed outage areas partition scheme, each area is restored step by step. The partition of outage areas avoids overlength, over-loading of transmission lines and system shock. In general, a outage area is sectionalized based on the following principles: (1) At least one blackstart generator should be contained in a subsystem; (2) Important loads should be included in a subsystem; (3) Generators output should fulfill the power demand of loads and

(4) The scale of each subsystem should be proper. When subsystems are restored completely, crews should check voltage difference of the synchronization point. If it meets the standard of synchronization, subsystems can be paralleled.

4. Selection of restoration paths

In a restoration scheme, the power system to be restored is converted into a radial structure in which the blackstart sources are selected to be head nodes. This way simplifies the grid structure and is convenient for crews to operate. Loads like hospitals, schools and government departments have a higher priority when considering the restoration scheme. In addition, all loads selected in the restoration scheme should balance the output of the power stations.

Selection of restoration paths are involved in the three stages (generators blackstart, network reconfiguration and loads restoration) of blackstart. Each stage has different objective when the dispatcher selects restoration paths. In the first stage, the general objective is to find a quick and safe way to start important blackstart power units. In the second stage, the general objective is to restore all power units and part of important loads. In the final stage, based on second stage's network configuration, all loads are restored in sequence as soon as possible.

1.1.2 **Development of distributed generators (DGs) in power system blackstart**

Distributed generators are generators with a small capacity (between 10KW and 50MW) and installed near the consumer or load center. Different from conventional power supply mode, distributed generators are paralleled in power grid by the inverter and they have advantages like high reliability, high efficiency and low pollution, etc. [3]. Now commonly used distributed generators are microturbine, photovoltaic, wind power, fuel cell, mini hydroelectric, biomass power generation, etc.

Distributed generators can be the supplementary power for centralized power generation and have a huge market potential. Distributed generation plays an important role in fields like energy conservation, environment protection, power security and renewable energy utilization, etc. A rational allocation of capacity and position can enhance the power utilization ratio and power system reliability.

Compared to conventional centralized long-distance power transmission, DGs have following the advantages:

1. Environmentally friendly

Some DGs utilize solar energy, wind power or natural gas as energy sources, which can reduce discharge of toxic substance.

2. Low cost and abundant economic benefit

Compared to long-distance transmission, DGs are close to load center and have no need to build costly transmission lines and power distribution stations, which can reduce distribution loss and cost. In addition, DGs have an abundant economic benefit because of low investment cost and economic space occupation

3. High reliability of power supply

Most DGs employ medium or small size power units and have advantages like easy operation and isolated power sources, etc. Because DGs are isolated, this will not lead to a large-scale outage and makes it easy to blackstart after outage.

4. Excellent load adjustment capacity

During the load peak of summer and winter, the Combined Cooling, Heating and Power (CCHP) system can fulfill the demand of cooling and heating and supply partial power to the power grid at the same time. As a result, it adjusts loads and eases the burden of power supply.

Distributed sources can be classified into different categories by energy mode, output mode, synchronization mode, capacity, etc. Table 1-2 shows DGs classified by power property. DGs are classified into three levels by capacity.

Power Sources	Primary Energy	Output	Interface	Capacity
Photovoltaic	Solar Energy	DC	Inverter	Small or Medium Size
Wind Power	Wind Energy	DC	Inverter	Small, Medium or Large Size
Hydroelectric	Hydro Energy	AC	Direct Connection	Small or Medium Size
Microturbine	Fossil Fuel	AC	Direct Connection	Small Size
Fuel Cell	Fossil Fuel	DC	Inverter	Small, Medium or Large Size
Geothermal-Power	Geotherm	AC	Direct Connection	Medium or Large Size
CapacitorStorage	Grid or DGs	DC	Inverter	Small or Medium Size
Accumulator Storage-	Grid or DGs	DC	Inverter	Small, Medium or Large Size
Biomass	Chemical Energy	AC	Direct Connection	Small, Medium or Large Size

Table 1- 2 DGs classification

1.1.3 **Island Operation with DGs**

Distribution network with DGs has two operation modes: parallel operation and island operation. Generally, distribution network is at parallel operation mode and its power supplied by main grid and DGs. Breakers or disconnectors trip when main grid has faults or maintenance and DGs in distribution network will supply power to loads in island operation mode. If the power generated by DGs is much less than loads demand and even load shedding is useless, the island operation will break down soon. On the contrary, island operation will maintain stable if splitting point is pre-defined based on safe operation requirements. Figure 1-1 illustrates different scales of islands are formed because of different trip positions.

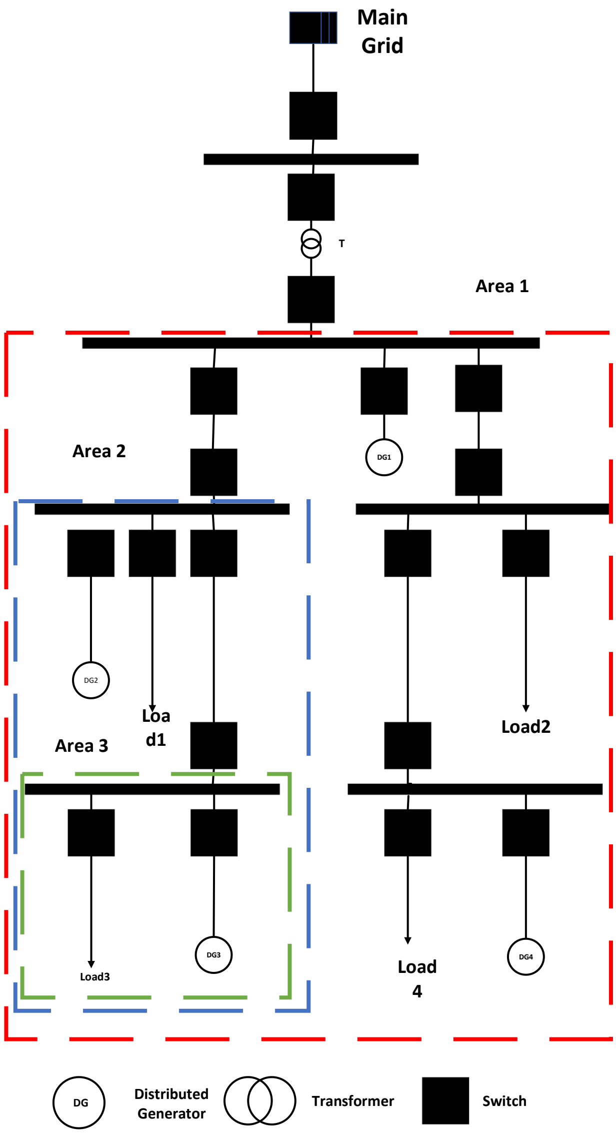

Figure 1-1 Islands with different scale

1.1.4 **Intentional islanding and the utilization of island operation**

The utilization of DGs becomes more and more popular in distribution network. A new IEEE Std.1547-2003 [4] regulation is proposed to allow the existence of intentional island. This regulation encourages network and consumer to realize an islanding operation by technology and reaches a consensus in the aspect of economy.

Intentional islanding is to separate system into several reasonable sections based on a safe operation standard and an effective control strategy. Local loads and generating capacity of DGs are taken into consideration as well. After splitting from the main grid, islands can have a smooth transition to a new stable operation state and maintain a sustaining power supply to loads in islands [5].

A rational utilization of intentional islanding is an effective method to deal with fault in distribution network with DGs. The dispatcher can make the best of DGs' generating capacity to fulfill the power demand of loads, especially important loads, in distribution network. In this way, the loss of power outage can be reduced

At present, a representative intentional islanding practical application is the "Manitoba Hydropower System Intentional Islanding Plan" in Canada. In this plan, the North and South of Canada are connected by one link line and when a critical fault occurred in the South, the relaying on link line will have an action. In this way, the North comes into an intentional islanding operation and avoids a potential outage [6].

1.2 The application of intelligent algorithm in power system blackstart

1. Intelligent optimization algorithm

Intelligent optimization algorithms like Genetic algorithm, Simulated Annealing algorithm, Tabu Search algorithm, Ant Colony Optimization algorithm, and Particle Swarm optimization algorithm are comprehensively applied in power system restoration scheme. These algorithms have features like strong versatility, good optimal performance and can be parallel computed. In references [7] and [8], the author utilized Genetic algorithm and Particle Swarm Optimization algorithm to solve the loads' dynamic restoration problem and restored a maximum of loads. In reference [9], the author exploited Greedy algorithm to restore as many important loads as possible and proposed an optimal loads restoration sequence scheme. In reference [10], the author employed Greedy algorithm, Modified Genetic algorithm, Particle Swarm Optimization and Simulated Annealing algorithm to solve the optimal loads restoration problem at the ultimate stage of blackstart. In reference [11], the author combined Shortest Path algorithm with Genetic algorithm and found the optimal loads restoration combination. In reference [12]，the author employed Tabu Search algorithm to sectionalize the restoration system which led to a decrease of restoration time and outage cost.

2. Graph-theoretical algorithm

Graph-theoretical algorithm is widely used to solve practical problems. Because of the radial network configuration of the objective system, lots of path searching algorithms can be used. Popular algorithms like Depth First Search algorithm, Breadth First Search algorithm and Heuristic Search algorithm are widely employed. In reference [13], the author proposed a reasonable blackstart scheme and utilized Depth First Search algorithm to search the restoration paths in power system. Based on the algorithm, the author got a series of valid blackstart schemes for screening. In reference [14], the author made use of Shortest Path algorithm to formulate a restoration path scheme that had a good fulfillment of constraints in the third stage of blackstart process and realized a rapid restoration of important loads.

1.3 Main targets of power system blackstart

1. Optimal Network restoration configuration

A rational network reconfiguration strategy is to establish a high efficient target restoration network based on the topological characteristics of network and intelligent algorithms. In references [15] and [16], the author proposed a reconfiguration scheme which combined the restoration of serial systems and parallel systems. At the beginning of system restoration, the author utilized the Shortest Path algorithm to restore units serially and then utilized Minimal Spanning Tree Search to make each subsystem operate parallelly. In reference [17], the author restored all transmission lines and loads at first and disconnected them successively back to the original state to get an optimal transmission lines restoration sequence scheme. In reference [18], a comprehensive study on network reconfiguration scheme and loads restoration sequence were taken into consideration. Shortest Path algorithm and Cross Particle algorithm were utilized to decide the optimal restoration path scheme. A fast restoration of non-blackstart generators and important loads were realized.

2. Optimal units starting sequence

Optimal units starting sequence after a large-scale outage is a comprehensive optimization problem. Generally, the objective is to generate the maximum power or restore the maximum loads, etc. The starting sequence is rationally arranged based on units' starting and operating characteristic. In reference [19], several effective blackstart regulations were proposed and a simplified starting sequence scheme was obtained by employing Depth-First Search algorithm and Backtracking algorithm. In reference [20], an integer linear programming algorithm was employed to solve the units starting sequence problem. In reference [21], the largest weighted sum of generated energy in a period was treated as the objective of optimal starting sequence problem and Shortest Path search combined with Backtracking algorithm was utilized to obtain the reasonable blackstart scheme.

3. Optimal loads restoration

A quick and comprehensive restoration of loads after blackout was the ultimate objective. In reference [22], Genetic Simulated Annealing algorithm was utilized to formulate a loads restoration scheme and a high efficiency power flow calculation algorithm was introduced to compute the system's frequency. Penalty function was used to deal with constraints when computing fitness value. Consequently, the maximum loads restoration scheme was obtained.

1.4 Research Objective and Thesis Layout

In this thesis, two main distribution network restoration strategies are proposed. Firstly, a network reconfiguration strategy based on topological characteristics of power system will be proposed. By combining indices, a network reconfiguration strategy which aims to restore as many important loads and transmission lines as possible are investigated. Secondly, DGs are introduced in distribution network to solve the restoration problem. DGs have the advantages like flexibility and high reliability. They can enhance the self-healing ability of network greatly. Therefore, an islanding strategy considering the DGs' capacity and loads' importance will be proposed.

In chapter two, a network reconfiguration strategy based on topological characteristics will be investigated and the objective function aiming to contain as many important loads and significant transmission lines will be proposed. In chapter three, an islanding strategy considering both the loads' importance and the capacity of DGs will be formulated. Case studies will be done in chapter four. Finally, the conclusions will be presented in chapter five.

Chapter 2 Network Reconfiguration Strategy Based on Topological Characteristics

2.1 Introduction

Blackstart is defined as the process that a system suffers from a complete blackout and restarts by reconstructing its networks and restoring its service depending on its self-starting units without help from other systems [23]. Because of the intensive demand for stable and reliable power supply, a long-time and large-scale outage cannot be accepted in modern power system. As an extreme and urgent situation for power system, the blackstart is a complex decision-making and control problem for operators. Among methods proposed so far for developing start schemes, the operation cost such as, operation or switching time, is preferred to be chosen as the optimization objectives while maintaining a certain level of security [24]. However, most of methods proposed neglect the important diversity of different compositions like loads, generators and transmission lines in system and solve the optimal problem without a difference analysis which will lead to an inaccuracy of restoration scheme. Taking loads in system as an example, loads like hospitals, government buildings and schools are loads we called first-level loads and loads like these are institutions which cannot be blacked out or it will attribute to a huge loss to country and society. These loads should have the highest priority and need to be restored as soon as possible when developing a restoration proposal. So it is necessary to take important diversity into consideration.

A complicated power system can be translated into a scale-free skeleton network based on its topological characteristics and little work has been done to investigate the restoration process from the network topological structure point of view. When a complex power system is translated into a scale-free skeleton network, a multiple of topological characteristics of graph theory can be implemented to weigh the importance of elements like loads, generators and transmission lines. A rational restoration scheme based on network topological characteristics can locate importance loads and relieve restore burden so that it paves the way for the following restoration steps.

In this chapter based on topological characteristics of scale-free networks, a network reconfiguration strategy is proposed. First, the actual power system network is converted into a scale-free skeleton network. Then, the importance of loads, generators and transmission lines are ranked quantitatively by computing node importance degrees. After that a restoration efficiency index subjected to network structure and lines capacity is proposed as the optimization objectives. Furthermore, an intelligent optimization algorithm called Discrete Particle Swarm Optimization (DPSO) is utilized to find out the best fitness value. Consequently, an optimal network reconfiguration scenario is formed after the four steps above.

The remainder of this chapter is organized in the following way: A network reconfiguration scenario based on topological characteristics of scale-free network is presented in section 2.2. The parameter setting, and model test are presented in section 2.3. The summary of this chapter is given in section 2.4.

2.2 Model Establishment

A power system network can be modeled by a graph *G(V, E)* that contains a set of nodes *V* and a set of edges *E* [25]. Therefore, power system restoration can be formulated as a problem of identifying the desired graph topology subject to various constraints [26].

2.2.1 **Basic knowledge of graph theory**

The first step to combine graph theory with power system restoration is to convert a real power system into a topological graph and get the graph matrix. So some basic knowledge about graph theory must be introduced.

The set of nodes and edges is defined as a graph in graph theory. In graph *G(V,E)* each edges composed of two nodes and there is no common point existing between edges. If the shortest path between node *i* and node *j* only has one edge, the node *i* and *j* are defined direct connected. On the contrary, if the shortest paths of two nodes are composed of two or more edges we say these two nodes are indirectly connected. In general, set of nodes in graph *G(V,E)* is denoted as *V(G)*and set of edges in *G(V,E)* is denoted as *E(G)*. A specific situation is *E(G)* can be empty and if *E(G)* is empty, there is only nodes existing in *G(V,E)*.

For example, in figure 2-1:

V(G1)=*{1,2,3,4,5,6}*and E(G1)=*{(1,2),(2,4)(4,3),(2,3),(3,1),(4,5),(3,5),(5,6),(6,5)}*.

In figure 2-2:

V(G2)=*{1,2,3,4,5,6}* and E(G2)=*{(1,2),(2,4),(4,3),(2,3),(3,1),(4,5),(3,5),(5,6)}*.

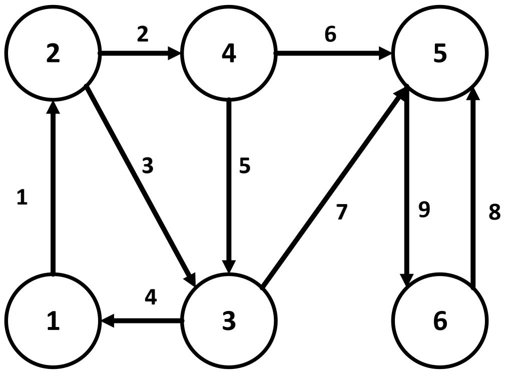

Figure 2-1 Islands with different scale

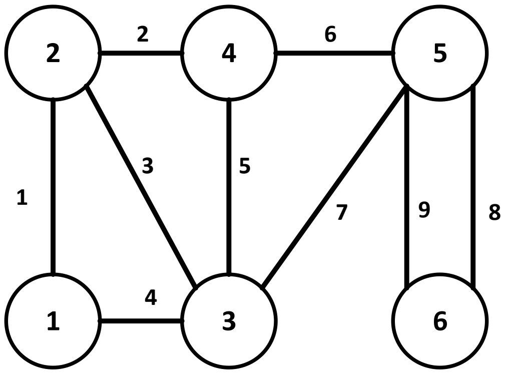

Figure 2-2 Undirected graph

As shown above, the main difference between a directed graph and an undirected graph is whether directivity exists in edges. In my thesis, I mainly employ undirected graph to solve the network reconfiguration problem.

After getting a topological graph of power system, graph matrix should be obtained. Graph matrix has two main matrixes, namely, adjacent matrix and incidence matrix. Adjacent matrix is a matrix that represents adjacent relation of nodes in the system. If node i and j are directly connected, the corresponding position in adjacent matrix is assigned 1. We assume that $G(V,E)$ has n nodes and adjacent matrix of $G(V,E)$ is a n-order square which has the following characteristic: For undirected graph the adjacent matrix is a symmetrical matrix and all diagonal elements are zero.

In undirected graph the node degree is defined as the sum of one column in matrix and in directed graph the definition of node degree is composed of indegree and outdegree [27].

The memory space of adjacent matrix is n^2 but the adjacent matrix of undirected graph is symmetrical so only the upper or lower matrix need stored when saving data and memory space is only $\frac{n(n-1)}{2}$. So, the undirected graph of figure 2-2 can be represented by matrix below:

$$A = \begin{bmatrix} 0\,1\,1\,0\,0\,0 \\ 1\,0\,1\,1\,0\,0 \\ 1\,1\,0\,1\,1\,0 \\ 0\,1\,1\,0\,1\,0 \\ 0\,0\,1\,1\,0\,1 \\ 0\,0\,0\,0\,1\,0 \end{bmatrix} \tag{2.1}$$

The flow chart to generate an adjacent matrix is illustrated below:

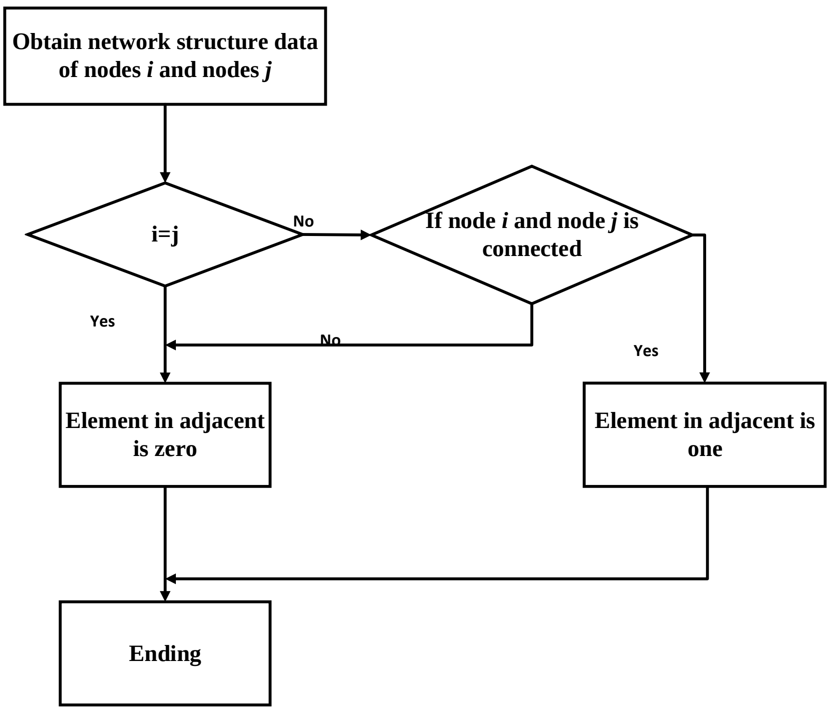

Figure 2-3 Formation of an adjacent matrix

Incidence matrix bring in minus one to represent the direction of edges in topological network. Because the scenario proposed in this chapter is based on undirected graph the characteristic of incidence matrix is not mentioned too much here.

2.2.2 **Introduction of topological characteristic of network**

1. Scale-free network

In a conventional random network, node degree fulfills Poisson distribution which means most of nodes have the same edges and nodes with more or less edges are few. When investigated the World Wide Web in 1998, Barabasi accidentally discovered that the distribution of node degree follows exponential law [28]. It means most of nodes have a small node degree, but few nodes have large node degree.

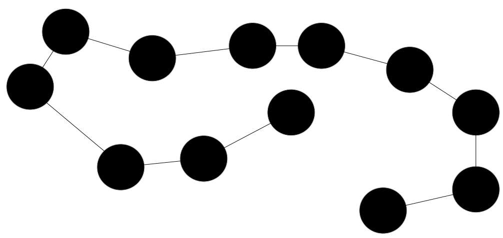

Figure 2-4 A simple random network

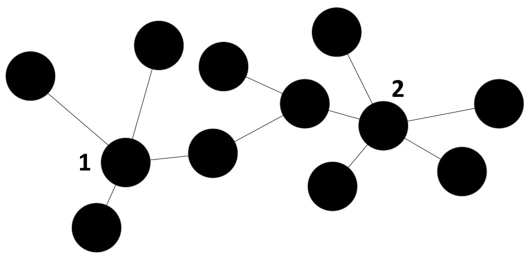

Figure 2-5 A simple scale-free network

Figure 2-4 and Figure 2-5 shows a simple random network and simple scale-free network respectively. Nodes one and two in scale-free network have larger node degree than other nodes.

Scale-free takes on small-world effects that imply fewer but connected intensively hub-nodes exist in a network [29]. In power system reconfiguration these hub-nodes can be treated as a restoration target.

2. Node importance degree（α_i）

As mentioned above hub-nodes in power system is important and when operators intend to restore a totally blackout system these important nodes are the first to be considered. So how to weigh a node's importance is the key to restore the whole system successfully. Traditionally, node degree is utilized to weigh the importance of a node, which indicates that a node with more edges occupies an important position in the whole system. But sometimes hub-nodes are not as many edges as common nodes and nodes with more edges are less important than hub-nodes. So node importance degree is proposed to reflect the importance of a node. Before giving an example to prove the validity, a concept called node contraction is proposed.

Node contraction is widely utilized in graph theory and it paves the way to define the node importance degree. Node contraction operation occurs relative to a particular edge *e*. The edge *e* is removed and its two incident nodes, *i* and *j* are merged into a new node k and a set of edges maybe performed by contracting each edge [30]. Before computing node importance degree of an exact node, all nodes directly connected to this node must be contracted into a new node.

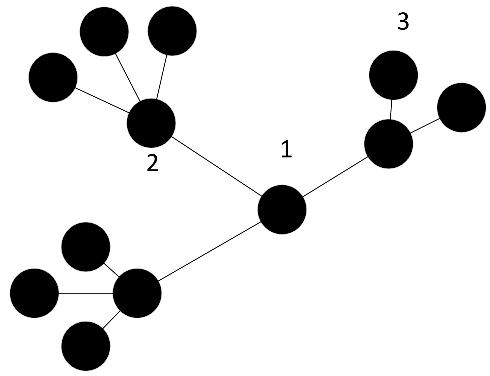

Figure 2-6 A demonstration of node contraction

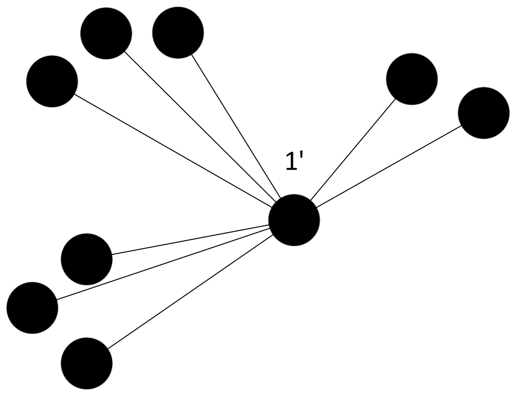

Figure 2-7 A new network after node 1 contraction

A simple system with 12 nodes is shown in figure 2-6 and all nodes directly connected to node 1 is merged into a new node 1 prime which is shown in figure 2-6. The definition of node importance degree α_i is given by following formula:

$$\begin{cases} \alpha_i = \frac{1}{n_i \cdot l_i} \\ l_i = \frac{\sum_{i,j \epsilon v_i} d_{min,i\,j}}{n_{i(n_i-1)}/2} \end{cases} \tag{2.2}$$

Where n_i is the total number of nodes after node contraction and l_i is the average shortest path of new network after node contraction; $d_{min,i\,j}$ is the shortest path between node *i* and node *j* denoted with the number of edges; v_i is the set of nodes after node contraction [31]. From this formula, the node importance degree α_i is decided mainly by two factors, namely, total number of nodes after node contraction and average shortest path of new network. So it is a variable decided simultaneously by these two elements. Above all, it is more likely that nodes have more edges and connected to more nodes will have a smaller n_i because after node contraction more nodes are merged into one node and n_i becomes smaller. These kinds of nodes are always at a relative central position compared to other nodes. However, the parameter l_i is an important influence factor too. Nodes with smaller average shortest distances after node contraction are more important. Because these nodes are always at pass location of the system and they build bridge to nodes from different area. The edges between two nodes are distinctly reduced after node contraction.

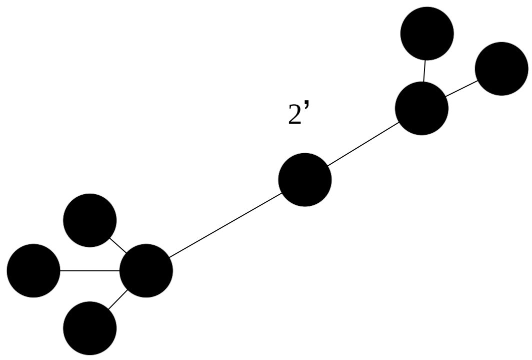

Figure 2-8 A new network after node 2 contraction

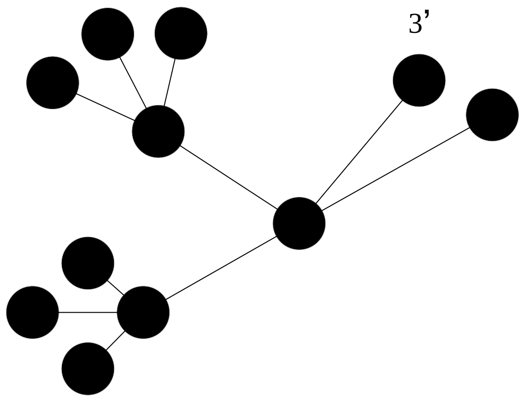

Figure 2-9 A new network after node 3 contraction

A simple case is given here. A node importance degree comparison of node 1 and 2 is given. Network structure after node 2 and node 3 contracted is shown above. n_i of node 1 prime, node 2 prime and node 3 prime are 9, 8 and 11 respectively which means more edges connected to node 2 before node contraction and therefore more nodes are merged into one node. However, the average shortest distances after node 1, node 2 and node 3 contracted are 0.222, 0.393 and 0.418. In a result the node importance degree is 0.50, 0.318 and 0.217 respectively. The computation results are shown below:

Node No.	**Total Number of Nodes after Node Contraction (n_i)**	**Average of the Shortest Distances (l_i)**	**Node Importance Degree (α_i)**	**Node Degree**
1	9	0.222	0.5	3
2	8	0.318	0.393	4
3	11	0.217	0.418	1

Table 2- 1 Node importance values of three nodes

Only from the network given in figure 2-6 point of view we can guess that node 1 is more important because of the central position it locates. The results are shown above and from this simple case we can discover that a node with more edges connected or larger node degree is not necessary more important. So, it proves the validity of using node importance degree to weigh a node's importance.

3. Clustering coefficient（β_i）

Clustering coefficient is an index to reflect the degree to which nodes in a graph tend to cluster together. To be specific, it shows the interconnection degree of nodes neighbor and it shows the connection complexity of nodes in the vicinity of node i. The definition formula of clustering coefficient is demonstrated below:

$$\beta_i = \frac{t_i}{k_i(k_i-1)/2} \tag{2.3}$$

In the formula, $t_i$represents the number of connected edges near the node i. k_i represents total number of nodes in the vicinity of nodes i and if all these nodes are fully connected there will be $k_i(k_i-1)/2$ edges. Here an example is given below:

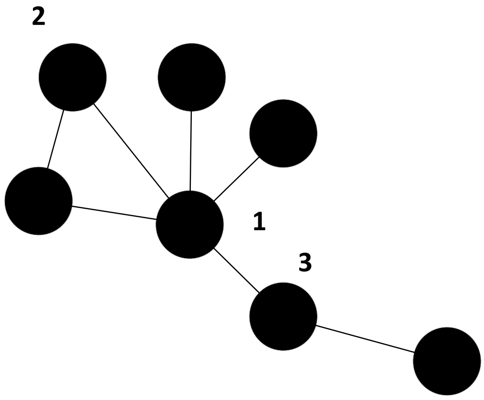

Figure 2-10 A simple case of computation clustering coefficient

As figure 2.10 shown the number of nodes in the vicinity of node 1 is five and if these five nodes are fully connected there will be ten edges but in there is only one edge in fact. So the clustering coefficient of node 1 is 1/10. Similarly, the clustering coefficient of node 2 and node 3 are 1 and 0 respectively. The local clustering coefficient usually plays a negative role in the spreading process [31] [32], as well as in the growth of an evolving network [33]. So, when considered the reconfiguration scenario the nodes to be restored are better to have a small clustering coefficient value.

4. Line betweenness centrality (θ_i)

Node importance degree and clustering coefficient are indices to indicate the importance of nodes in a power system but the importance of transmission lines is also needed to be weighed. The concept of line betweenness centrality was firstly proposed by Bavelas in 1948 [34], and then restated by Shimbel and Shaw in the view of a node's potential power in controlling the information flow in a network [35]. In 1977, Freeman [36] applied this concept to the graph theory and show it the way we use today. This index reflects the importance of one transmission line by calculating the frequency of one line passed by the shortest path of two nodes. The definition of line betweenness centrality is shown below：

$$\theta_i = \sum_{i \neq s, i \neq t, s \neq t} \frac{g_{st}^i}{g_{st}} \tag{2.4}$$

Where g_{st}^i is total number of the shortest paths passing through the line *i* and g_{st} is the total number of the shortest paths between node *s* and node *t*. A case is given below:

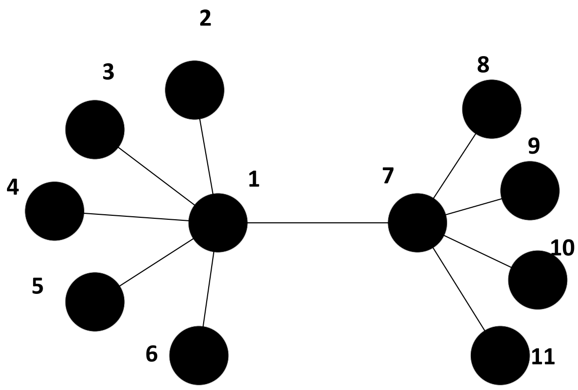

Figure 2-11 A simple case of calculation of line betweenness centrality

From the network we can guess that line 1-7 is the most important line among all these lines because line 1-7 connect two subsystems which are consist of nodes 1, 2, 3, 4, 5, 6 and nodes 7, 8, 9, 10, 11. So the line betweenness centrality of line 1-7 is calculated and the rest of lines are computed too. The results are shown below:

Line No.	Line Betweenness Centrality (θ_i)
1-7	0.667
1-2,1-3,1-4,1-5,1-6,7-8,7-9,7-10,7-11	0.192

Table 2- 2 Line betweenness centrality values of edges

When calculating the value of line betweenness centrality in a huge power system, how to get the total number of the shortest paths between two nodes and the number of shortest paths passing one edge is a problem. So I bring in an algorithm called Floyd-Warshall to solve the shortest path problem.

The Floyd-Warshall algorithm is an example of dynamic programmingand was published in its currently recognized form by Robert Floyd in 1962 [37].The theory of Floyd-Warshall algorithm is that $D_{i,\ j,\ k}$ is the shortest path between node *i* and *j* and the nodes in the middle of node *i* and *j* are nodes 1 to k. If the shortest path from node *i* to node *j* is longer than path from node *i* to node *k* and then to node *j* the shortest path will be updated to $D_{i,\ k,\ k-1}+D_{k,\ j,\ k-1}$. So, based on this algorithm the number of shortest path can be calculated.

2.2.3**Network reconfiguration objective function (η)**

Power network restoration consists of two processes: Proposing an efficient network reconfiguration scenario and determining a reasonable restoration sequence leading to the proposed reconfiguration scenario. In this thesis I mainly focus on proposing a rational scenario. So the primary step, which is to establish an efficient network, should find a valid index to measure the efficiency of reconfiguration scenario. Based on graph theory and network topological characteristic proposed before, an evaluation index called network reconfiguration efficiencyη is employed. Network reconfiguration efficiency η is determined by network structure parameters. Here a network reconfiguration efficiency definition equation based on network structure parameters is given. The reconfiguration efficiency η is determined by parameters $\overline{\alpha}, \bar{\beta}$ and $\bar{\theta}$ and η defined is shown below:

$$\eta = \frac{\overline{\alpha}+\mu\bar{\theta}}{\bar{\beta}} \tag{2.5}$$

$$\overline{\alpha} = \frac{\sum_{i=1}^{n_L} \alpha_i}{n_L} \tag{2.6}$$

$$\bar{\theta} = \frac{\sum_{k=1}^{N_l} \theta_i}{N_l} \tag{2.7}$$

$$\bar{\beta} = \frac{\sum_{j=1}^{n_C} \beta_i}{n_C} \tag{2.8}$$

Where $\overline{\alpha}$ is the average node importance degree of total n_L load nodes selected in reconfiguration scenario network and only load nodes are considered because all generators must be contained in new network and it will not change the efficiency. $\bar{\theta}$ is the average line betweenness centrality of transmission lines in reconfiguration senario network selected and $\bar{\beta}$ is the average clustering coefficient of total n_C nodes selected in reconfiguration scenario network, μ is regulatory factor that affects the selection of transmission lines.

The larger the value of η is the more efficient the reconfiguration. $\bar{\theta}$ and $\bar{\beta}$ are common elements in η. $\overline{\theta}$ is the closeness betweenness centrality of a reconfiguration network and as mentioned before this index is to reflect the average importance of transmission lines selected in reconfiguration scenario, so if more important transmission lines are contained in scenario the reconfiguration network is more efficient. $\bar{\beta}$ is the clustering coefficient of a reconfiguration network and it reflects the interconnection degree of nodes neighbor and it shows the connection complexity of nodes in the vicinity of node i. In the preliminary stage of network restoration, restore nodes with small $\overline{\beta}$ is expected because distant loads can be restored quickly and people also expect to control the ratio of transmission lines in reconfiguration scenario because of a reduction of reconfiguration burden. In the network reconfiguration efficiency η, index $\bar{\alpha}$ is selected to reflect the nodes importance. So, we expect nodes with more edges connected and at passing position are selected in reconfiguration scenario. The reconfiguration effect of objective function will be given in chapter four.

2.2.4 **Constraints and power flow calculation method**

The objective function, namely, network reconfiguration efficiency η is subjected to some constraints of power system. The constraints are shown below:

$$\begin{cases} L < L_{max} \\ V_i^{min} \le V_i \le V_i^{max} \\ P_i \le P_{max} \\ g \epsilon G \end{cases} \tag{2.9}$$

When reconfiguring transmission lines, over-voltage is notable with lines' length increasing. So the line length must be limited corresponding to different voltage level in order to maintain prescribed over-voltage limit [38]. Similarly, the voltage of selected nodes must fulfill the upper and lower bound of voltage required. In addition, the active power of nodes selected must be less than power offered by generators in network. And moreover, g that is the network topological structure must be radiational and reconfiguration must be connected totally in topological structure. All the constraints must be fulfilled, and it makes the reconfiguration scenario feasible in practice.

To check if the reconfiguration scenario fulfills the constraints of voltage, active power and even the length of transmission lines, an efficient power flow calculation method must be utilized. There are three main power flow calculation methods which are Newton-Raphson Method, Gauss Seidel Method and Forward-backward Sweep Method.

The basic theory of Newton-Raphson Method is to expand the power flow equation by Taylor series and the second order and higher order terms are omitted when calculated the equation. The core of solving process is to translate nonlinear equations calculation into an interactive calculation of linear equations [39]. This method has a good astringency and logic is easy to understand, so it is a method widely utilized in practice. Gauss Seidel Method is based on superposition principle, namely, the voltage of line *i* can be calculated by iteration of root node voltage and the voltage generated by current [40]. This method has a bad astringency and a large amount of calculation. Forward-backward Sweep Method is to calculate the power of head end from the tail end and calculate the voltage drop of every part of branch. After several repeated calculations the voltage of each node is obtained with an acceptable voltage deviation. This method has a large amount of calculation too.

Therefore, in my thesis the Newton-Raphson Method is selected to be the power flow calculation method and it is utilized in the chapter four.

2.2.5 Introduction of discrete particle swarm optimization (DPSO)

Particle swarm optimization (PSO) is a population-based optimization method first proposed by Kennedy and Eberhart in 1995 [41] and the inspiration comes from the simulation to the movement of bird flock in a D-dimensional space. The interaction and interplay between individuals and groups reflect the information sharing mechanism of organism. PSO is the algorithm to simulate this society, namely, individual learns experience from each other and groups develop simultaneously based on information sharing. Moreover, PSO is an evolutionary computation method and moves the individuals to the best area based on the fitness value determined by optimization function. But what is different from other evolutionary computation methods is PSO treats each individual massless and volume less particle and moves randomly by velocity V_{id} in the space. As an efficient parallel optimization algorithm, PSO is robust in solving problems featuring nonlinearity， multiple optima, and high dimensionality through adaptation, which is derived from social-psychological theory [42].

The basic theory of PSO is a group of particles initialize randomly in a space and each of them has an initial position x_{id} and velocity v_{id} which represents a candidate solution to the problem. Where *i* represents the total number of particles and *d* represents the dimension of space. In the space each particle moves by a velocity and has a fitness value determined by objective function. In addition, each particle is aware of the best position *pbest* so far, current position x_{id} and the global best position *gbest*. The way to update particles' position is based on information of current velocity v_{id}, current position x_{id}, gap between x_{id} and *pbest* and gap between *pbest* and *gbest*. Equation 2.10 shows how each particle peruses the best particle and updates their information at t to find a best solution.

$$\begin{cases} v_{id}(t+1) = v_{id}(t) + c_1 r_{1d}(t)[p_{id}(t) - x_{id}(t)] + c_2 r_{2d}(t)[p_{gd}(t) - x_{id}(t)] \\ x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \end{cases} \quad (2.10)$$

Where p_{id}, p_{gd} and x_{id} are the personal best position and group best position and current position respectively. The update of particle is accomplished by tracing p_{id} and p_{gd} and two pseudorandom sequences r_{1d}, r_{2d} ~$U(0,1)$ are used to affect the stochastic nature of the algorithm. Acceleration coefficient c_1 and c_2 control how far a particle will move in a single iteration and typically they are set to a value of 2.0 [43].

In this thesis, nodes or edges are converted into a series of binary numbers in a matrix and the optimal calculation has to be operated under the discrete space. Since the problem is original PSO algorithm, it only can be operated in a continuous space. When PSO is operated in discrete space only 0 or 1 is allowed for p_{id}, p_{gd} and x_{id}. So, a modified PSO algorithm called Discrete Particle Swarm Optimization (DPSO) is employed here.

In a binary space, a particle moves by flipping various numbers of bits. In terms of changes of probabilities that a bit will be in one state or the other a particle moves in a state space restricted to zero and one on each dimension, where each v_{id} represents the probability of bit x_{id} taking the value 1 [42]. For an example, if v_{id}=0.3 the particle has thirty percent chance to be one and seventy percent chance to be zero. If the *pbest* is zero, the outcome of (p_{id}-x_{id}) is -1, 0 or 1 and used to weigh the change in probability v_{id} in the next step. So the *pbest*, *gbest* and current position are all integers in{0,1}. The modified PSO algorithm equation is shown below:

$$\begin{cases} v_{id}(t+1) = v_{id}(t) + c_1 r_{1d}(t)[p_{id}(t) - x_{id}(t)] + c_2 r_2(t)[p_{gd}(t) - x_{id}(t)] \\ if\ \big(S\big(v_{id}(t+1)\big) > rand()\big) then\ x_{id}(t+1) \neq x_{id}(t) \\ else\ x_{id}(t+1) = x_{id}(t) \end{cases} \tag{2.11}$$

Where $S(v_{id}(t+1))$ is a logistic transformation and $rand()$ is a quasirandom number as threshold selected from a uniform distribution in [0,1]. From this equation, it is evident that x_{id} takes 0 or 1 if vid bigger than threshold. Otherwise it will be unchanged.

So, the DPSO is appropriate to be utilized in optimal fitness value calculation. By utilizing DPSO algorithm, the best fitness value of my objective function, namely, $f = \frac{1}{\eta}$ can be calculated.

2.2.6 **Algorithm Summary**

The flow chart of a rational network reconfiguration scenario realized by DPSO is shown in figure 2.12 and some critical steps of network reconfiguration are explained as follow.

Step 1, an actual power network should be simplified and converted into a one-line diagram in which loads and transmission lines are replaced by nodes and edges respectively in a diagram. In addition, each edge should be numbered because of the using of DPSO during best fitness value calculation.

Step 2 and 3, three kinds of network topological indices are calculated. The three indices are foundation for the proposing of objective function. These three indices reflect the importance of a network by loads importance, transmission lines importance and the complexity of one node.

Step 5, initialization is the base for DPSO optimization. In this step, a series of random transmission lines matrix is generated which has a $1 \times N_l$ scale and the dimension of the matrix is pre-set to be the number of transmission lines in system. When a certain transmission line is selected in a potential reconfiguration scenario, the corresponding position in matrix will takes 1. Otherwise, 0 is taken in that position. So, a matrix, which consists of a series of 0 and 1 value, represents a potential reconfiguration scenario. In addition, the population size of particles should be regulated.

Step 6, a series of potential reconfiguration scenarios is generated randomly but for practical purpose the rationality of reconfiguration scenario must be checked. An important principle of reconfiguration scenario is that the connected restoration network must contain at least one generator and a restoration network without generator cannot be restored.

Step 8, the objective of my reconfiguration scenario is to propose a most efficient scheme in which important loads; transmission lines are contained as many as possible. So the index η is introduced and the bigger the value of η is the more efficient the scenario is. Besides, the performance of each individual particle is justified by its fitness value determined by objective function, which is η here. So $f = \frac{1}{\eta}$ is introduced and the smaller the fitness value the better the particle is. In addition, the personal best position p_{id} should be updated if the fitness of one potential scheme is the optimal.

Step 9, 10, 11, 12, 13, comparison is made at every moment. One certain particle with best personal position and fitness value will be compared with global particles and if the personal fitness value is better than others the best position of global particles will be updated until a maximum iteration step or a given iteration step.

Step 14, 15, 16, when an optimal potential reconfiguration is obtained, the constraints should be fulfilled. Power flow check is necessary because the output of generators in restoration network should meet the requirement of loads in network and if the optimal and sub-optimal scenarios are consistent to security restriction the feasible scenario is obtained. Consequently, the outcome of particles is converted into target network. Selected transmission lines with loads and generators connected are presented in optimal and sub-optimal restoration scenario.

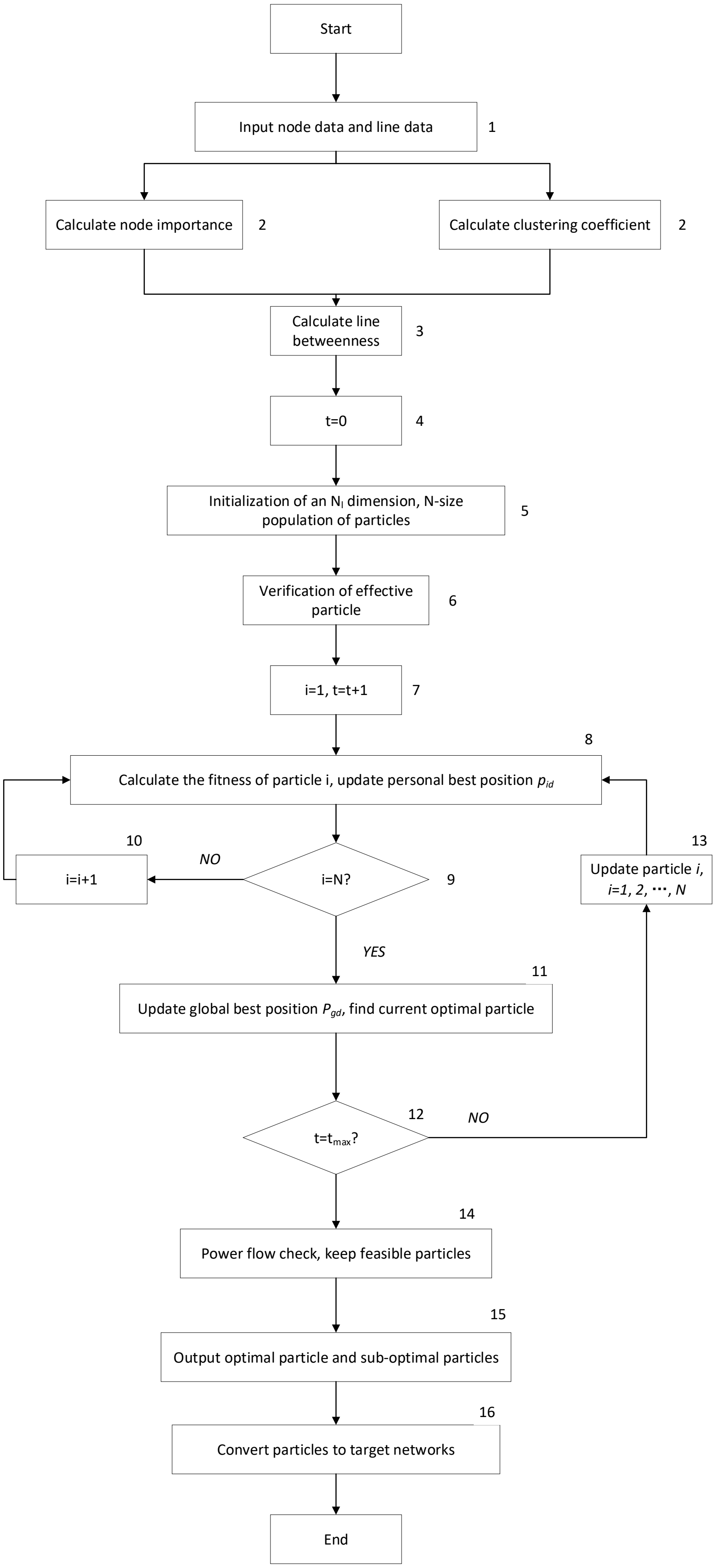

Figure 2.12 Algorithm flow of network reconfiguration strategy

2.3 Conclusion and Future work

In this chapter a power system network reconfiguration scheme after large-scale outage is proposed. First and foremost, a practical power system network is converted into a one-line diagram and based on graph theory and after all lines are numbered the foundation of the reconfiguration scheme is established. Then three indices based on topological characteristic of network are utilized to reflect the importance of loads, generators and transmission lines in network. After that, a comprehensive index called network reconfiguration efficiency η is proposed. Network reconfiguration efficiency η describes the efficiency of a scheme bycontaining as many important loads and transmission lines in a potential reconfiguration scheme as possible. To obtain the most efficient reconfiguration scheme, namely, a scheme with the biggest η, DPSO is utilized to solve the optimization problem. By employing the DPSO algorithm the smallest fitness function $f = \frac{1}{\eta}$ is calculated and the most efficient restoration scheme can be obtained.

Future work can be focused on following aspects: based on graph theory, indices that can describe the topological characteristics of network more comprehensively should be utilized. Besides, blackstart includes two steps: propose an optimal reconfiguration scheme as a restoration target and organize a starting sequence to bring the outage power system into the target network proposed before. So, the future work should formulate a switching operation sequence scheme to restore the outage network to the target network.

Chapter 3 An islanding restoration strategy for distribution network with Distributed Generators (DGs)

3.1 Introduction

In recent years, with the development of distributed energy, the utilization of DGs has risen sharply in distribution network. It plays a critical role in the future Smart Grid to modernize the power grids at the distribution level [44]. The emerging Smart Grid technology, which enables self-sufficient power systems with DGs, provides further opportunities to enhance the self-healing capability [45].

DGs have merits like making most use of renewable sources and reducing the consumption of fossil fuel, etc. Among these advantages, the superiority of improving the reliability and stability of distributed network by islanding operation becomes remarkable [46]. A distribution network with DGs can be separated after a large-scale outage and hence, the load in separated area can be restored quickly [47]. In addition, the customer in restoration area may be able to avoid extended outages. How to divide an outage power network into several reasonable restoration areas becomes a topic worth investigating.

Generally, the load demand after power system outage is more than the power supplied by DGs and some large generators, which is not out of work. So the problem should be how to restore as much load as possible in the condition of limited power supply and separation operation based on the principle of separated start.

In this chapter, the principle of DGs start sequence is introduced and the stability of distribution network is investigated when adding DGs to the network. After bringing in DGs, a separation strategy based on the property of DGs and the distribution of DGs is proposed. The remainder of this chapter is organized in the following way. A selecting principle of DGs is introduced in 3.2. In 3.3 the classification of DGs is given. The principle of DGs' start sequence is presented in 3.4. A simple case to test the stability of network when bringing in DGs is shown in 3.5. The separation objective and method of distribution network with DGs is given in 3.6. The summary of this chapter is given in 3.7.

3.2 The selection principle of DGs in islanding operation

When a large-scale outage occurred in power system, the power supplied from large power station or generators may be interrupted because of the fault of transmission lines or electrical devices. DGs have the merits like decentralization, modularization flexibility and low cost, so they are now widely utilized in power system restoration. But DGs' capacity is the key point, which does not allow the entire replacement of large generators. When starting a distribution network with DGs, the DGs with blackstart capability should start first to supply voltage to island system and then non-blackstart DGs are restored by the support of blackstart DGs. After these two steps, the generated energy in islands increases gradually and island operation successes ultimately. Hence, the self-start capability of blackstart DGs is the key to restore distribution network successfully without a sufficient support of external power grid or large generators.

Blackstart DGs should have followed characteristics: Firstly, blackstart DGs should self-start rapidly without support from external power grid or generators; Secondly, DGs should have the voltage and frequency modulation capacity because blackstart DGs should operate independently for a period and during this time the DGs should stabilize the frequency and voltage in island. Thirdly, blackstart DGs should have a sufficient generating capacity because the blackstart DGs should bear the short time power shock from other non-blackstart DGs and meet the needs of system load and power loss. Fourthly, the DGs should have sufficient reserve capacity.

To sum up, microturbine, diesel generator, fuel cell and large capacity storage devices have characteristics like stable energy supply, flexible control, strong anti-interference capacity and quick self-start capacity, etc. Therefore, they are the priority selection of distribution network restoration. Accumulator has good regulation capacity because of the quickly charge-discharge capacity. Hence, it is selected to be blackstart power source too. Although photovoltaic and wind turbine units are affected by external elements like weather or temperature, lots of technology has been utilized to keep the output of them stable. So photovoltaic and wind turbine units can be employed as blackstart DGs as well.

3.3 The classification of DGs

The generated power of DGs cannot fulfill the demand of total load in distribution network especially at the initial stage of restoration. Therefore, it is necessary to separate the network based on the distribution of important load and the characteristics of DGs. However, different

DGs have diverse characteristics and some DGs have self-start ability and some are not. Here, a classification of DGs is given below:

1. DGs are classified into Blackstart DG (BDG) and Non-blackstart DG (NBDG) based on if DGs have self-start ability. BDG mainly includes generators like combined cycle generating unit, separately excited motor with passive inverter, wind and solar power units with energy storing devices; NBDG mainly includes self-excited motor, wind and solar power units without storing devices.

2. DGs can be classified into two categories based on if DGs have stable output. Stable DG (SDG) mainly includes microturbine, fuel cell; Non-stable DG (BSDG) mainly has wind and solar power units without storing devices and is vulnerable to weather.

3. DGs can be classified into Controllable DG (CDG) and Non-controllable DG (NCDG) based on if DGs have communication capability and control protocol.

3.4 The start sequence principle of DGs in islanding operation

The first problem needs to be solved is how to arrange a reasonable DGs start sequenceafter distribution network separation. Therefore, a basic principle of start sequence is given below:

1. BDG, SDG and CDG start ahead. NBDG starts finally because it has no self-start ability.

2. DGs with large capacity start ahead because they can supply more power to the system.

3. DGs that are close to important load start ahead. The importance of load can be ranked to first-order load, second-order load and third-order load in general. In my thesis, the node

importance can be ranked by an index called node importance degree mentioned in chapter two.

4. DGs with voltage and frequency modulation capacity start ahead. For the purpose to drive the islanding operation.

5. NBDGs that are closer to BDGs should start ahead. The number of switches between two DGs can judge the distance.

3.5 Stability analysis of distribution network with DGs

To test the effect of DGs when they are added to the distribution network, a 10 bus system has been established with PowerWorld software. PowerWorld is a user-friendly and highly interactive power system analysis and visualization platform which can be utilized to establish a large-scale power network and integrate many commonly performed power system tasks like contingency analysis, time-step simulation, fault analysis, sensitivity analysis, and optimal power flow (OPF) calculation.

In figure 3.1, a ten-bus system case with 7 generators (6 DGs and 1 large generator) and 15 branches is shown. In this part, the effect of DGs is investigated and to check the effect of DGs and all DGs are assumed to be blackstart DGs. The basic information of DGs and large generator pre-set is given below:

Title	Category	Output Power /MW
DG1	BDG/Photovoltaic units	4.0
DG2	BDG/ Wind turbine	40
DG3	BDG/Photovoltaic units	10
DG4	BDG/ Wind turbine	30
DG5	BDG/Photovoltaic units	30

DG6	BDG/ Wind turbine	8.0
Large Generator	/	182.4

Table 3-1 Data for DGs and large generator in 10 bus system

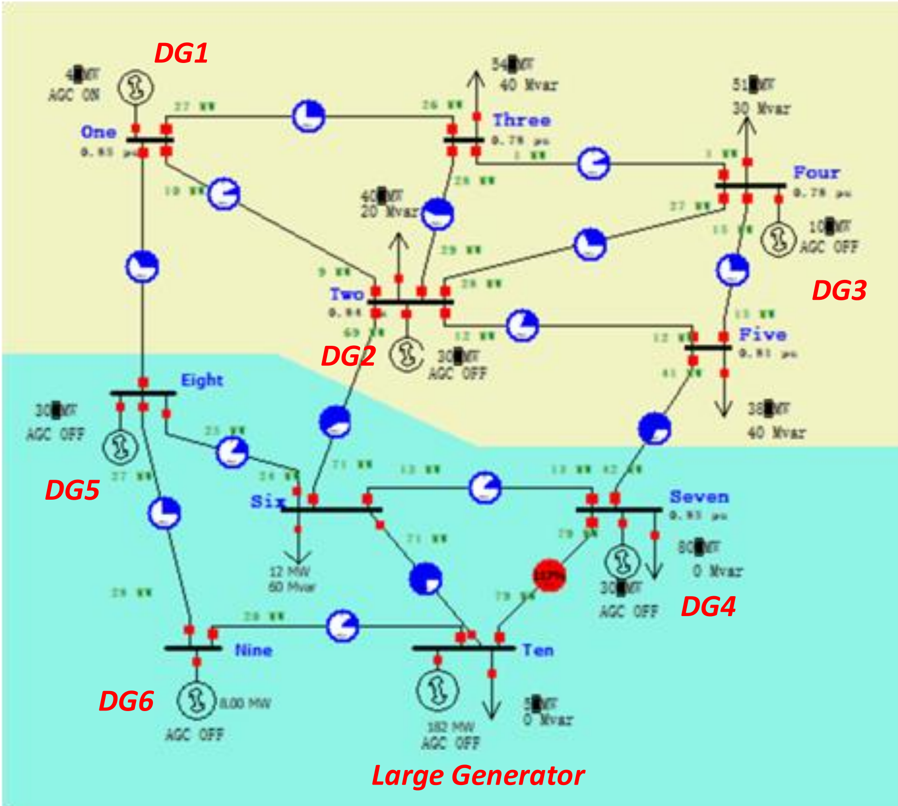

Figure 3-1 Network diagram of ten bus test system

The generator type and output power are set in the generator options window of PowerWorld. After setting the output power of each DG and large generator and the category of each DG, the starting sequence of each generator should be assumed. In the Transient Stability Analysis option of PowerWorld, the starting time of each generator can be set and thus, the starting sequence of each generator can be represented by different starting time.

To compare the stability of a distribution network with DGs and without DGs, a situation that only large generator existing in network is emulated. The voltage, active power and reactive power of load point 2 are shown in figures below:

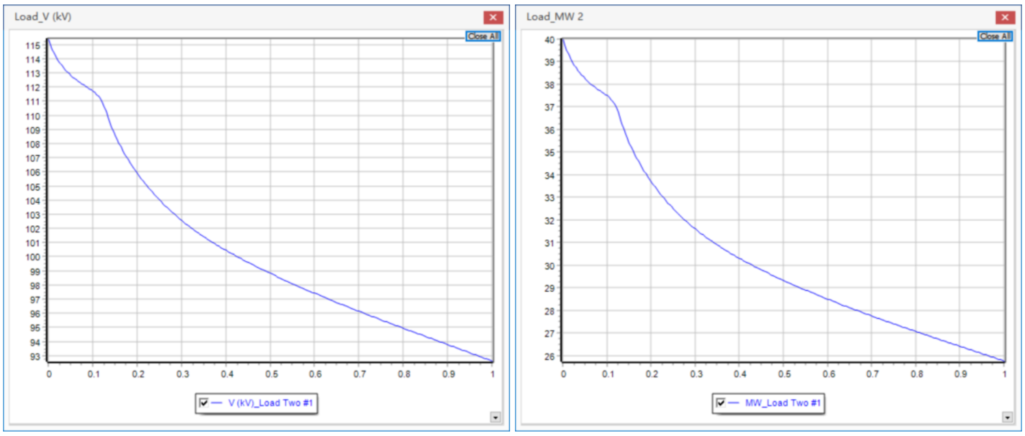

Figure 3-2 Voltage and active power at load two

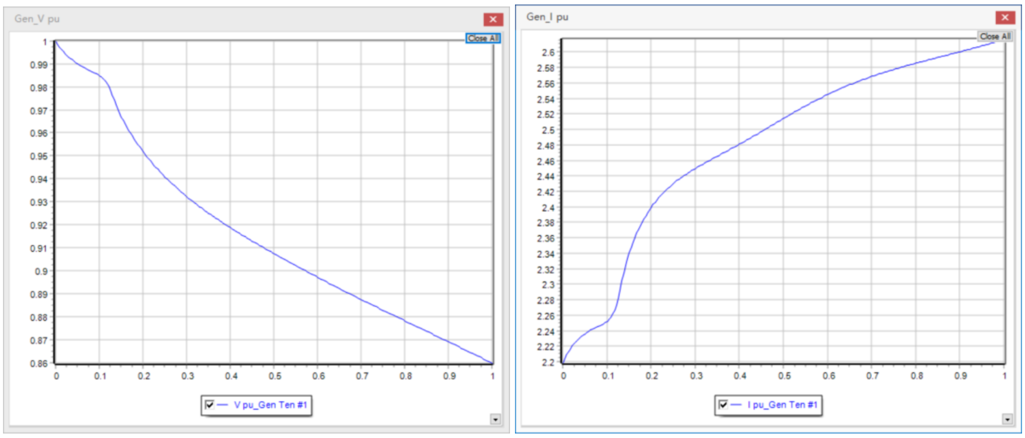

Figure 3-3 Voltage and current of large generator

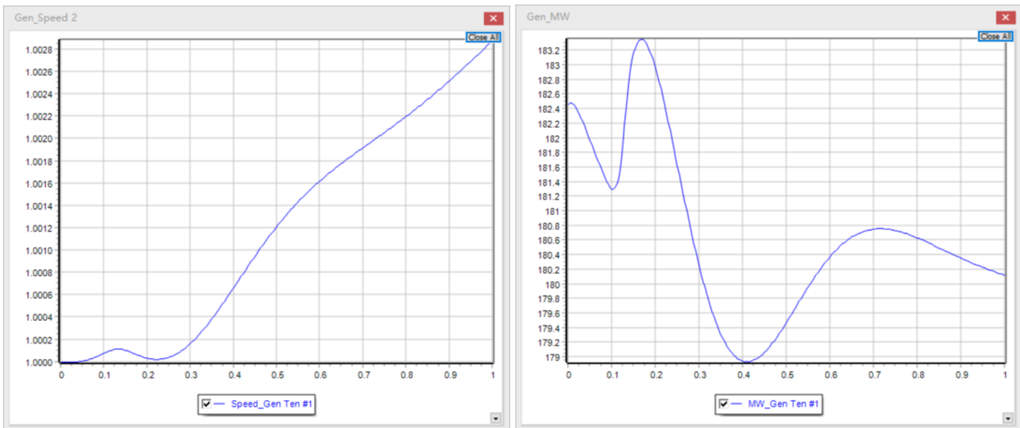

Figure 3-4 Frequency and output power of large generator

In figure 3.2, the voltage and active power is shown. From the figure, we can notice that the voltage and active power decline gradually and all the way down to 0 at the end. The reason why I get such a curve is that only one large generator exists in network and the power generated cannot fulfill the whole 10 bus system's load demanding. Therefore, a 10-bus system collapses, and it is failed to restore the system.

In figure 3.3 and 3.4, they show voltage, current, frequency and output power of the large generator. The voltage of large generator decreases to 0 and current increases to infinite. Because with the collapse of system, large generator is in a no-load state and it is very dangerous state for power system. At the same time, the rotor in large generator will idle and the rotor rotates in an infinite speed. The output power of large generator fluctuates during the process.

To sum up, when only one large generator exists in a 10-bus system and the output power cannot fulfill the demanding of total load at the same time, the system cannot maintain a stable state and it will collapse soon.

To establish a stable system, the DGs are added to the system. The situation that DGs are switched in system by the principle of starting sequence introduced before is emulated. According to the principle, DG_2 is a BDG with storing capability and therefore, it starts first. Then, according to the second principle, the DGs with larger capacity should start ahead. The starting time of each DG is set as follow:

NO.	**Starting Time/s**

DG2	1
DG4	1.5
DG5	1.5
DG3	2
DG6	3
DG1	3.5

Table 3-2 Starting time of each DG in 10 bus system

As a result, the starting sequence is arranged as DG_2, DG_4, DG_5, DG_3, DG_6 and DG_1. After setting down all the time parameters in the Simulation Window of Transient Stability analysis, the voltage and active power at load two are given below:

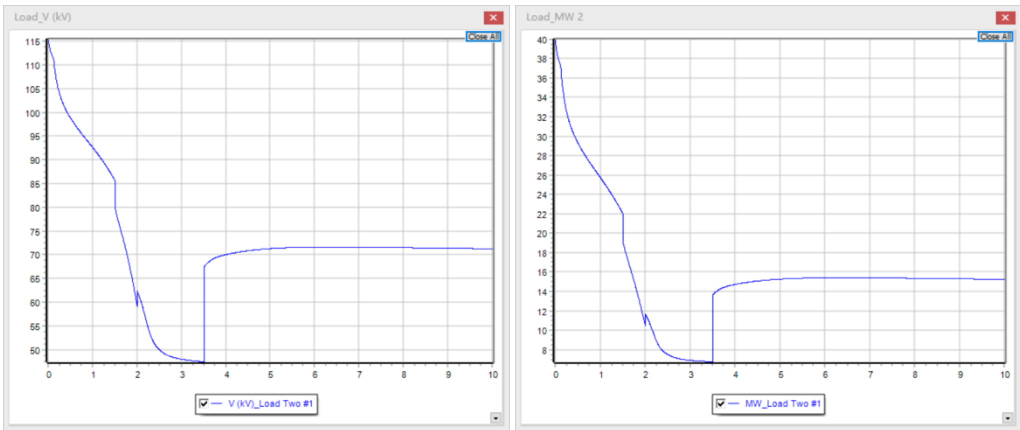

Figure 3-5 New voltage and active power at load two

From the simulation outcomes, we can observe that there is a gradually decline until 3.5 seconds in the voltage curve of load two. By analyzing the switching-in time of DGs, all DGs are added into network until 3.5 seconds and after 3.5 seconds the power supplied meets the demanding of load in 10 bus system. Therefore, the voltage of load two reaches a stable value after 3.5 seconds and the whole system stays in a steady state. The outcome of active power has a same curve as the outcome of voltage and it can be analyzed in the same way. After a total switching in of DGs, the whole system reaches a stable state and the active power supply at load two is at a dynamic stability.

In a conclusion, if the power demanding of load can be fulfilled by generators in system, the switching in of DGs based on the principle of starting sequence can make a collapsed system back to a stable state.

3.6 Islanding objective and method of distribution network

3.6.1 **Tree model of distribution network**

When DGs are added into the network, the structure is not changed because of the radiational characteristic of network. The only change is one branch line is added to the original network. Generally, the number of branches or nodes will increase search path and add complexity when calculating and therefore, the network should be simplified based on following principles: when a DG is added to a network, there is no need to add a new node and it can be directly merged into one node. The power value of the node can be updated to $P_{Li} + P_{Gi}$ (P_{Li} is the load power of node $i$and P_{Gi} is the power of DG) and the node is viewed as power source node.

3.6.2 **Model establishment of distribution network separation**

The key to establish an islanding separation model is that utilize limited generated power to restore as much important load as possible and keep stable operation of island. In my thesis, the DGs capacity is the main point I focus on when separating a distributed system and the separation outcome should fulfill three conditions:

1. Supply power to important load in network as much as possible.
2. NSDG and NCDG cannot operate alone and they must be separated into the island with good operation capability.

3. At least one BDG should be contained in an island.

Based on the three conditions above, the objective function of islanding can be given:

$$f = \sum_{i=1}^{C_n} l_{Li} h_{Li} P_{Li} \quad (3.1)$$

In formula 3.1, l_{Li} represents if node i is putted into work. If node i is putted into work, l_{Li} is assigned 1 and l_{Li} is assigned 0 is not; h_{Li} is a parameter to represent the importance of load and here the index average node importance degree $\bar{\alpha}$ introduced in charpter two is utilized again and if node selected is power source, h_{Li} is assigned zero; P_{Li} is the power value of load i; C_n is total number of nodes. The bigger the value of objective function is, more important load with larger power demanding are contained in the islanding area.

At the same time, the objective function is subject to a series of constraints:

1. Power balance

$$\sum_{K=1}^{N_G} l_{Gk} P_{Gk} - \sum_{i=1}^{C_n} l_{Li} P_{Li} > 0 \quad (3.2)$$

In formula 3.2, l_{Gk} represents if generator k is contained in island. If generator k is in island, l_{Gk} is assigned 1 and l_{Gk} is assigned 0 if not; P_{Gk} representsthe capacity of generator k;N_G is the total number of generators; C_n is the number of nodes in island. In order to get a better separation scheme, those separation schemes which do not fulfill the power balance constraint but in the allowed range of load shedding can selectively remove some load which is not that important. If a scheme can satisfy the constraint by load shedding in an allowed range, the scheme is regarded as a rational scheme.

2. Power connectivity

$$\begin{cases} \exists L_g \in G, l_{Lg} = 1; \\ \exists L_d \in I, l_{Lg} = 1; \\ \forall l_{Li} = 1, \exists l_{Lj} = 1, n_{Li-Lj} = 1 \end{cases} \tag{3.3}$$

Where, $l_{Lg} = 1$ represents generator Lg is contained in island and $l_{Lg} = 0$ represents that generator Lg is not contained in island, namely, island contains at least one generator; samely, $l_{Lg} = 1$ represents that island contains at least one load; $n_{Li-Lj} = 1$ represents node *i* and node *j* are adjacent; *G* is the set of power source; *I* is the set of nodes.

3.6.3**Network connectivity examination based on Depth-First Search Algorithm (DFS)**

After getting a series of potential separation islanding scheme, the connectivity should be examined. Here DFS algorithm is utilized to check the connectivity of island. A version of DFS was investigated in the 19th century by French mathematician Charles Pierre Trémaux as a strategy for solving mazes [48]. The theory of DFS is that from an arbitrary node and explore as far as possible along each branch before backtracking. Therefore, all branches are to be searched after utilizing DFS.

An example is given to describe the algorithm in specific: start from a node *i* and select an unsearched branch *(i,j)* to search. When searching to node *j*, the node *j* is marked as 'visited' and after all paths from node *j* has been searched the searching should be backtracked to node *i*. As described above, all branches from node *i* are searched by using DFS. Based on the searching process, each network's connectivity is checked. If graph *G* is a connected graph, each node is marked and DFS finishes. If graph *G* is not a connected graph, an unmarked node is selected to be a new source node and DFS is employed again until every node is marked.

3.6.4 **Solution to islanding optimization problem**

DPSO which is employed in chapter two to solve the optimal network reconfiguration problem is still utilized on the islanding optimization problem, but the difference between chapter two and chapter three is the coding scheme. In chapter two, binary number 0 and 1 are used to represent if a certain line is selected and binary number is used to represent if a certain node is selected in chapter three. Therefore, when generating a potential solution matrix, it is necessary to change the matrix size. Besides, the power connectivity of random particle swarm should be checked by using DFS and the power connectivity standard is: each separation scheme has several islands; each island must contain at least one generator and one load as well. However, if the power in an island is not connected, several steps can be implemented to adjust the nodes contained in island as followed:

1. Randomized particle separation schemes are usually composed by several disconnected islands. By searching each island in scheme in turn, the binary number in island is set 0 if no generator exists in island.

2. If an island only has generators and no load exists, the binary number in the island should be set 0 or the generator can be classified into an adjacent island. Figure 3.6 demonstrates a simple case of operation method to the islands generated.

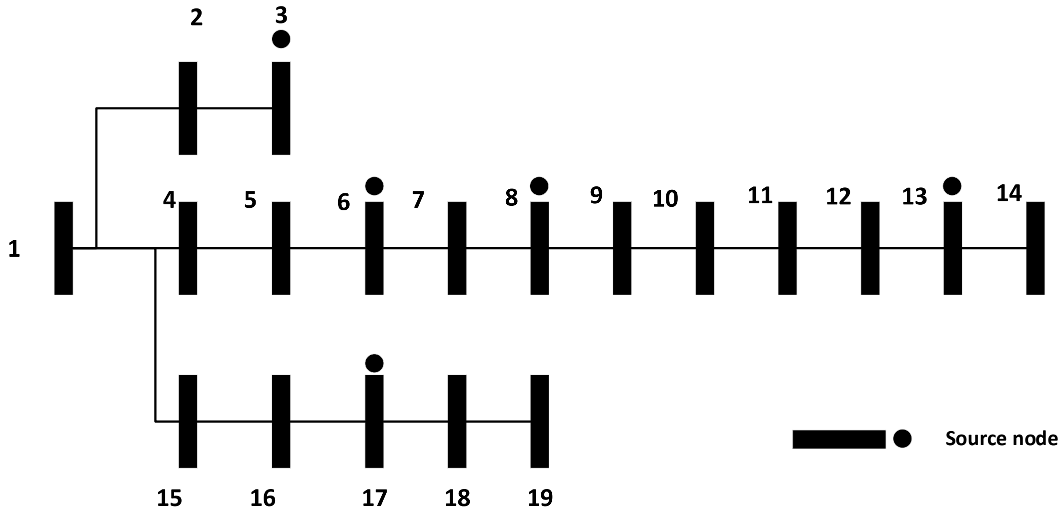

Figure 3-6 A 19 nodes one-line diagram

A series of 19-dimension matrix can be initialized randomly and the coding of one random matrix can be assumed as:

$$[0\ 0\ 0\ 1\ 1\ 1\ 1\ 0\ 1\ 1\ 1\ 0\ 1\ 1\ 1\ 0\ 1\ 0\ 0] \tag{3.4}$$

From this outcome matrix, node 4, 5, 7, 15 compose one island and two generators exist in this island. Therefore, it is a valid island situation and no adjustment needs to be done. Island contains node 9, 10, 11 and island contains node 13, 14 have no generator included in these two islands, so binary number of these five positions in the matrix should be converted into 0. Node 17 can be converted into 0 because this island has only one generator. Therefore, the outcome after adjustment is:

$$[0\ 0\ 0\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0] \tag{3.5}$$

The concrete adjustment method can be presented in the following flow chart:

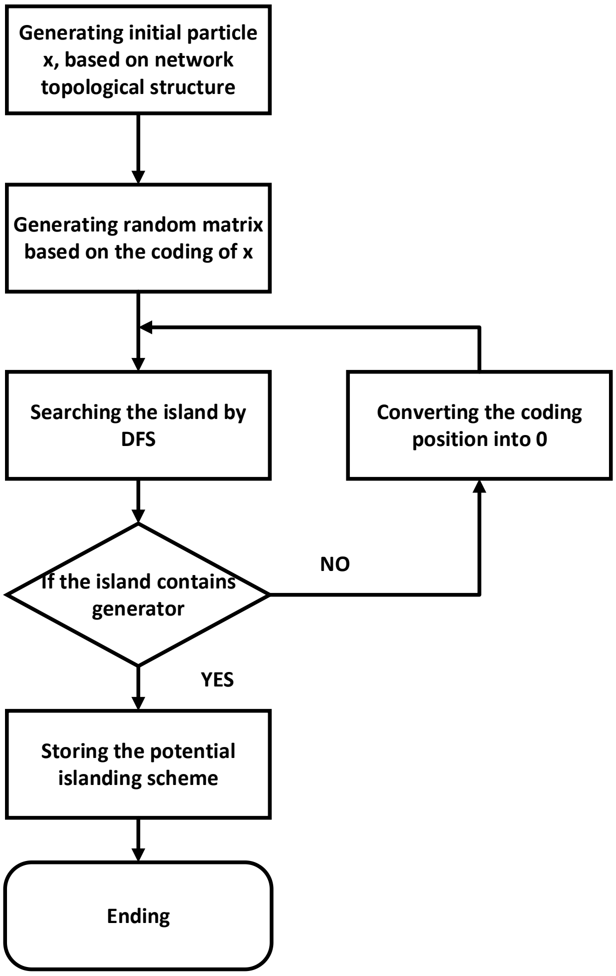

Figure 3-7 Flow chart of connectivity checking and adjustment method

After obtaining a series of potential island separation scheme, the fitness value can be calculated by utilizing DPSO and the scheme with the smallest fitness value is the relatively optimal scheme.

3.7 Conclusion and Future work

A simulation to emulate the stability of distribution network when DGs are switched in based on the starting sequence principle is conducted. The results showed that when the power supply cannot meet the demand of load in distribution network, the voltage and active power at load point will be decline to 0. Similarly, the frequency, voltage, active power and current at generator point become extremely unstable. After adding DGs to distribution network in sequence, the voltage and active power supply at load point convert into a stable state gradually. Therefore, it proves the switching in of DGs based on the starting sequence principle can convert an undersupply network into a stable network. Hence, when a large-scale of outage occur in distribution network, it is helpful to bring in DGs to enhance the power supply to distribution network and separate the distribution network to restore efficiently. In the latter part of chapter three, the distribution network separation objective function based on a maximum load restoration target is proposed and the optimization algorithm DPSO is proposed to solve the optimal problem.

Future work can be focused on the following aspects: In my thesis, the main separation objective is to restore as much load as possible in a separated island, so I only focus on the capacity of generators. However, the frequency and voltage fluctuation of DGs should be considered when DGs are added to the distribution network. Control method like Droop control, P/Q control can be utilized to investigate the problem.

Chapter 4 Case Study

4.1 Introduction

In this chapter, several standard test systems are proposed to be implemented and the chapter is divided into two main parts. In the first part, several IEEE standard test systems are proposed to test the effect of network reconfiguration scheme. In the second part, an islanding restoration scheme is tested on an IEEE standard system.

For the network reconfiguration scheme part, the IEEE 14-Bus system and IEEE 30-Bus are employed to test the effect of network reconfiguration scheme and indices α_i and β_i which weigh the importance of load based on network topological structure are calculated. A new index to weigh the importance of transmission lines called line betweenness centrality θ_i is added when calculate the reconfiguration efficiency. IEEE 57-Bus system is employed to test the effect of new reconfiguration scheme and the effect of old and new reconfiguration scheme are compared.

For the islanding restoration scheme part, the outage areas of an undersupply network are calculated in IEEE-57 system. To test the effect of different switching in position of DGs, cases are proposed, and the islanding restoration areas are obtained. Besides, an extreme situation that all large generators in distribution network are out of work and large generators are replaced by DGs is tested.

The remainder of this chapter is organized in the following way. The case study for network reconfiguration scheme which only considers the importance of load is tested on IEEE-14 and

IEEE 30-Bus system in section 4.2. A case to study the effect of θ_i on IEEE 57-Bus system is given in section 4.3. Two cases to test the effect of switching in position of DGs are given in section 4.4. The summary of this chapter is given in section 4.5.

4.2 Case study of network reconfiguration scheme based on topological structure

In this section, two cases about the network reconfiguration scheme based on topological characteristics are studied. Firstly, a network reconfiguration scheme is tested on IEEE 14-Bus. The network structure diagram of IEEE 14-Bus is shown below:

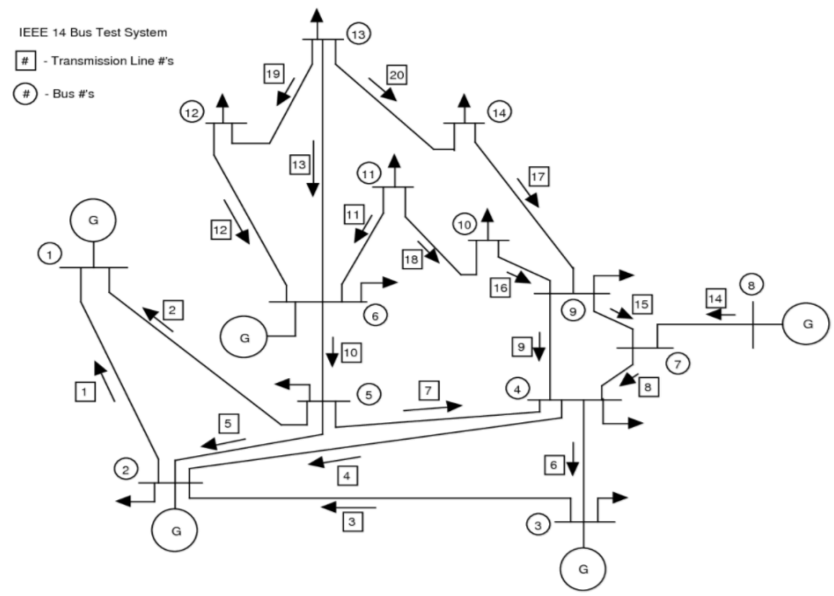

Figure 4-1 Diagram of IEEE 14-Bus system

The IEEE 14 Bus Test system represents a part of the American Electric Power System (in the Midwestern US) and it was proposed in February 1962. A hardcopy data was provided by Iraj Dabbagchi of AEP and entered in IEEE Common Data Format by Rich Christie at the University of Washington in August 1993 [49]. This test system has 14 bus, 5 generators, 11 loads and 20 transmission lines.

First, to calculate the node importance degree α_i of IEEE 14-Bus conveniently, the diagram of IEEE 14-Bus system should be converted into one-line diagram, which only consists of nodes and lines. The one-line diagram of IEEE-14 system with a mark of nodes and line is given below:

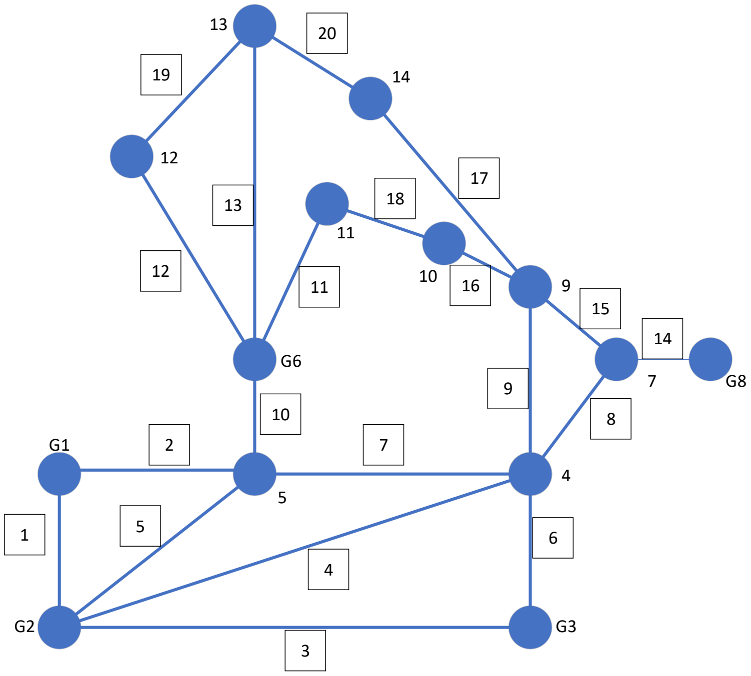

Figure 4-2 One-line diagram of IEEE 14-Bus system

Secondly, the index node importance of degree α_i that reflects the importance of nodes is calculated:

Node No.	**α_i**	**Node No.**	**α_i**
1	0.0110	8	0.0110
2	0.0134	9	0.0125
3	0.0127	10	0.0124
4	0.0133	11	0.0122
5	0.0144	12	0.0119
6	0.0144	13	0.0125
7	0.0123	14	0.0119

Table 4-1 Node importance degree of nodes in IEEE 14-Bus system

The calculation of nodes importance degree obtains a smaller value for some of the source nodes because of a small importance based on graph theory. For instance, the node importance degree of source node 1 is smaller than load node 4. Therefore, it is necessary to identify the relative importance of power sources and loads to distinguish the difference between source nodes and load nodes. Two regulatory factors are multiplied to α_i to normalize the node importance degree. The importance rank of source nodes in IEEE 14-Bus is given below and it is should be noted that the node 1 is assumed to be crank power in the initial stage, so it has the highest priority among these five generators:

No.	**1**	**2**	**3**	**6**	**8**
Rank	1	0.98	0.85	0.85	0.80

Table 4-2 Importance rank of source nodes

The importance rank of load nodes in IEEE 14-Busisgiven below:

No.	**Rank**	**No.**	**Rank**
4	0.85	12	0.66
5	0.78	13	0.85
7	0.88	14	0.64
9	0.90		
10	1		
11	0.68		

Table 4-3 Importance rank of load nodes

Thirdly, the clustering coefficient β_i which represents the degree to which nodes in a graph tend to cluster together is calculated:

Node No.	$\boldsymbol{\beta_i}$	**Node No.**	$\boldsymbol{\beta_i}$
1	1	8	0
2	1/3	9	1/6
3	1/6	10	0
4	1/3	11	0
5	1/3	12	1

6	1/6	13	1/3
7	1/3	14	0

Table 4-4 Clustering coefficient of loads

After obtaining these topological characteristics of IEEE 14-Bus system, DPSO is utilized and programmed with MATLAB to calculate the best fitness value of the objective functionη. The dimension of particle N_l, the population size N and maximum iteration step t_{max} take value of 20, 30 and 150 respectively.

Then, a series of random matrixes are initialized. The power connectivity is checked by using DFS and the global best and person best position can be obtained after pre-set iteration steps. Several relative optimal network reconfiguration schemes are given in table 4-5:

No.	**1**	**2**
Branches Involved	1,3,5,6,8,10,13,14,15	1,3,5,6,8,10,13,14,15,16
$\bar{\alpha}$	0.813	0.790
$\bar{\beta}$	0.215	0.256
f	0.296	0.324

Table 4-5 Network reconfiguration scheme for IEEE 14-Bus system

Two relative optimal network reconfiguration schemes are obtained and the scheme 1 has a smaller fitness value, which means the network structure selected to be restored is the most efficient one. Therefore, scheme 1 is the best network reconfiguration scheme for IEEE 14-Bus system after blackout. The transmission lines selected which is colored red and load selected are shown in figure 4.3.

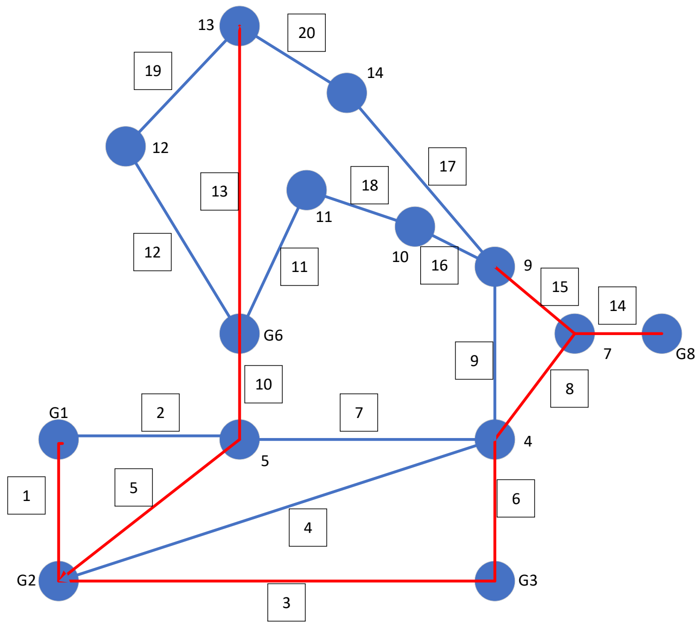

Figure 4-3 Transmission lines and load selected in reconfiguration scheme

In this case, no transmission lines exceed the line distance constraints and no exceeding transmission lines capacity happens, so it is a reasonable reconfiguration scheme. Besides, the outcome shows that after 120 iteration steps, the best fitness value is obtained and when the best fitness value calculation is repeated for 30 times, the outcome presents a small fluctuation. It shows that DPSO algorithm has a very stability and a very fast calculation speed. Figure 4.4 shows the motion trail of best particle and the distribution of best fitness value with 30 times iteration.

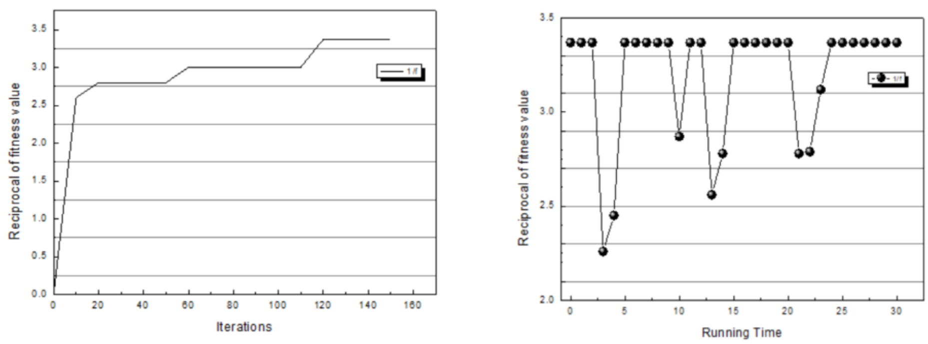

Figure 4-4 Motion trails of best particle and best fitness value distribution

Similarly, the most efficient network reconfiguration scheme of IEEE 30-Bus system can be obtained by the same optimization method and procedure. The one-line diagram of IEEE 30-Bus system is shown below:

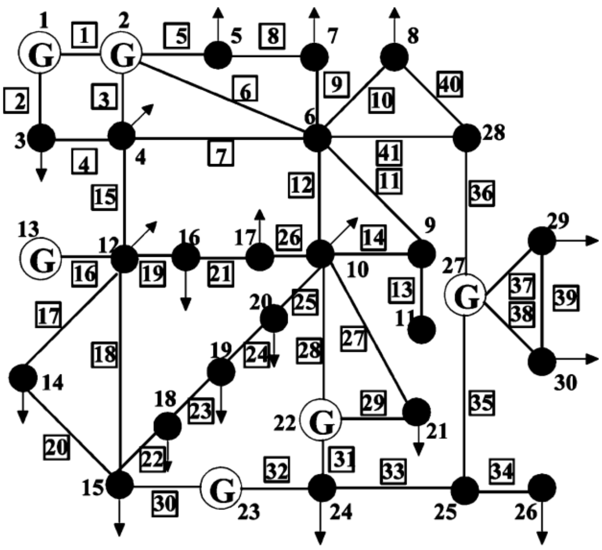

Figure 4-5 One-line diagram of IEEE 30-Bus system

The IEEE 30 Bus Test Case represents a portion of the American Electric Power System (in the Midwestern US) and it was proposed on December, 1961. This test case contains30 buses, 6 generators and 40 branches [50].

The node importance degree of 30 nodes, importance rank of source nodes and importance rank of load nodes are presented below:

No.	α_i	No.	α_i	No.	α_i
1	0.0110	11	0.0103	21	0.0120
2	0.0125	12	0.0135	22	0.0125
3	0.0110	13	0.0108	23	0.0123
4	0.0133	14	0.0115	24	0.0130
5	0.0109	15	0.0138	25	0.0104
6	0.0165	16	0.0114	26	0.0130
7	0.0110	17	0.0114	27	0.0126
8	0.0115	18	0.0116	28	0.0126

9	0.0119	19	0.0116	29	0.0114
10	0.0142	20	0.0116	30	0.0114

Table 4-6 Node importance degree of IEEE-30 nodes

No.	**1**	**2**	**13**	**22**	**23**	**27**
Rank	1	0.95	0.80	0.93	0.88	1

Table 4-7 Importance rank of source nodes

No.	**Rank**	**No.**	**Rank**	**No.**	**Rank**
3	0.68	11	0.65	20	0.72
4	0.83	12	0.85	21	0.64
5	0.68	14	0.63	24	0.78
6	0.70	15	0.83	25	0.77
7	0.68	16	0.67	26	0.67
8	0.70	17	0.67	28	0.79
9	0.73	18	0.72	29	0.72
10	1.00	19	0.72	30	0.72

Table 4-8 Importance rank of loads

The dimension of particle N_l, the population size N and maximum iteration step t_{max} take value of 30, 30 and 150 respectively. Three valid network reconfiguration schemes are shown in table 4-9:

No.	**1**	**2**	**3**
Branches Involved	1,3,6,12,15,16,18,28,30,31, 33,35,36,40	1,3,5,11,14,15,16,18,28, 30,31,32,35,36,41	1,3,6,8,9,12,15,16 18,28,30,34,35,36,41
$\bar{\alpha}$	0.834	0.817	0.790
$\bar{\beta}$	0.256	0.311	0.322
f	0.306	0.380	0.408

Table 4-9 Reconfiguration schemes for IEEE 30-Bus system

The scheme 1 has the smallest fitness value, so it is the optimal network reconfiguration scheme. The most efficient reconfiguration scheme structure in IEEE 30-Bus system is shown below:

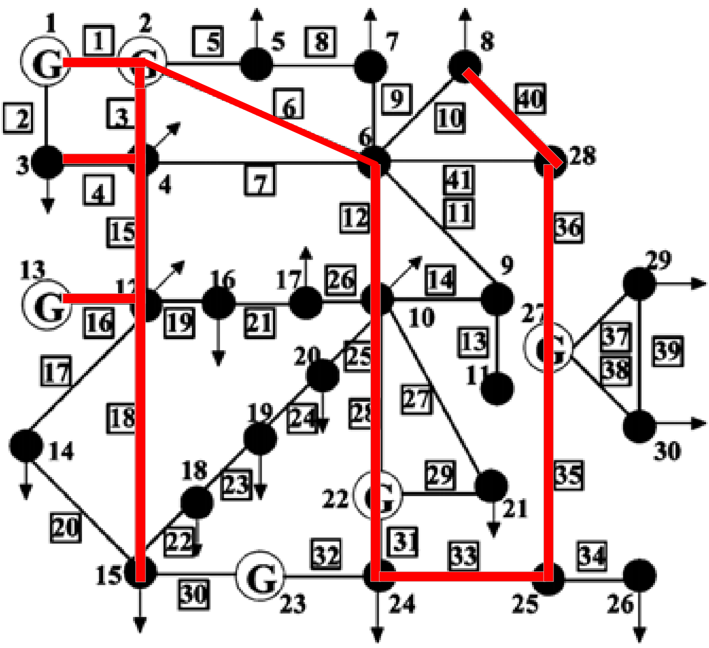

Figure 4-6 Transmission lines and load selected in reconfiguration scheme

In this case, no transmission lines exceed the line distance constraints and no exceeding transmission lines capacity happens, so it is a reasonable reconfiguration scheme.

4.3 Case study of an evolved network reconfiguration scheme

In section 4.2, a network reconfiguration method based on node importance degree and clustering coefficient is tested on IEEE 14-Bus system and IEEE 30-Bus system. A relatively optimal distribution network reconfiguration scheme is formulated. However, the reconfiguration scheme only considers the importance of load and ignores the significance of transmission lines. In this section, an evolved network reconfiguration scheme that considers the importance of transmission lines is employed. Figure 4.7 shows the diagram of IEEE 57-Bus system and it contains 7 generators and 80 transmission lines, the node importance degree of IEEE-57 system is presented in Appendix A [51].

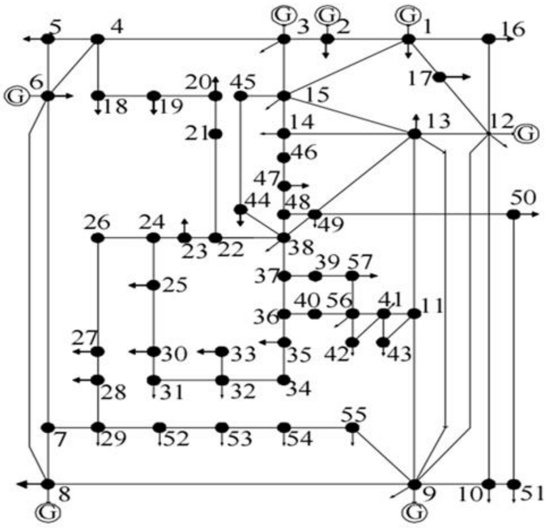

Figure 4-7 IEEE 57-Bus system

By calculating the objective function of section 4.2, the loads and transmission lines selected to be restored are presented below:

No.	**1**
Branches Involved	1-2,2-3,3-15,13-15,14-15, 14-46,46-47,47-48,1-17,12-17,13-15,9-13,6-8,8-9
$\bar{\boldsymbol{\alpha}}$	0.886
$\bar{\boldsymbol{\beta}}$	0.287
$\boldsymbol{f}$	0.325

Table 4-10 Reconfiguration schemes for IEEE 57-Bus system

Bringing in the line betweenness β_i into the objective function which is presented in Appendix B, the new network reconfiguration is shown in table 4-11.

No.	**1**
Branches Involved	1-2,2-3,3-15,13-15,14-15, 14-46,46-47,47-48,1-17,12-17,13-15,9-13,6-8,8-9,38-48,22-28,36-37,37-38
$\bar{\boldsymbol{\alpha}}$	0.893
$\bar{\boldsymbol{\beta}}$	0.303
$\boldsymbol{\mu\bar{\theta}}$	0.254
$\boldsymbol{f}$	0.264

Table 4-11 New reconfiguration schemes for IEEE 57-Bus system

Comparing the new reconfiguration scheme which considers the importance of transmission lines with the old one, 4 new transmission lines are included in new scheme.

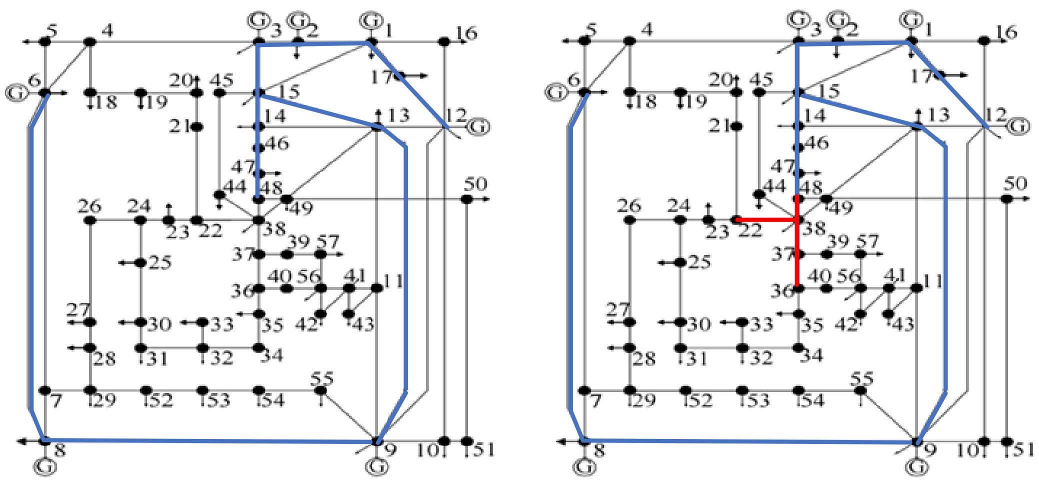

Figure 4-8 Comparison of old and new reconfiguration scheme

By analyzing the outcome of new reconfiguration scheme, the four transmission lines are important for the whole systems because they connect the rest network and they are also the paths to transfer power generated by large generators to the rest of loads which would be restored later.

4.4 The effect of switching in position of DGs in distribution network

The utilization of distributed generators (DGs) has risen sharply in distribution network and it plays a critical role in the future Smart Grid to modernize the power grids. In addition, the emerging Smart Grid technology, which enables self-sufficient power systems with DGs, provides further opportunities to enhance the self-healing capability. Therefore, three small cases are completed to test the effect of switching in position of DGs on distribution network restoration in this section. The work is also completed on the IEEE 57-Bus test system. In the first case, the generator three which is circled in red in figure 4.9 has a capacity of 40 MW and it is assumed to be removed. The power flow of the whole system is calculated by using Newton-Raphson method in Matlab.The outcome shows that node 3 has no sufficient power supply to the rest part of network and the rest part of the network is also affected slightly by the removing of generator 3 because of a local effect. Therefore, the transmission lines 2-3, 3-4 and 3-15 are no longer have sufficient power transfer and the power of rest part of loads which are circled in blue are supplied by the remaining 6 generators stably.

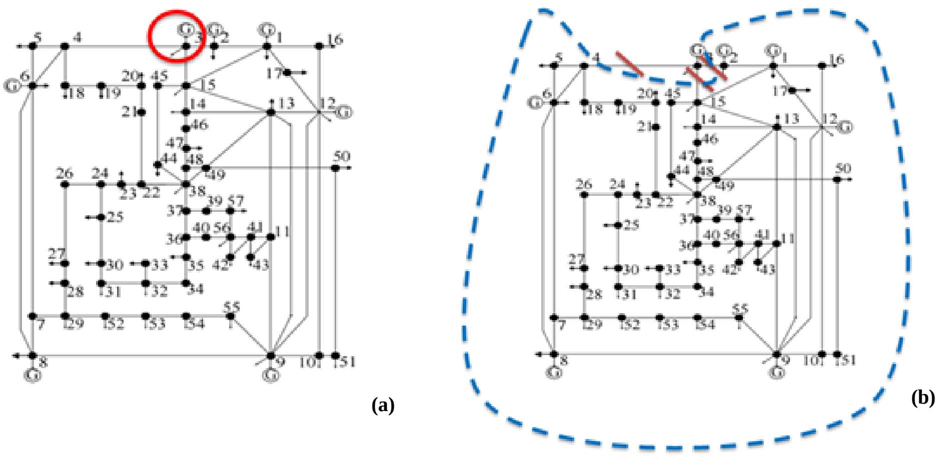

Figure 4-9 (a) Diagram that generator 3 is removed (b) Stable operation parts of IEEE 57-Bus system

In order to restore the three transmission lines, DG1 with 21.04 MW capacities and DG2 with 21.0548 MW capacities are added into the network at node point 4 and 15, respectively. By adjusting the capacity parameters in MATLAB program, the outcome shows the three transmission lines have power transfer again and the whole system back to a stable operation state. The figure 4-8 is the network with two DGs added to node 4 and node 15.

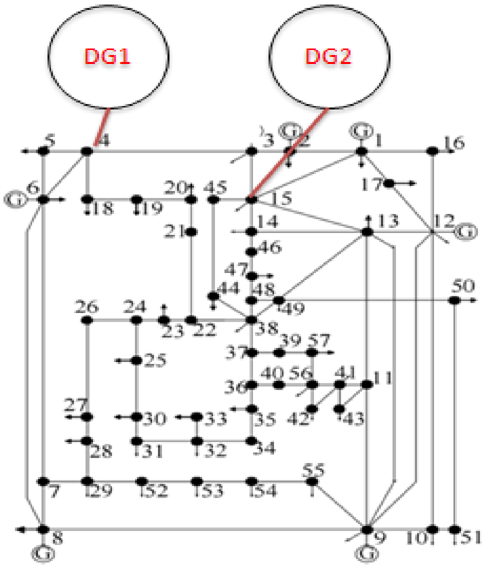

Figure 4-10Switching in points of two DGs

In the second case, a power supply decline is simulated. The power of generators at node 1, 8 and 12 which are 479 MW, 450MW and 310 MW respectively are decreased to 225 MW, 225 MW and 150 MW respectively. Totally 639 MW is declined. The power flow of the power decline system is calculated by using Newton-Raphson method and the three outage areas because of a power shortage is shown in figure 4.11.

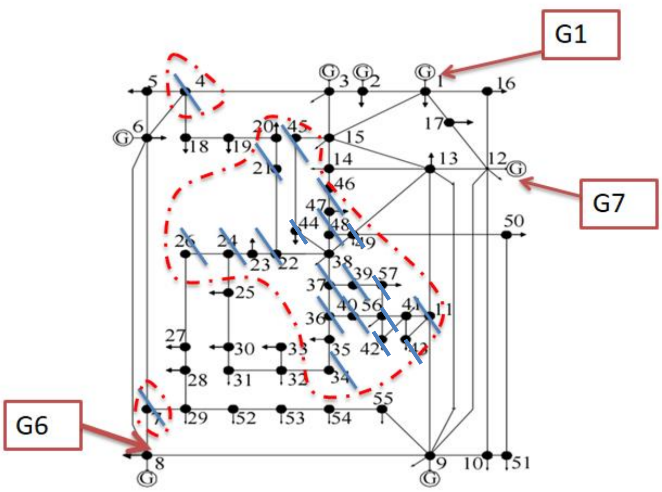

Figure 4-11 Three outage areas after power decline

To restore as much important loads as possible in the outage areas, three DGs with same 50 MW capacities are added to node 18, 29 and 32 respectively. The reason why three DGs are added at these three nodes is the local effect in power network and the DGs can affect the power supply of adjacent loads. After calculation, the load 4, 7, 34 and 35 are restored but the rest part of outage area is still blackout. In figure 4.12, the red area represents the area which is still blackout and the blue areas are the areas restored successfully.

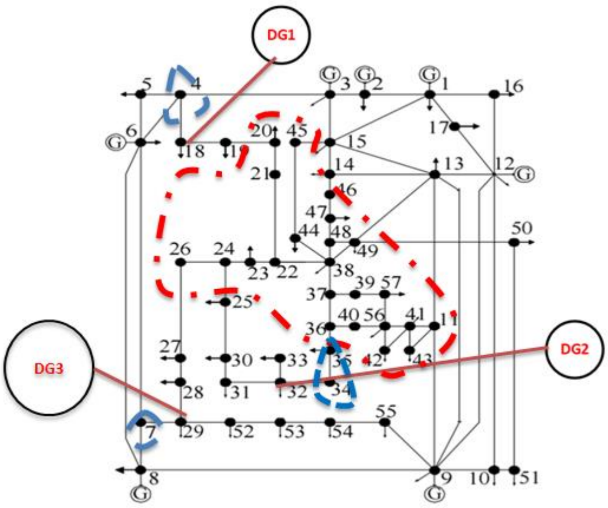

Figure 4-12 Areas restored successfully and unsuccessfully

In the third case, three same DGs are switched in within the limits of outage area and nodes 20, 34 and 44 are selected to be added DGs. Figure 4.13 showed the switching points of three DGs.

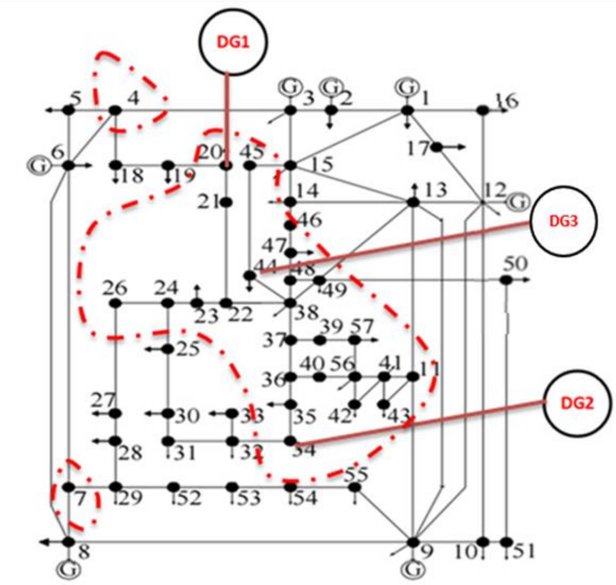

Figure 4-13 Switching points of three DGs

According to the objective function $f = \sum_{i=1}^{C_n} l_{Li} h_{Li} P_{Li}$, the best fitness value of potential islanding scheme is obtained by using DPSO in which the dimension of particle N_l, the population size N and maximum iteration step t_{max} take values of 27, 200 and 150 respectively. The best fitness value calculated by DPSO is 0.0031. The motion trail of optimal particle and distribution of optimal solution are shown in figure 4.14 (a) and (b), respectively.

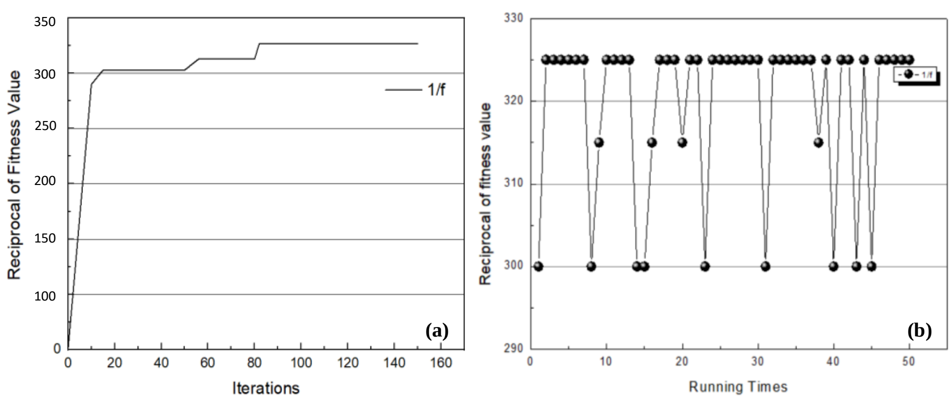

Figure 4-14 (a) Motion trail of optimal particle (b) Distribution of optimal solution

From figure 4.14 (a), the optimal solution is obtained at 80 iterations which indicates that DPSO can find the optimal solution quickly. From figure 4.10 (b), it shows that the DPSO finds 37 times optimal solutions and the probability to find optimal solution is 74%. Besides, the difference between the worst and optimal solution is small which indicates a good stability of DPSO algorithm.

The nodes matrix is obtained after DPSO calculation:

$$[0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0] \quad (4.1)$$

The restoration areas are shown in table 4-12:

No.	Load
Area1	20,21,22,23,24,25,26
Area2	34,35,36,37,38,39,40
Area3	44,45

Table 4-12 Islands of IEEE-57 system

Consequently, the loads which are selected to be restored are shown in figure 4-15:

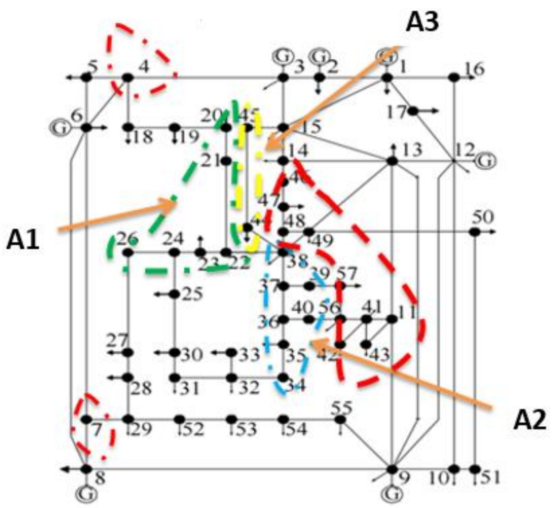

Figure 4-15 Areas restored successfully and unsuccessfully when DGs are added in outage area

The green, yellow and blue parts are areas that restore successfully when DGs are added to nodes 20, 34, 44. Because of the limited power supply by DGs and the local effect, the loads in red areas still cannot be restored. Besides, the power balance constraint $\sum_{K=1}^{N_G} l_{Gk}P_{Gk} - \sum_{i=1}^{C_n} l_{Li}P_{Li} > 0$ is checked after islands are separated. By calculating the power demanding in island areas by MATLAB, the power demanding of area 1 is 49.8 MW; power demanding in area two is 49.7 MW; power demanding in area three is 48.8 MW. The power demanding are all smaller than power supplied by DG in those areas, so a reasonable islanding scheme is obtained.

4.5 Conclusion and future work

In this chapter, two IEEE test systems are employed to study the validity of network reconfiguration scheme proposed in chapter. After calculating the node importance of nodes and clustering coefficient of nodes, DPSO is used to find the optimization solution of objective function. Two reasonable reconfiguration schemes are shown in this chapter. Then, the index line betweenness centrality which describes the importance of transmission lines is considered. An IEEE 57-Bus system is used to compare the new and old reconfiguration scheme and outcome is analyzed. Consequently, most of important loads and transmission lines are contained in the reconfiguration scheme proposed. In the second half of this chapter, three cases are studied to find the effect of DGs' switching in position to the islanding restoration scheme. It is found that the DGs can restore part of outage loads in blackout areas because of the capacity limitation and local effect which proves DGs can enhance the stability of distribution network and it is practical for restoring important loads at the primary stage of network restoration.

The future work can be focused on following aspects: firstly, based on the reconfiguration scheme, the sequence of switching operations to bring the outage system to target system should be considered. Secondly, the voltage and frequency unstable problem of DGs when they are brought in network should be studied. Thirdly, the rationality of proposed reconfiguration strategy and islanding strategy should be studied on meshed distribution network.

Chapter 5 Conclusions

In this thesis, two kinds of power network restoration planning problems are investigated. A high efficient network reconfiguration scheme and a comprehensive islanding method to distribution network with DGs are proposed. The ideas and conclusions are as follows.

Firstly, aiming at the first stage of power network restoration, namely, determining a relative optimal configuration as a restoration target, a reconfiguration scheme based on topological characteristics of scale-free networks is studied. Combining with graph theory, indices like node importance degree, line betweenness centrality and clustering coefficient are utilized to weigh the loads and transmission lines' importance in the test network. Then, the optimization solution objective functionηwhich reflects the efficiency of potential reconfiguration scheme by including as many important loads and significant transmission lines is calculated by using DPSO. IEEE 14-Bus system, IEEE 30-Bus system and IEEE 57-Bus system are employed to test the validity of network reconfiguration method and three reasonable network reconfiguration schemes which contain most of important loads and key transmission lines are presented in case study.

Secondly, to enhance the network restoration efficiency and restore as many important loads as possible at the primary stage, DGs which have flexibility and convenience merits are utilized. The start sequence of DGs is proposed based on the selection principle and classification of DGs. Then a stability analysis to test if the bringing in of DGs can make a system gets a steady state ultimately is completed. The outcome shows that an undersupply network can be restored successfully if DGs are added to network in sequence based on the start principle of DGs. The validity of islanding strategy is tested on IEEE 57-Bus system and DPSO is still used to obtain the optimization solution. To adding DGs to test system, the capacity of large generators in test system is declined. The islanding outcomes show that restoration areas are variationally with the switching in position. Besides, most of important loads are restored, however, there are still a few loads are not restored because of the capacity of generators and local effect.

The future work can be focused on following aspects:

- Based on graph theory, more comprehensive indices which can describe the topological characteristics of network should be utilized.
- The rationality of network reconfiguration strategy and islanding strategy on meshed distribution network should be studied.
- Blackstart includes two steps: propose an optimal reconfiguration scheme as a restoration target and organize a starting sequence to bring the outage power system into the target network proposed before. So, the second step should formulate a switching operation sequence scheme to restore the outage network to the target network.
- The voltage and frequency unstable problem of DGs when they are brought in network should be studied and the control method should be investigated.

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Appendices

Appendix A：Node Importance Degree of IEEE 57-Bus System

No.	α_i	No.	α_i	No.	α_i	No.	α_i
1	0.0141	16	0.0117	31	0.0126	46	0.0117
2	0.0113	17	0.0117	32	0.0132	47	0.0117
3	0.0124	18	0.0117	33	0.0110	48	0.0126
4	0.0118	19	0.0117	34	0.0117	49	0.0122
5	0.0108	20	0.0117	35	0.0117	50	0.0117
6	0.0135	21	0.0117	36	0.0126	51	0.0117
7	0.0111	22	0.0126	37	0.0117	52	0.0117
8	0.0122	23	0.0117	38	0.0117	53	0.0117
9	0.0164	24	0.0126	39	0.0156	54	0.0117
10	0.0145	25	0.0117	40	0.0117	55	0.0117
11	0.0138	26	0.0117	41	0.0131	56	0.0122
12	0.0164	27	0.0117	42	0.0132	57	0.0115
13	0.0133	28	0.0117	43	0.0131		
14	0.0144	29	0.0117	44	0.0132		
15	0.0146	30	0.0117	45	0.0117		

Appendix B：Line Betweenness Centrality of IEEE 57-Bus System

No.	θ_i	No.	θ_i	No.	θ_i	No.	θ_i
1	0.921	21	0.827	41	0.875	61	0.831
2	0.756	22	0.838	42	0.886	62	0.812
3	0.856	23	0.865	43	0.898	63	0.935
4	0.845	24	0.776	44	0.892	64	0.916
5	0.643	25	0.864	45	0.871	65	0.937
6	0.786	26	0.752	46	0.966	66	0.963
7	0.789	27	0.721	47	0.954	67	0.977
8	0.846	28	0.832	48	0.943	68	0.839
9	0.887	29	0.866	49	0.832	69	0.854
10	0.934	30	0.876	50	0.826	70	0.834
11	0.912	31	0.857	51	0.777	71	0.757
12	0.856	32	0.958	52	0.778	72	0.763
13	0.898	33	0.944	53	0.782	73	0.747
14	0.766	34	0.833	54	0.744	74	0.865
15	0.756	35	0.866	55	0.835	75	0.876
16	0.676	36	0.937	56	0.724	76	0.782
17	0.897	37	0.828	57	0.889	77	0.867
18	0.987	38	0.954	58	0.886	78	0.836
19	0.923	39	0.814	59	0.888	79	0.849
20	0.933	40	0.858	60	0.844	80	0.845

Appendix C：Node Importance Degree of IEEE 57-Bus System

Bus No.	P_{Gi}	P_{Di}	Q_{Di}	V_i	V_i^{max}	V_i^{min}
1	4.7926	0.5500	0.1700	1.0400	1.10	0.90
2	0.0000	0.0300	0.8800	1.0100	1.10	0.90
3	0.4000	0.4100	0.2100	0.9850	1.10	0.90
4	0.0000	0.0000	0.0000	0.9783	1.06	0.94
5	0.0000	0.1300	0.0400	0.9757	1.06	0.94
6	0.0000	0.7500	0.0200	0.9800	1.10	0.90
7	0.0000	0.0000	0.0000	0.9819	1.06	0.94
8	4.5000	1.5000	0.2200	1.0050	1.10	0.90
9	0.0000	1.2100	0.2600	0.9800	1.06	0.94
10	0.0000	0.0500	0.0200	0.9857	1.10	0.90
11	0.0000	0.0000	0.0000	0.9732	1.06	0.94
12	3.1000	3.7700	0.2400	1.0150	1.10	0.90
13	0.0000	0.1800	0.0230	0.9779	1.06	0.94
14	0.0000	0.1050	0.0530	0.9688	1.06	0.94
15	0.0000	0.2200	0.0500	0.9871	1.06	0.94
16	0.0000	0.4300	0.0300	1.0133	1.06	0.94
17	0.0000	0.4200	0.0800	1.0174	1.06	0.94
18	0.0000	0.2720	0.0980	0.9751	1.06	0.94
19	0.0000	0.0330	0.0060	0.9515	1.06	0.94
20	0.0000	0.0230	0.0100	0.9497	1.06	0.94
21	0.0000	0.0000	0.0000	1.0004	1.06	0.94
22	0.0000	0.0000	0.0000	1.0029	1.06	0.94
23	0.0000	0.0630	0.0210	1.0010	1.06	0.94
24	0.0000	0.0000	0.0000	0.9842	1.06	0.94
25	0.0000	0.0630	0.0320	0.9378	1.06	0.94
26	0.0000	0.0000	0.0000	0.9453	1.06	0.94
27	0.0000	0.0930	0.0050	0.9727	1.06	0.94
28	0.0000	0.0460	0.0230	0.9896	1.06	0.94
29	0.0000	0.1700	0.0260	1.0043	1.06	0.94
30	0.0000	0.0360	0.0180	0.9201	1.06	0.94
31	0.0000	0.0580	0.0290	0.8999	1.06	0.94
32	0.0000	0.0160	0.0080	0.9259	1.06	0.94
33	0.0000	0.0380	0.0190	0.9236	1.06	0.94
34	0.0000	0.0000	0.0000	0.9491	1.06	0.94
35	0.0000	0.0600	0.0300	0.9575	1.06	0.94
36	0.0000	0.0000	0.0000	0.9682	1.06	0.94
37	0.0000	0.0000	0.0000	0.9778	1.06	0.94
38	0.0000	0.1400	0.0700	1.0071	1.06	0.94
39	0.0000	0.0000	0.0000	0.9758	1.06	0.94
40	0.0000	0.0000	0.0000	0.9653	1.06	0.94
41	0.0000	0.0630	0.0300	0.9938	1.06	0.94
42	0.0000	0.0710	0.0440	0.9631	1.06	0.94
43	0.0000	0.0200	0.0100	1.0083	1.06	0.94
44	0.0000	0.1200	0.0180	1.0121	1.06	0.94
45	0.0000	0.0000	0.0000	1.0334	1.06	0.94
46	0.0000	0.0000	0.0000	1.0570	1.06	0.94
47	0.0000	0.2970	0.1160	1.0292	1.06	0.94
48	0.0000	0.0000	0.0000	1.0229	1.06	0.94
49	0.0000	0.1800	0.0850	1.0328	1.06	0.94
50	0.0000	0.2100	0.1050	1.0207	1.06	0.94
51	0.0000	0.1800	0.0530	1.0513	1.06	0.94
52	0.0000	0.0490	0.0220	0.9676	1.06	0.94
53	0.0000	0.2000	0.1000	0.9546	1.06	0.94
54	0.0000	0.0410	0.0140	0.9866	1.06	0.94
55	0.0000	0.0680	0.0340	1.0276	1.06	0.94
56	0.0000	0.0760	0.0220	0.9641	1.06	0.94
57	0.0000	0.0670	0.0200	0.9600	1.06	0.94

53	22	38	0.0192	0.0295	0.0000	99.00
54	11	41	0.0000	0.7490	0.0000	99.00
55	41	42	0.2070	0.3520	0.0000	99.00
56	41	43	0.0000	0.4120	0.0000	99.00
57	38	44	0.0289	0.0585	0.0020	99.00
58	15	45	0.0000	0.1042	0.0000	99.00
59	14	46	0.0000	0.0735	0.0000	99.00
60	46	47	0.0230	0.0680	0.0032	99.00
61	47	48	0.0182	0.0233	0.0000	99.00
62	48	49	0.0834	0.1290	0.0048	99.00
63	49	50	0.0801	0.1280	0.0000	99.00
64	50	51	0.1386	0.2200	0.0000	99.00
65	10	51	0.0000	0.0712	0.0000	99.00
66	13	49	0.0000	0.1910	0.0000	99.00
67	29	52	0.1442	0.1870	0.0000	99.00
68	52	53	0.0762	0.0984	0.0000	99.00
69	53	54	0.1878	0.2320	0.0000	99.00
70	54	55	0.1732	0.2265	0.0000	99.00
71	11	43	0.0000	0.1530	0.0000	99.00
72	44	45	0.0624	0.1242	0.0040	99.00
73	40	56	0.0000	1.1950	0.0000	99.00
74	56	41	0.5530	0.5490	0.0000	99.00
75	56	42	0.2125	0.3540	0.0000	99.00
76	39	57	0.0000	1.3550	0.0000	99.00
77	57	56	0.1740	0.2600	0.0000	99.00
78	38	49	0.1150	0.1770	0.0030	99.00
79	38	48	0.0312	0.0482	0.0000	99.00
80	9	55	0.0000	0.1205	0.0000	99.00