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Study of Modern Reconfiguration on Distribution System based on Flow Algorithms

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Study of Modern Reconfiguration on Distribution System based on Flow Algorithms

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Abstract

The conventional electrical distribution power system is facing with several new challenges, as the requirement of online management, the interconnection of the distributed generators (DG) and time-varying nature of load files. As a result, the efficiency of distribution system management is required to be improved. This thesis mainly focuses on modern reconfiguration techniques, and highly efficient reconfiguration method is proposed respectively to cope with the above mentioned challenges.

This thesis firstly focuses on online reconfiguration of distribution network for loss minimization. The relationship between line loss and voltage profile is investigated on the distribution network model. Based on the observed properties, a new reconfiguration algorithm, named intelligent flow algorithm (IFA), is proposed. The proposed IFA finds the optimal network configuration in a short computation time based on the monitored load distribution. The proposed algorithm is validated by simulations with 33-bus and 43-bus test distribution systems. Simulation results show that the proposed IFA is accurate, fast, stable and robust.

Interconnection of the DGs to the power system would cause the efficiency degradation of distribution system management. Minimization of voltage deviation by network reconfiguration is one of the important solutions of this problem. The authors accordingly proposes an extension of IFA, named extended flow algorithm (EFA), which can more effectively find the optimal network configuration for the distribution system with massive DG installation. The EFA is a two-stage method, where the configuration uniformly supplying loads, named balanced configuration, is generated firstly, and the optimal configuration is searched based on the balanced configuration by an improved branch-exchange approach. Accordingly, more simplifications are given to the EFA to improve its computation speed on large scale system. The performance of the proposed methods is tested through case studies with four test distribution systems on the MATLAB environment. The enhanced performance of the EFA to cope with DG installation and large scale system is clearly established.

Network reconfiguration has also been involved in voltage deviations by considering the time-varying nature of loads. With the integration of renewable energies to the power grid, optimal configuration should be determined corresponding to the variations in loads and DGs. Based on the previous studies, a long-term reconfiguration method named long-term expanded flow algorithm (LTEFA), which improves timeliness of

configuration behaving on time-varying load, is proposed to substitute for the past short term ones. Moreover, optimal reconfiguration instants are achieved by a novel approach of optimal daily schedule named accumulation of unbalanced load distribution (AULD) based on the trade-off of switching operations costs and voltage deviations reduction. The proposed methods were tested by case studies of two test distribution systems under real-time measured data with interconnection of photovoltaic (PV) generators in the MATLAB environment. By applying the proposed methods, the total operating cost of the network is reduced significantly within reasonable computation time, and its efficiency was also compared with fixed configuration, online reconfiguration policies and daily schedule proposed on other publications.

As a brief conclusion, the reconfiguration techniques proposed in this research are proved to be successful, applicable and also in high efficiency, which is expected to bring reconfiguration issue of distribution system into the next generation.

Keywords: distribution system reconfiguration, power distribution planning, distributed generation, large scale power system, minimization of voltage deviation, daily optimal schedule of reconfiguration.

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Chapter 1. Introduction

1.1 Distribution System Operation

1.1.1 Construction of Electrical Power Systems [1]

An electrical power system contains all electric equipment necessary to supply the consumers with electric energy, as generators, transformers, transmission lines, cables and switches. The electrical power system is divided mainly into three parts, as shown in Fig. 1.1.

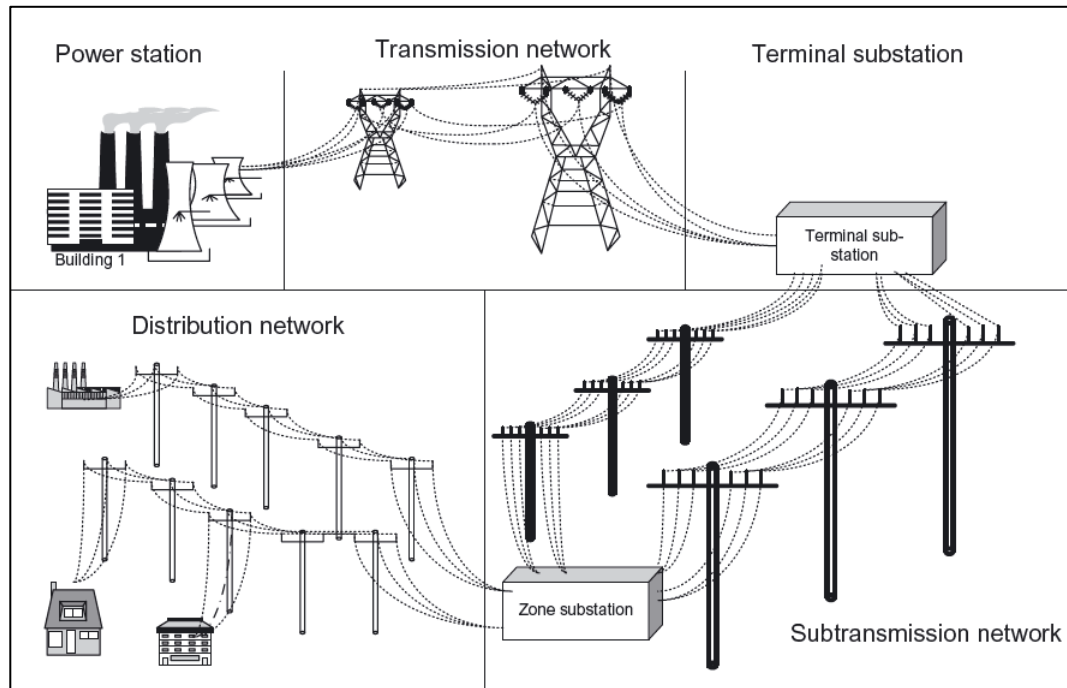


Fig. 1.1. Electrical power system [1].

The first part of the electric system is the generation system, where the electricity is produced in power plants owned by an electric utility or any independent supplier. The generated power is at the generation voltage level [2], which is increased by using step-up power transformers, in order to transmit the power over long distances considering economic conditions. The second part is the transmission system that is

responsible to delivery electric power to load centers through transmission lines. The transmitted power is increased as extra high voltage (EHV) [3] or high voltage (HV). The third part is the distribution system where the voltage is stepped down at the substations to the medium voltage (MV) or low voltage (LV) level, where power is distributed from load centers to customers.

1.1.2 Distribution Systems [1]

The modern distribution system begins with the primary circuit out from the substation and ends as the secondary service enters the customer's meter socket. Distribution circuits serve many customers, which are fed from a transformer in the substation. The voltages of distribution systems are reduced from the high values used for power transmission to the low values. The transition from transmission to distribution in a power substation has the following functions [4]:

- 1) Circuit breakers or switches disconnect the substation from the transmission grid or from distribution lines.
- 2) Transformers step down voltages from 35 kV or more, down to distribution voltages, which are medium voltage circuits, usually considered as 600-35,000 V.
- 3) From the transformer, power goes to the bus and be split as the distribution power in multiple directions. The bus distributes power to distribution lines, which are transformed to the customers.

A few of extra-large consumers are directly fed from distribution voltages, but most customers are connected to a transformer which reduces the distribution voltage once more to relatively low voltage for utilizing. The transformer may be pole-mounted or set on the ground in a protective enclosure. Urban distribution is mainly underground, often in common utility ducts, and on the other hand, rural distribution is mostly above ground with utility poles, and meanwhile the distribution way is a mix in suburban areas.

Distribution networks are typically in two types, radial or loop [5]. A radial network starts from the station, passes through the network area, and enter the customers without other connections to any other supply, which are mainly applied rural lines with isolated load areas. On the other hand, a loop network is generally used in more urban areas which have multiple connections to other power supplies. These connections are normally opened but various configurations are allowed by the operating utility by closing and opening switches, which is also called reconfiguration. Operation of the switches is mainly remotely controlled by a control center. The benefit of the loop model is that a part of network can be isolated to maintain power supply in a fault. Configuration of the distribution networks follows one or a combination of the following standard supply approaches:

- 1) Radial system where the loads are all supplied by single feeder;
- 2) Open-ring system where the loads are supplied by one from two available feeders, which is in fact one side of the ring;
- 3) Closed-ring system where the loads are supplied by the two sides of the ring simultaneously;
- 4) Dual-ring system where the loads are connected with two rings at the same time, thus it actually has four incoming feeders;
- 5) Multi-radial system where the loads are supplied by more than one radial feeder.

These systems can be applied to establish the distribution network at either the MV or the LV mentioned before.

1.1.3 Distribution Management System [6]

Distribution management system (DMS) is defined as an integrated decision support system as all operational aspects of the distribution system are made visibly and operably by a central source where advanced algorithms are used to optimize the system in real time or previously. DMS is the distribution equivalent of the energy management system (EMS) [7], which is used in the transmission system to manage the operations. DMS is a combination of multiple applications which are designed to efficiently and reliably monitor, operate and control the entire distribution network, whose main role is acting as a decision support system to assist the control room with the monitoring and controlling system. Improving the reliability and quality of service, reducing outages, minimizing outage time, maintaining acceptable frequency and voltage levels are the key tasks of the DMS. In details, the objectives for DMS implementation are mainly as follows:

- 1) Enhancing safety of system by providing better visibility and control on system energization and de-energization;
- 2) Extending the using life span of system devices by properly managing their operation;
- 3) Improving reliability of system by reducing system outage times;
- 4) Enhancing efficiency of system and optimizing the use of available resources.

Major purposes of DMS are concluded as follows:

- 1) Reduce the duration of outages;
- 2) Improve accuracy of outage predictions;
- 3) Reduce crew patrol and drive times through improved outage locating;
- 4) Improve the operational efficiency;
- 5) Determine the crew resources necessary to achieve restoration objectives;
- 6) Effectively utilize resources between operating regions;

- 7) Determine when best to schedule mutual aid crews;
- 8) Increased customer satisfaction;
- 9) Provide customers with more accurate estimated restoration times;
- 10) Improve service reliability by tracking all customers affected by an outage, determining electrical configurations of every device on every feeder, and compiling details about each restoration process.

DMS's functionality can be mainly divided into three categories: 1) system monitoring; 2) decision support tools; 3) control, as shown in Fig. 1.2.

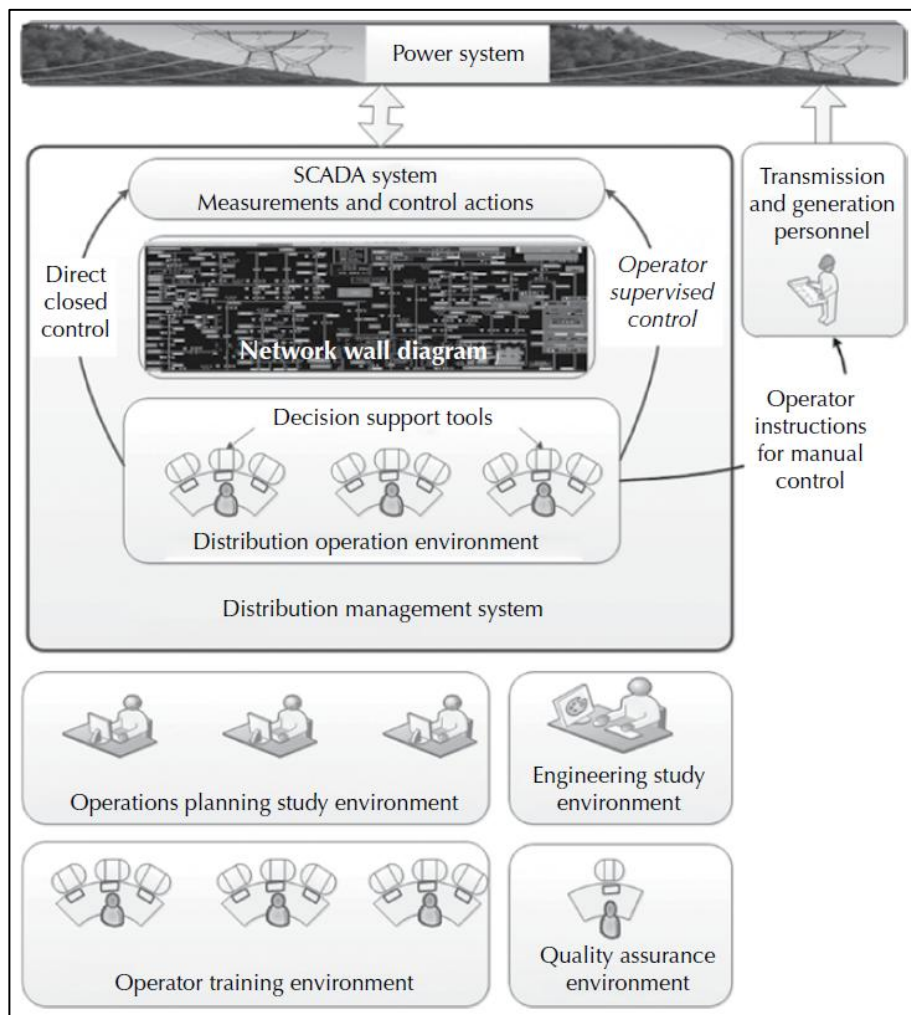


Fig. 1.2. DMS functionality and functional environments [1].

The DMS environments are offered in the following domains: 1) distribution operation environment; 2) engineering study environment; 3) operations planning environment; 4) training simulator system; 5) quality assurance system. The distribution system operators provided by operation environment are mainly system visibility, decision support, and

control for managing the distribution operation. The operations planning study environments conduct operations planning, and similarly, the engineering studies environments develop historical system performance indices. Study systems are used for the performance of what-if studies, as an example, operations planning engineers may examine alternatives produced by the production systems to check whether a transmission line out can be taken safely or not. The training simulation domain deals with an environment that caters to providing scenarios for training system operators. These scenarios are executed using scripts to provide system conditions that operators face and the actions they need to take. Finally, the quality assurance system is used for testing new applications and upgrades before introducing them to the production system.

The DMS hardware mainly comprises the following subsystems: 1) Data acquisition subsystem; 2) computer subsystem; 3) man/machine subsystem; 4) auxiliary power subsystem / uninterruptible power supply. The DMS software consists of various decision support tools as well as other administration and support functions needed in DMS working. A short description for each software is provided as follows:

- 1) SCADA: Supervisory control and data acquisition system performs data acquisition, alarm processing, man-machine updating, as well as execution of control actions in the field [8];
- 2) Distribution network modeler: This tool is responsible for maintaining a single line diagram model of the bulk electricity supply;
- 3) State estimation: This is a mathematical method that uses available power system measurement values to recreate values for all other unknown system state variables [9];
- 4) Remedial action system (RAS): These programs are intended to assist the operators in arriving at appropriate remedial control actions to correct for any security violation in the normal system condition and after credible contingencies [10];
- 5) Power flow: This program provides distribution operators with the electrical conditions and flows in the three-phase distribution system to establish abnormal conditions out on the feeders, such as low voltage at the feeder extremities and overloaded line sections;
- 6) Static security (contingency analysis): This is a method to identify the system's thermal and voltage violations during normal conditions and after credible contingencies [11];
- 7) Load estimation: A load estimation mechanism is required to divide the main bus load among the distribution service transformers [12];
- 8) Short-circuit analysis: This function calculates the voltages and currents on any of the three phases due to postulated fault conditions with due consideration of

-
- pre-fault loading conditions. The calculated fault currents can be compared against switchgear breaking capabilities or device fault-current limits [13];
- 9) Voltage var optimization (VVO): the VVO determines optimal control actions to minimize an objective function such as load demand or energy consumption while maintaining acceptable voltage and loading at all feeder locations [14];
 - 10) Fault location, isolation, and service restoration (FLISR): the FLISR is a function for restorations as faults occurs. This functionality improves system reliability by reducing the number of customer interruptions and the time to restore the system, by using controllable devices such as circuit breakers, re-closers, automated line switches, ties switches, fault detectors, and other facilities for monitoring and control [15];
 - 11) Optimal network reconfiguration: This function provides the recommended actions necessary to accomplish an objective function without violating any loading or voltage constraints on the feeder. Reconfiguration, by exchanging the functional links between the elements of the system, represents one of the most important measures which can improve the operational performance of a distribution system. The optimization problem through the reconfiguration of a power distribution system, in terms of its definition, is a single objective problem with constraints. Since 1975, when Merlin and Back introduced the idea of distribution system reconfiguration for active power loss reduction [16], until nowadays, a lot of researchers have proposed diverse methods and algorithms to solve the reconfiguration problem. The reconfiguration issues for the distribution system will be the main discussion in this thesis, and illustrations are given more clearly in Section 1.3;
 - 12) Short-term load forecasting: This function uses historical load and weather data to forecast the system load automatically for a period of time such as a week [17];
 - 13) Tagging: DMS has the ability to place tags on any device to inhibit certain remote control commands on the associated facilities in accordance with operating procedures;
 - 14) Distribution training simulator: This tool provides a realistic environment for hands-on dispatcher training under simulated normal, emergency, and restorative operating conditions. The training is based on interactive communication between instructor and trainee with a complete replica of the DMS user interface;
 - 15) System reporting: These tools collect data to produce alarms and the necessary online and historical data and summary displays and reports.

1.2 Renewable Energy and Distributed Generation (DG)

1.2.1 Renewable Energy Resources [18]

The design and development of the power grid requires studying renewable energy sources and their technologies such as wind, photovoltaic (PV), biomass, and fuel cells, estimating their penetration levels, and conducting impact assessments to the traditional system for the target of modernization. The roadmap envisions widespread deployment of distributed energy resources (DERs) in the near future. Renewable technologies have been positioned to reduce both dependence on foreign oil and the environmental impacts of energy production. Renewable energy technologies and their integration introduce several issues including enhancement of efficiency and reliability, and the development of state-of-the-art tracking to manage variability.

Architecture designs which include optimal interconnections, optimal sizing and siting DERs for optimum reliability, security, and economic benefits are also critical aspects. Additionally, computational development of the smart grid to permit estimation and forecasting models for fast real-time accurate predictions of these variable power sources need to be addressed.

A) PV Devices [19]

Solar energy utilized by the use of photovoltaic (PV) cells was first discovered in 1839 by French physicist Edmund Becquerel [18]. The technology can be a single panel, a string of PV panels, or a multitude of parallel strings of PV panels. Solar PV has renewable advantages, such as no emissions, high reliability, and minimum requirement of maintenance.

The PV system generally considers: 1) availability of solar energy converting to electricity. Insolation levels will be affected by the operating temperature of PV cells, intensity of light, and the composition of the solar panels. 2) PV emission levels are environmental friendly.

The PV output is variable due the unreliable solar radiation and surface temperature. The data of predicting the solar input is mainly based on several years of measurements of irradiance on the past data. The above statistical measures are mainly estimated from meteorological data available from the site, from a nearby site which has similar irradiance features, or from an official solar atlas or database. Solar insolation has been modeled as probabilistic model, and variability studies of PV systems are modeled as Gaussian (normal) and Beta probability density functions.

Several inverter systems convert the DC power into the AC one in the grid-connected

PV systems (shown as Fig. 1.3). Penetration of PV into the power grid mainly requires variability and conversion technologies. The mathematical models and probability density mainly used to model PV behavior are Beta and Rayleigh density functions. Enough power points are obtained by tracking method based on fuzzy and GA technologies for effective delivery. Siting and sizing problem of PV can be handled by classical and computational intelligence methods and make decisions based on real-time data.

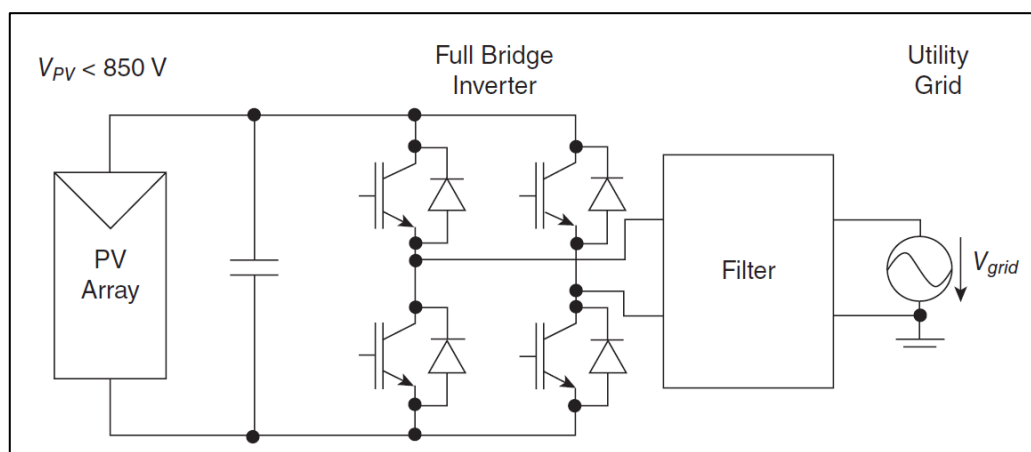


Fig. 1.3. PV inverter system for DC-AC conversion [18].

B) Wind Turbines Systems [20]

Besides PV generation, wind power is another fastest-developing renewable energy taking observation on the whole world (as shown in Fig. 1.4). Wind turbines produce electricity with the most affordable cost, and on the other hand, additional investments in infrastructure such as constructing transmission lines are not needed. A wind turbine is consisted by a rotor, generator, blades, and a driver or coupling device. Compared with PV, wind is more economically competitive renewable, as no CO₂ or pollutants are produced by wind turbines. By mention to technique difficulty, wind power mainly has three drawbacks: 1) output cannot be controlled, as wind generations' output is affected both by wind speed and the height of pole-mounted units; 2) wind farms are most suited for peaking applications; 3) generation is only available as wind is sufficiently speedy and strong.

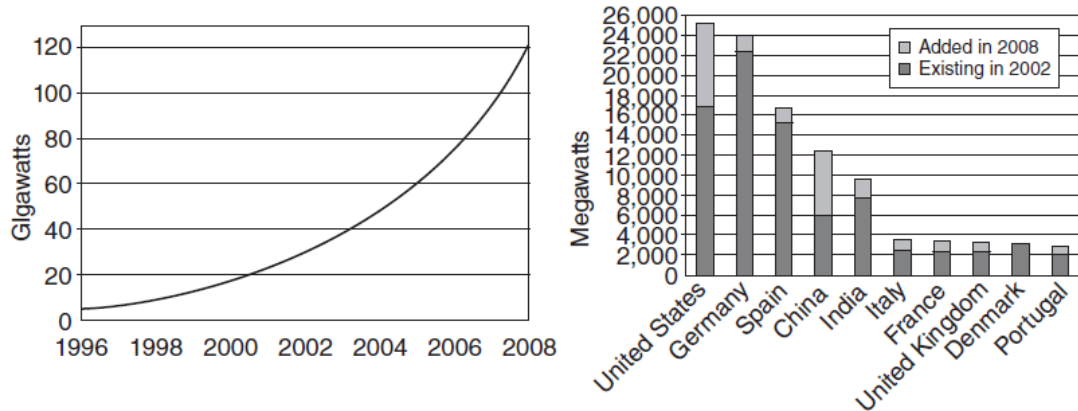


Fig. 1.4 (left) Wind power, existing world capacity, 1996-2008; (right) wind power capacity, top ten countries, 2008 [18].

C) Biomass-bioenergy [21]

Bioenergy is the generation form where energy is derived from organic waste matter such as corn, wheat, soybeans, wood, and even chemicals and materials can be produced by bioenergy's residues. Bio-power is obtained gas from a process called gasification, and converter the obtained gas to gas turbines for electricity generations.

Biomass is the traditional way used for cooking and heating in developing countries, which produces power only in the condition of sufficient bio-products and the conversion process being undertaken. Biomass can be converted directly into fluid fuels such as ethanol, alcohol or biodiesel derived from corn ethanol. Biomass does produce CO₂ and other emissions but it is renewable. The desirable scheduling and allocation strategy of biomass in real time requires the power capability for including variability of the modeling using new system theory concepts.

D) Fuel Cell [22]

Fuel cells are also important power generation to enhance power delivery in the modern grids. Fuel cells are able to be simply obtained from hydrogen, natural gas, methanol, and gasoline. Without Carnot limits, the efficiency of transferring fuel to electricity can be as high as 65%. Fuel cells are friendly to environment by efficient using fuels, which are a good fit for green power and premium power. Fuel cells seldom produce virtual and pollutant emissions like CO₂, and maintenance of fuel cells are also minimum due to seldom location moving, but their facilities are reasonably high, compared with the conventional generations.

The efficiency of fuel cells ranges from 40 – 80% [18]. Two common types of fuel cell are phosphoric acid fuel cells (PAFC) and proton exchange membrane fuel cells

(PEMFC). The PAFC generally operates at higher temperatures, and an external water cooling system is necessary to cool the stack. The PEMFC operate at a relatively lower temperature compared to common fuel cells, and its main merit is considered that chemical substances, such as liquid acids or molten bases, are contained, which might cause corrosion on construction materials.

E) Geothermal Heat Pumps [23]

Geothermal power is utilizing the underground steam or hot water from deep drilling into the earth. Energy conversion starts from pumping hot water to drive conventional steam turbines, and as a consequent, to generators are driven to produce electrical power. The utilized water is able to recycle back into earth for next iteration, thus it is a continuous energy cycle with few emission. Main types of geothermal power plants include dry steam which draws water from the steam reservoirs and flash stream, and binary cycle which take energy from the recycled hot water reservoir. Heat pumps, agriculture, fishing, farming, and food processing are main applications of geothermal power. Challenge of geothermal projects is that it requires significant a large number of previous investment for exploration, drilling wells, and equipment, while exploration risk and environmental impacts are mainly considered in the projects.

1.2.2 Distributed Generations [24]

The arrangement of electrical power system (generation, transmission and distribution) indicates that the power flow is a unidirectional flow which is from the generation plants to the distribution substations and finally terminates at the consumers. However, integration of distribution generations (DG) to the power system (shown as Fig. 1.5) permits consumers to produce electricity for the target to self-feed their loads, to feed critical devices in emergency or outage as back-up resources. Therefore, DG is equipped around the customers to meet all or a part of the load needs, which generally ranges in size from less than 1 kW to tens or hundreds of kW.

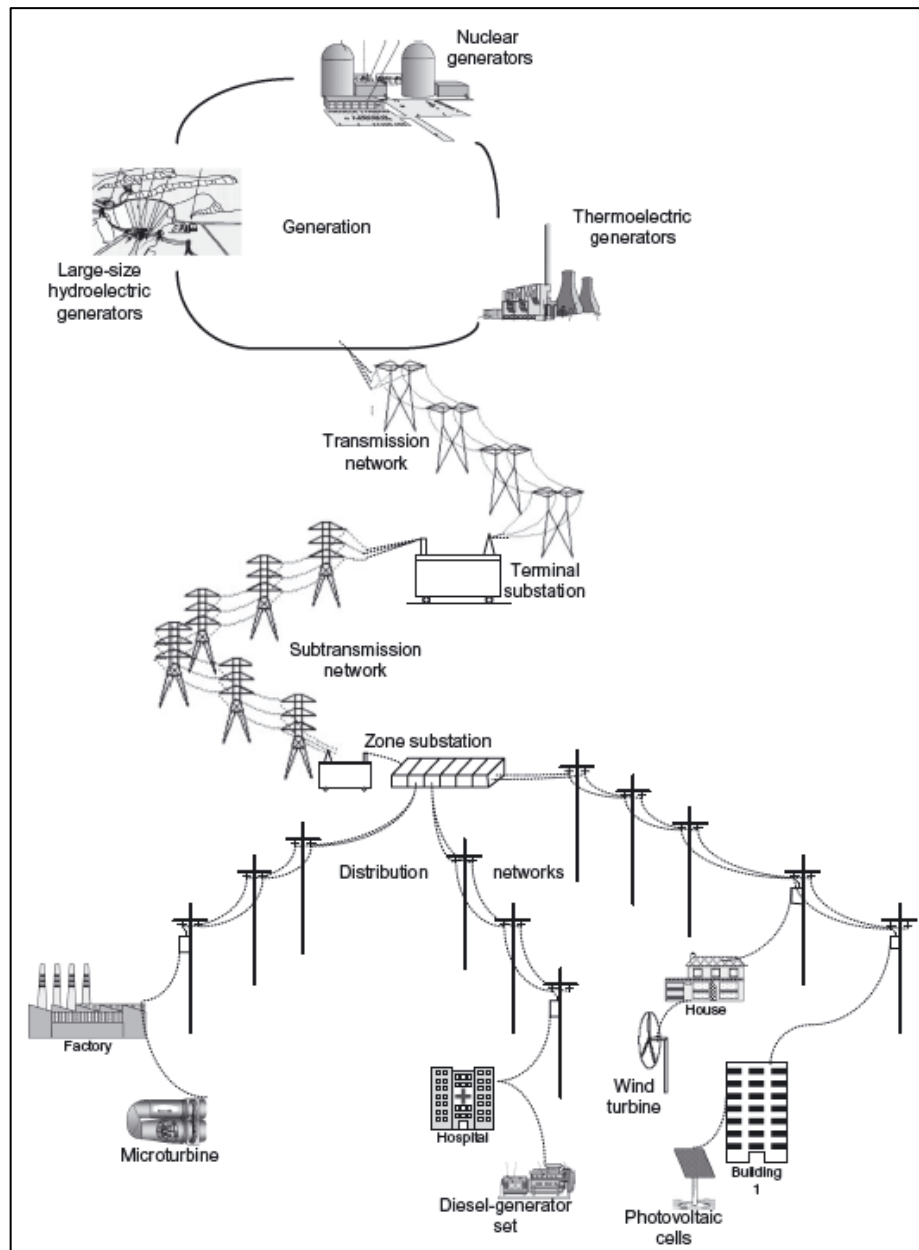


Fig. 1.5. Power system arrangements with distributed generation [24].

The electrical capacity of DG is usually designed to exceed customers' needs in common operation conditions in the target of efficient utilization by its application on the following purposes:

- 1) Supplying electricity to remotely-located but small-need loads in the condition that it is more economical to equip DG than to construct new transmission lines;
- 2) Offering heat or steam to hospitals or any other industries in cogeneration systems;
- 3) Providing high-quality power supplying for critical and sensitive electronic equipment;

-
- 4) Backup power source in terms of emergencies and outages, in particular, for critical consumers which require uninterrupted power supply;
 - 5) Supporting peak-shaving function, that is power of DG can be transferred to high-cost periods resulting in supplying balance and reduction of overall operation costs;
 - 6) Reducing air emissions and pollutions since all DG is taken by renewable energy sources;
 - 7) Reducing distribution system's construction investments;
 - 8) Adding power capacity to utilities;
 - 9) Dispatching DG to optimize power flow, in order to achieve most economical operation particularly considering the priority of supplying independent producers;
 - 10) Reducing power transmission for losses reduction.

Based on the above analysis, DG is expected to provide more secure and reliable operation for power system in condition that it is installed to the distribution system and electric is available to be sold to the utilities. DG will be worth to be utilized in large amount for both technical and economic reasons. However, installation of DG systems to the existing distribution network also brings most critical and difficult problems not only technically but also economically. The main technical problems are listed as follows:

- 1) A part of on-load tap changer transformers and relay protection system are not designed for reverse power flow which frequently occurs in DG installations.
- 2) Fault levels may be increased unpredictably.
- 3) Nuisance tripping of some healthy parts in distribution systems.
- 4) Existing distribution networks are not well designed for high voltage rise caused by DG.
- 5) Equipment and communication system between meters and data center should be modified or redesigned.

Acceptable techniques for solving the technical problems are discussed by researchers in recent years. On the other hand, economical problems may also cause a significant barrier for installing DG to distribution system. Both considering benefits brought by DG connection and new challenges caused by DG. Current power system is facing determining which supplying way is most financial for system operations.

1.3 Network Reconfiguration

1.3.1 Feeder Reconfiguration

Reconfiguration of distribution network (RODN) is one of important roles of distribution system operation. The major purpose of reconfiguration of distribution network is to decide the on/off status of the sectionalizing switches for the optimization of the distribution system (shown in Fig. 2.1) to mitigate voltage deviations [25], [26], as well as to balance the load [27], [28], and to reduce the line losses [16], [29].

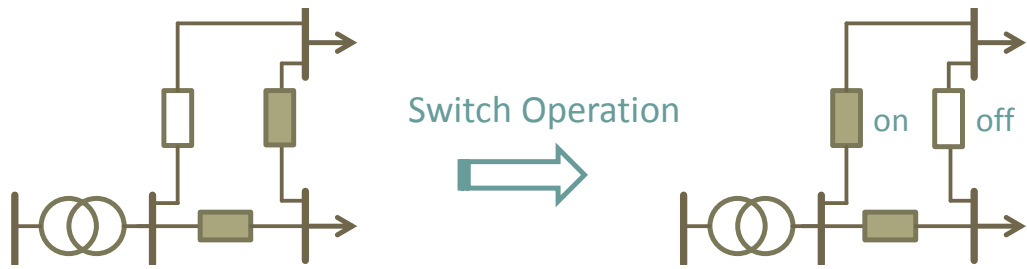


Fig. 2.1. Basic concept of RODN.

Load balancing via feeder reconfiguration is an essential application for utilities where multiple feeders are feeding area with congested load. To balance the loads on a network, the operator rearrange supplying path of the loads to other parts of the network. The feeder load management detects the critical location and indices to monitor the whole distribution system, and identify dangerous areas so that the distribution operator can be forewarned and pay attention on where it is most needed. It requires more rapid decision computation supports and correction of existing problems, and to enable multiple possibilities for problem solutions, in the target to improve reliability and energy delivery performance of distribution system. On a similar note, loss minimization is another target of feeder reconfiguration. The total energy and revenue losses should be minimized for effective operation, in the reason that the utility network may be operated within the maximum capability or operational constraints without predictable consequences of faults occurring. The DMS application utilizes switching management application (reconfiguration) for network optimization, and meanwhile the losses minimization problem is solved by the optimal power flow function, as a consequence, the optimal operation is realized.

Mathematically, the problem of RODN is regarded as a combinatorial nonlinear optimization problem, which is generally difficult to solve in a practical computation time. The detailed mathematical definitions of RODN will be given in each chapter based on situations.

1.3.2 Meta-heuristic Reconfiguration Methods

Many algorithms for RODN have been developed. Among past developments, the most major approaches are application of meta-heuristic algorithms.

The ant colony search (ACS) method was aiming to search for an optimal path in a graph, based on the behavior of ants seeking a path between their colony and a source of food. The ACS was applied to solve reconfiguration problem in [30]–[35]. In the ACS, applying of the positive feedback method guarantees rapid searching, and the distributed computation by hiring ant colony avoids premature convergence.

In [36]–[40], the particles hired in particle swarm optimization (PSO) will share the best information of the previous best solution of a particle and the best solution of the population so far, to lead the moving toward the target. The PSO is initialized with a population of random solutions and searches for optima by updating generations. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles.

In [41], the EP method is applied, which has the advantage to ensure the radial topology of searched strings, and the grey correlation analysis (GCA) has been proposed to solve multi-objective problem in reconfiguration issue.

In [42]–[44], Simulated annealing (SA) is particularly well suited for a large combinatorial optimization problem since it can avoid local minima by accepting improvements in cost. However, it often requires a meaningful cooling schedule and a special strategy, which makes use of the property of distribution systems in finding the optimal solution.

The genetic algorithm (GA) method [45]–[52] is more likely to obtain the global optimal solution than other meta-heuristic search methods and takes less time than the exhaustive search. The GA has the main advantage of using representation of objects (strings) instead of manipulating the objects themselves, but its main problem is the coding of the objects into strings.

Common principle among meta-heuristic methods is iterative calculation process, which can find the optimal or sub-optimal solution with a simple algorithm, but requires relatively long computation time.

1.3.3 Heuristic Reconfiguration Methods

Compared with the meta-heuristics or artificial intelligence techniques, heuristic algorithms are more suitable for online operation because they are simpler and easier implemented. The optimal switches' state, i.e., closed / opened switches, are obtained one

by one in heuristic approaches, so global optimality cannot be guaranteed. In spite of this drawback, the approach has a strong advantage in computation stability by designing heuristics rule to avoid infeasible solutions without any heavy computation processes.

Branch-exchange is a classical heuristic method for RODN, and previous works [16], [29], [53], [54] indicated that it was easy to implement and suitable for online management. Generally, multiple tie (normally opened) switches exist in a distribution system, and all of them may be exchanged with normally closed switches. The main demerit of the branch-exchange approaches is definition of initial structure, since the final result depends on the initial configuration, the burden of excessive computational complexity is inevitable and the result is uncertain.

While a hybrid heuristic method based on branch-exchange presented in [55] is a hybrid heuristic method consisting of a circular minimum-branch-current updating mechanism and a circular neighbor-chain updating techniques, which defined initial configuration by opening switch with minimal current through in a single-loop iteratively, and this approach improved calculation accuracy a lot.

In [56], [57], the entire distribution system is decomposed into subsystems based on the connectivity of areas, and an individual agent is assigned to each decomposed sub-system. A two-stage method based on branch exchange method is defined for coordinating the reconfigurations of decomposed subsystems. The optimal configuration of the entire system results from collaborations of individual agents, and the decentralized approach significantly reduces the computation time.

A heuristic computational method based on the firefly movement equation is established in [58] which aims at minimizing the waste of line losses. The main idea of this paper is to simulate the fire flies movement towards preys or partners to match the insect positions, and the insects positions are discretized in the space correspond to the positions of the switches in the electrical system.

[59] presented an efficient, two-stage method, as the efficiency of the method is improved by stemming from the use of real power loss sensitivity with respect to the impedances of the candidate branches. This method uses loss sensitivities in the first stage, and a branch exchange procedure in the second stage to refine the solution.

[60] proposed a reconfiguration algorithm especially designed for large-scale systems. This heuristic algorithm starts as the system in a meshed status with all maneuverable switches to be closed. The switches are opened one by one by the order decided based on the calculation of the minimum total system losses, using a load-flow program. A refinement on this procedure, based on branch status exchange, is also described.

This heuristic algorithm in [61] starts as all maneuverable switches to be opened, and it closes the switch which leads to the minimal increase in the objective function at each step. The objective function is defined as increased losses divided by increased load served. A simplified loss formula is used as rough index for candidate switches, but a full

load flow calculation after each actual switch closing is operated to maintain accurate loss and constraint. A backtracking option mitigates the algorithm's greedy search. This algorithm takes more computer time than other methods, but it models constraints and control action more accurately.

[62] presents a heuristic method to solve the network reconfiguration problem in the presence of DG with the objective of minimizing real power loss and meanwhile improving voltage profile in distribution system. A meta-heuristic harmony search algorithm (HSA) is given to simultaneously reconfigure and optimize locations for DG units installations in a network. Sensitivity analysis is used to assist optimizations.

1.3.4 Reconfiguration Schedule

In spite of high development of computation accuracy and speed, the past algorithms [16], [25]–[44], [46]–[57], [63]–[68], which are called short-term reconfiguration methods hereafter, are not really practical for system management, since their solutions are obtained only depending on a single time interval's load data, however load condition in distribution system dynamically varies moment to moment, especially the growth of DGs' installation, e.g. photovoltaic (PV) generators, would enlarge the variation of load condition in both size and speed perspectives. From this viewpoint, the results of short-term reconfiguration methods soon lose effectiveness with time-varying load. The past works considered the time-varying nature of loads in the network reconfiguration problem by two policies in common. The conventional consideration is that the reconfiguration is employed for achieving a fixed configuration at specific time, e.g. initial time or the time of peak load, ignoring the time-varying nature of loads [69], [62]. Another policy considers time-varying load by monitoring system state and deriving the optimal configuration over all period of time, for example, over a day [70]. This policy, also called online reconfiguration, is valid by assuming that the network is equipped with the remotely operated tie switches. The advantage of the first policy is that the number of switching operations is minimal. However, the drawback of these studies is that due to uncertain nature of loads, the fixed network configuration is not continuously optimal over a period of time, especially when networks are installed by some intermittent DGs. Although online reconfiguration can result in better reduction of voltage deviations compared to one fixed configuration, the overall cost of switching operations for online reconfiguration may exceed profits from reduced voltage deviations. In this case, network reconfiguration is ineffective for economic reasons. Although [45] hired the GA to seek the optimal combination of reconfiguration instants, the configurations obtained by short-term reconfiguration method, were still successively fixed to operate on time-varying load for a long period between two reconfiguration instants.

1.4 Contributions and Organization of Chapters

Inspired by the past works, the authors firstly proposed a two-stage heuristic methodology named intelligent flow algorithm (IFA) in Chapter 2, which can solve the online reconfiguration problem faster and more effectively. The IFA finds the initial configuration at where the loads are distributed uniformly, and revise the initial configuration into the optimal one by a switch revision function.

Massive DG installations will increase loads' unevenness, resulting in computation accuracy decrease in the heuristic methods. The main contribution of Chapter 3 is to improve the IFA method into an extended flow algorithm (EFA) to cope with massive DG installation to distribution systems. Since scale expanding of distribution systems will increase computation burden exponentially, the authors also give simplification for some functions in the EFA to reduce its computation time. The simplified method is more efficient for reconfiguration on large scale systems.

In Chapter 4, the authors proposed a novel approach for optimal daily schedule to specify reconfiguration instants over a day based on a comprehensive objective function, trade-off between reduction of voltage deviations and cost of switch operations, for the purpose of economic minimization of total operating by including realistic conditions and time-varying nature of loads on a typical day. Besides, a long-term reconfiguration method was also developed based on the EFA, which optimizes system network by considering the prospective load data, as its results has longer timeliness for time-varying system conditions.

Finally, the conclusions drawn from the present work are presented in Chapter 5, and subsequent researches are also given.

Chapter 2. Online Reconfiguration

The distribution loss depends on both the network configuration and the load distribution. Recent penetration of DG such as photovoltaic generation systems would vary the load profile widely in a short period. Therefore, RODN should consider the load profile in high geographical and temporal resolutions. Recent development and installation of sensor-embedded sectionalizing switches in distribution system or smart-meters enable precise and frequent system monitoring, and in the near future, online reconfiguration would be employed to cope with variety of load profile. For online reconfiguration, faster and more reliable optimization algorithm should be developed.

This chapter mainly proposes a new heuristic method, named intelligent flow algorithm (IFA), which can solve the reconfiguration problem faster and more effectively. The idea of IFA, different from the conventional heuristic approaches, is to generate the configuration for loss minimization based on its topological property. In Section 2.1, the problem formulations of reconfiguration are stated. In Section 2.2, the data based on the complete enumeration is studied to explore the properties between configuration and line loss. Based on the properties, the IFA is proposed in Section 2.3. In Section 2.4, the proposed algorithm is simulated with 2 distribution system models to certificate its effectiveness. In Section 2.5, the application of the IFA on multi-objective searching is briefly discussed. Finally, the conclusions are shown in Section 2.6.

2.1 Problem Statements

Fig. 2.1 [29] shows a graphical illustration of a sample distribution system, with each node and branch respectively corresponding to a bus and a distribution line, which are equipped with sectionalizing switches and tie switches, respectively.

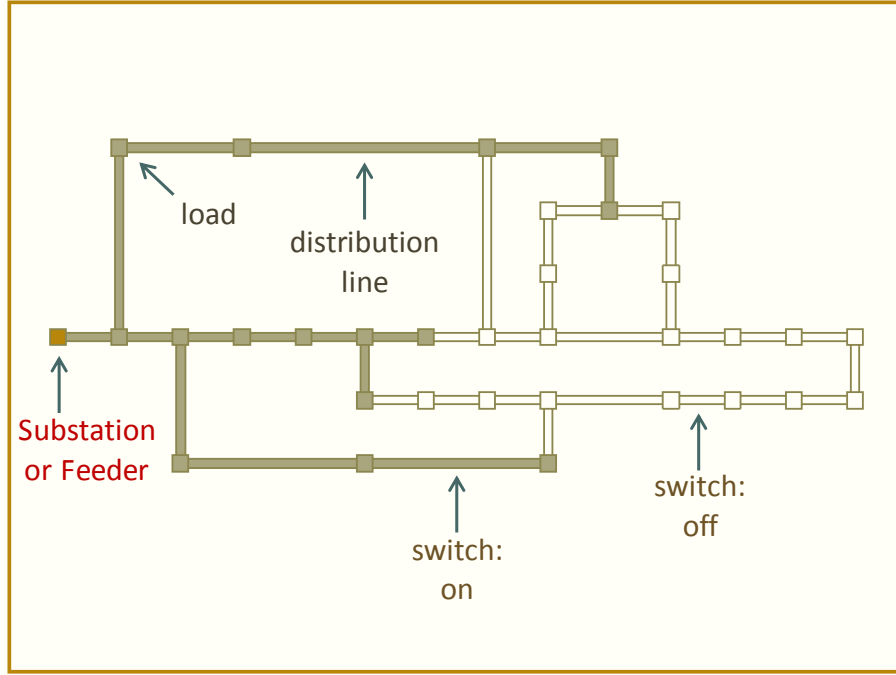


Fig. 2.1. A graphical illustration of a symmetric 33-bus test distribution system.

The equilibrium equations of the stated reconfiguration problem are as follows,

$$\Delta S_j = Z_j \frac{|S_{j,end}|^2}{|V_{j,end}|^2} \quad (2.1)$$

$$S_{j,head} = S_{j,end} + \Delta S_j \quad (2.2)$$

$$\Delta P_j = \text{real}(\Delta S_j) \quad (2.3)$$

$$I_j = \sqrt{\frac{\Delta P_j}{R_j}} \quad (2.4)$$

Where, ΔS_j and Z_j are the complex power loss and the impedance of branch j

respectively; $\check{V}_{j,end}$ is the complex voltage of end of branch j , and $\check{S}_{j,head}$ and $\check{S}_{j,end}$ are the complex voltage and the complex power flowing head and end of branch j , respectively. $\check{V}_{j,end}$ is obtained by the Newton-Raphson load flow calculation method.

Based on (2.1) and (2.2), $\check{S}_{j,head}$ and $\check{S}_{j,end}$ can be obtained by recursion, since distribution systems are kept radial. ΔP_j is the active power loss, and R_j is the resistance of branch j , respectively.

The online RODN for loss minimization is formulated as follows:

(Objective function)

$$\min f = \sum_{j=1}^L \Delta P_j = \sum_{j=1}^L R_j \frac{|\check{S}_{j,end}|^2}{|\check{V}_{j,end}|^2} \quad (2.5)$$

Where L is the total number of branches.

(Constraints)

$$V_{min} \leq |\check{V}_{j,end}| \leq V_{max} \quad (2.6)$$

$$|\check{S}_{tran,head}| \leq S_{max}^{tran} \quad (2.7)$$

$$|I_j| \leq I_{max}^j \quad (2.8)$$

Where V_{min} and V_{max} are voltage constraint, and considered as 0.95 and 1.05 respectively in this paper. S_{max}^{tran} and I_{max}^j is the limitation of capacity of transformer and distribution line respectively. The topological constraints are considered as follows:

- 1) Isolation constraint: all of buses should be energized.
- 2) Radial network constraint: distribution networks should be in a radial structure.

In this paper, all the numerical calculations are discussed in the standard of per unit value.

2.2 Balanced Configurations

To study the topological property of configurations with low line loss, the authors have enumerated all of possible network configurations for the 33-bus test distribution system (33 buses, 37 distribution lines, 5 tie-switches) shown in Fig. 2.2. With the combination of the positions of tie-switch, the size of solutions space is counted as $C_{37}^5 = 435897$, in which 50751 is radial networks, and the values of the line losses vary from 0.0131 to 0.2591 (per-unit) as statistics.

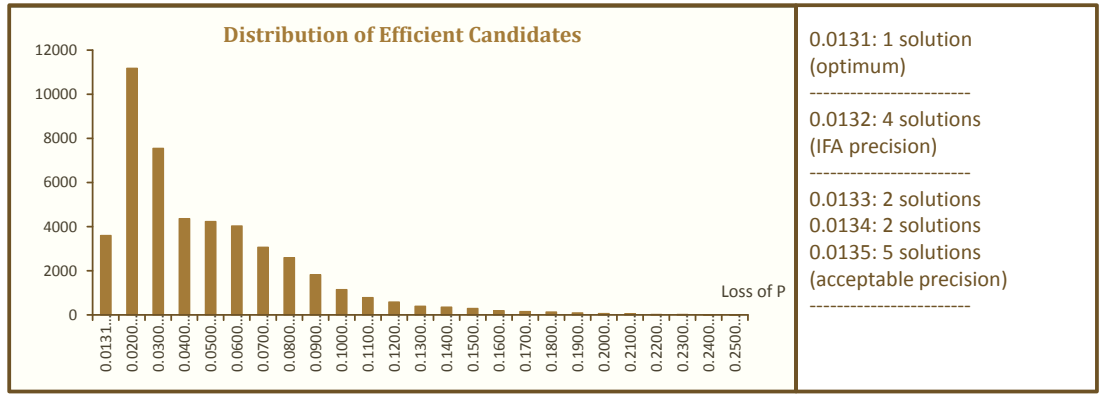


Fig. 2.2. Distribution of efficient (radial) candidates in the 33-bus system.

2.2.1 Topological Similarity of Configurations with Lower Line Losses

Structures of 5 configurations, which have the lowest line losses, are drawn in Fig. 2.3-A to E, and the common compositions of them are counted as Fig. 2.3-F. The approaches to calculate the common composition is shown in Fig. 2.4.

It is observed that the 5 configurations are homogeneous in topology. Analyzing in the layer model of system, the branches in lower layer (close to power source) are identical, and the branches in higher layer (remote to power source) diverse. Two features of configurations with relative low line loss can be concluded: 1) short supplying paths, 2) branches being uniformed to bear the loads. Configurations with above two features are defined as “balanced configuration”, shown in Fig. 2.5 in this paper.

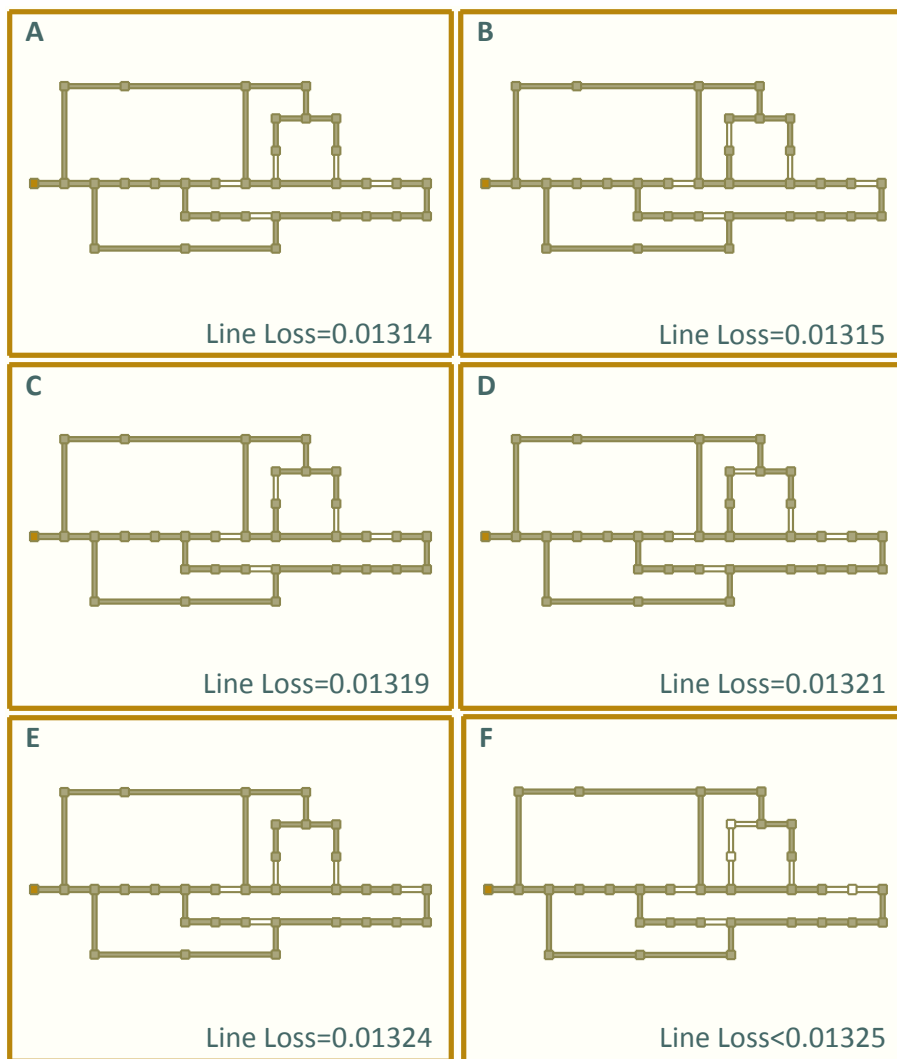


Fig. 2.3. Topological similarity of the configurations with relative low line loss.

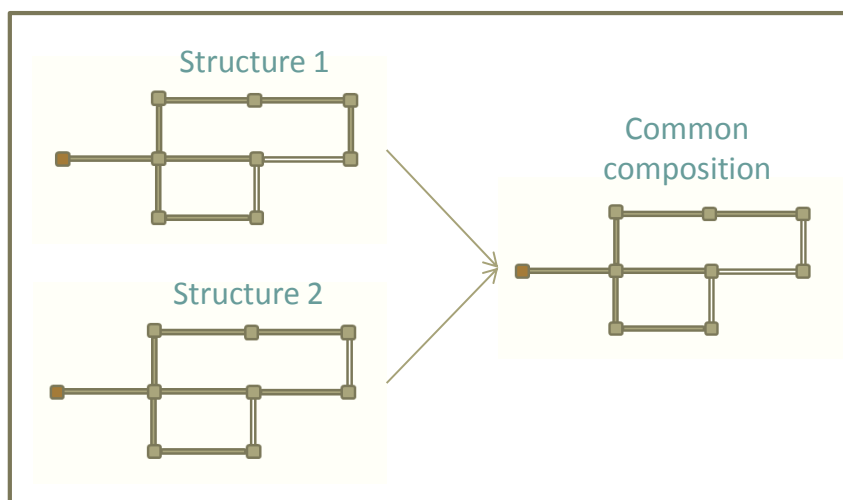


Fig. 2.4. Calculation of the common composition.

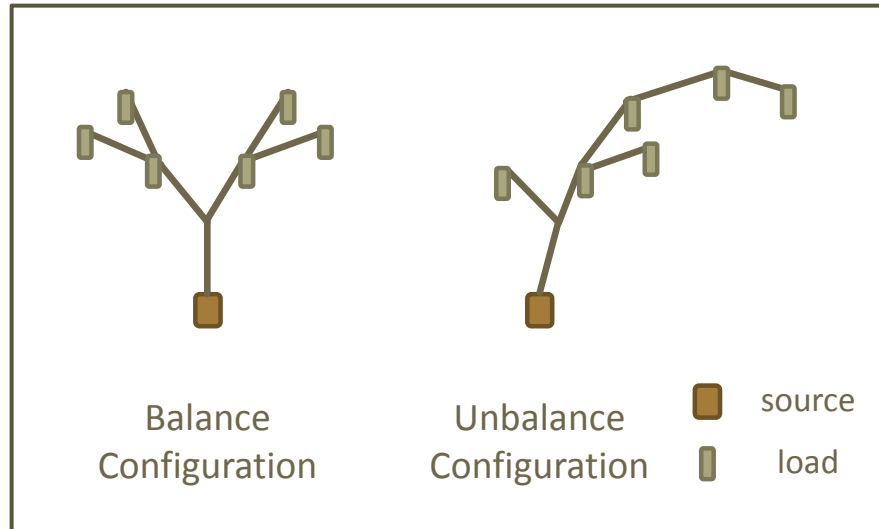


Fig. 2.5. Loads supplying of the balanced configuration and unbalanced configuration.

More configurations with higher line losses are counted to calculate the common compositions. Fig. 2.6 shows that with the limiting line loss becoming higher, the common compositions become less, but the branches in lower layer disappear later, that is, the configurations with higher line loss have lower balance degree of loads supplying. The topological properties of configurations can be concluded as follows: outstanding configurations with low line loss are homogeneous in topology, and configurations which are more homogeneous with the optimal one have lower line losses. The balance degree of loads supplying decides the quality of line loss, higher balance degree leads to lower line loss, in the opposite, lower balance degree leads to higher line loss.

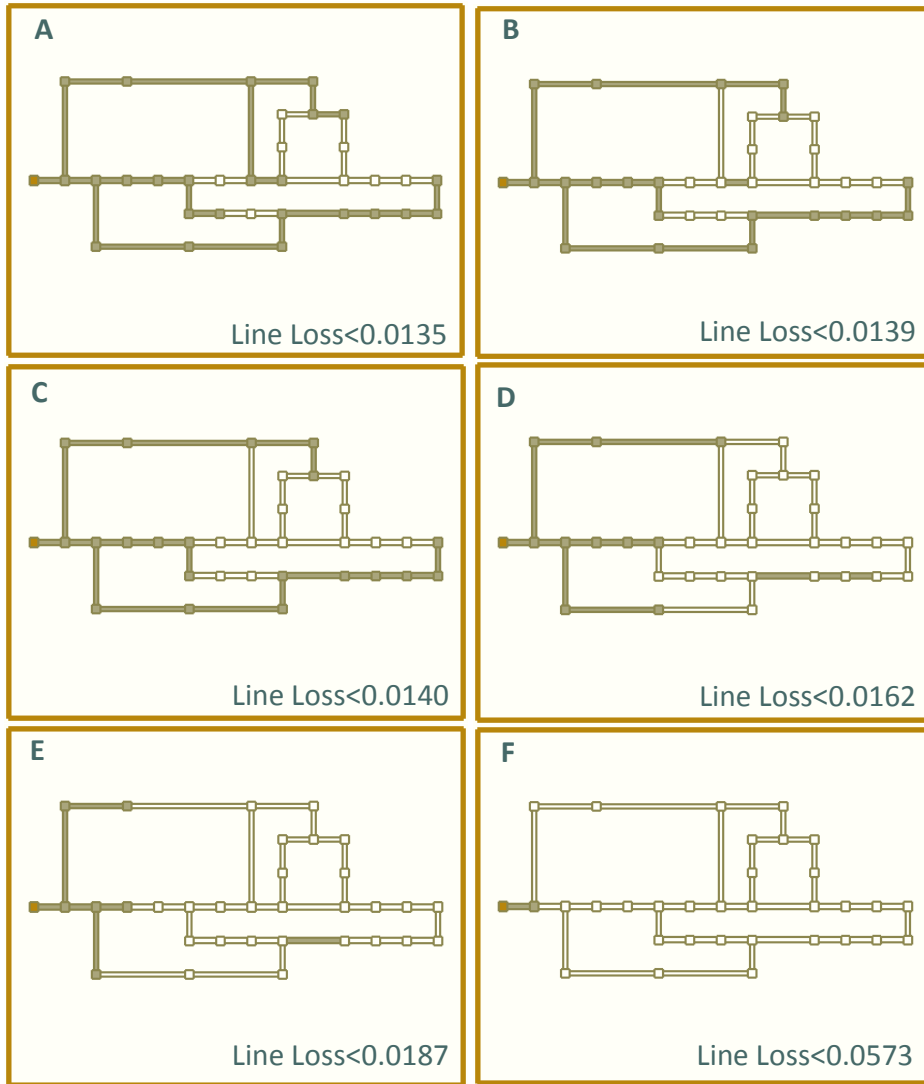


Fig. 2.6. Graduation of the common compositions with the increase of limiting line loss.

2.2.2 Correlation between Node Voltages and Line Losses

The voltage profiles are the crucial constraint conditions in reconfiguration issue. Collection between the line losses and the average node voltages of configurations of the 33-bus test system has been detected based on complete enumeration, shown as Fig. 2.7.

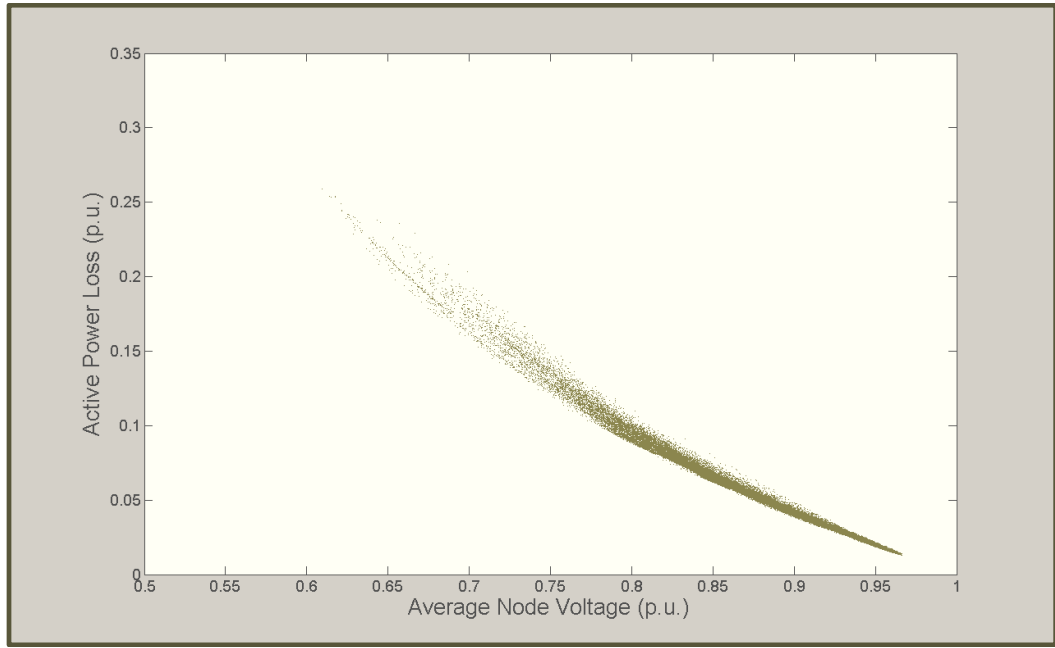


Fig. 2.7. Correlation between active power losses and average nodes voltages .

Fig. 2.7 shows that the line losses and the average node voltages are correlated strongly in different configurations. Configurations with low line loss are always in high average voltage, that is, the voltage profile has been improved with the optimization of line loss (voltages in loads are always lower than substation in the discussed system). The authors also detected other cases with different system conditions (conditions of cases are given in section 2.4.1), the converged correlation are always observed, in many cases, the lowest line losses and the highest average node voltages appear in the same solutions.

The collection between average node voltage and other state variables of power flow which are used to evaluate the system operational state, including magnitude of through complex power, magnitude of complex power loss, through reactive power, reactive power loss, voltage loss, through active power are also detected as shown in Fig. 2.8. It is observed that all above state variables are correlated, that is, the qualities of the state variables of power flows are trended to be improved integrally with the variation of system configurations.

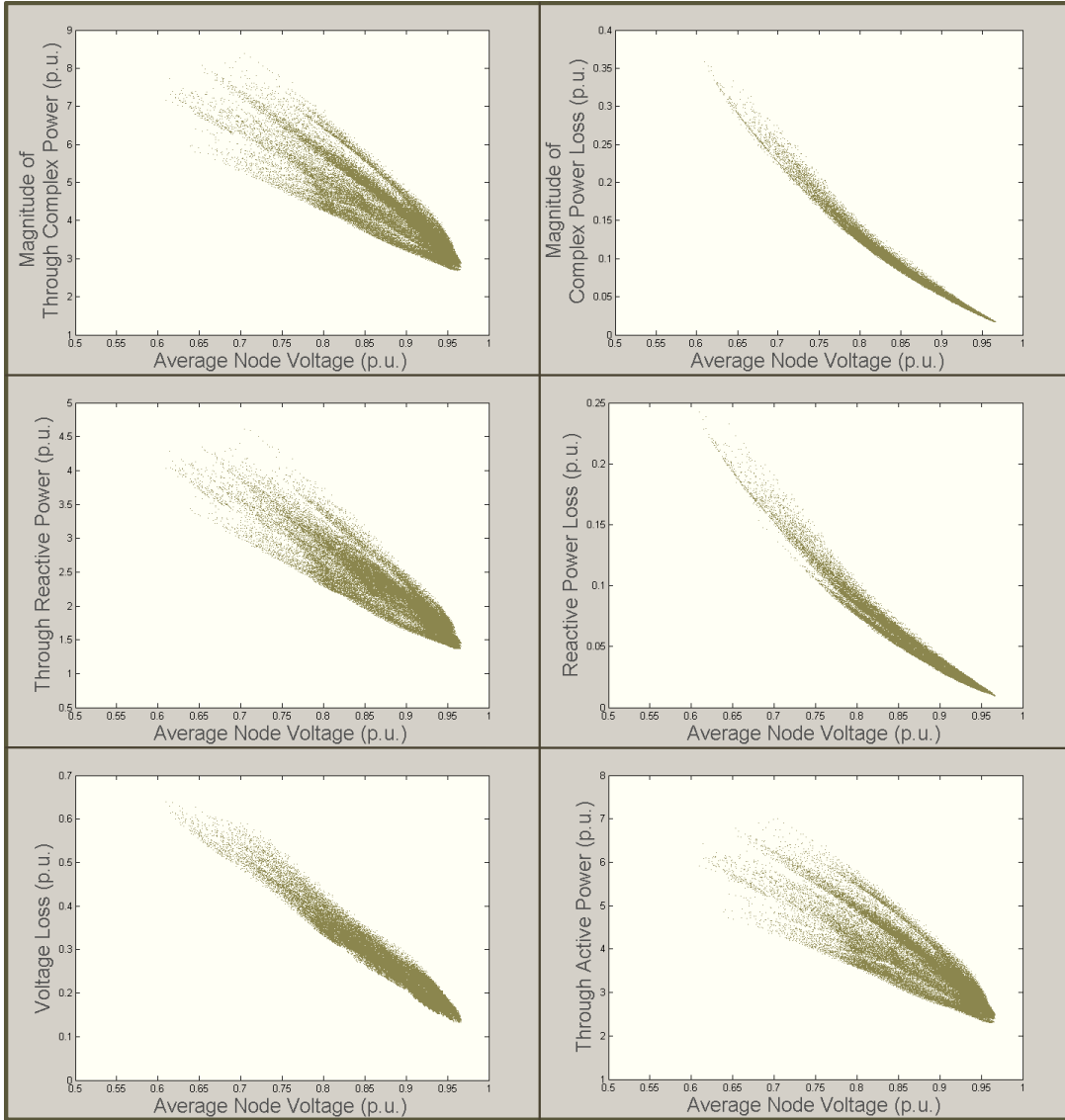


Fig. 2.8. Correlation of the state variables of power flows.

Based on the above analysis, a new view can be introduced into the definition of distribution system reconfiguration issue: reconfiguration is defined as the multi-objective optimization problem, but the multiple objectives are correlated strongly. Optimization of any objectives will lead to the improvement of others. Among the defined constraint conditions, radial network and connectivity constraints are requisite, but other power flow constraints, such as voltage profiles and capacity, are not necessary to be considered in the searching methods, since all state variables have been improved with the optimization of line loss. In the view of the solution space, the solutions in relative low line loss will be always in good condition in other operational conditions, while other state variables of power flow are also available to be used as the guidance to obtain the configuration with minimal line loss.

2.3 Proposal of intelligent flow algorithm (IFA)

Two points of the experimental knowledge have been studied in the previous sections: 1) qualities of the state variables of power flows have the trend to be improved integrally; 2) balanced supplying topology leads to configurations with good qualities of power flows. Accordingly, this paper proposes a new reconfiguration technique named intelligent flow algorithm (IFA).

The idea of the IFA is explained as an example in Fig. 2.9. The searching method can be explained to search the sweetest apple in a group of ones. The idea of common heuristic method is shown in the left graph, in which apples should be tasted one by one. However, the characteristic can be explored that the sweet apple must be red in appearance. With this knowledge, the searching method can select red apples firstly, and find the sweetest one by tasting. In that way, the efficiency of the searching method can be improved.

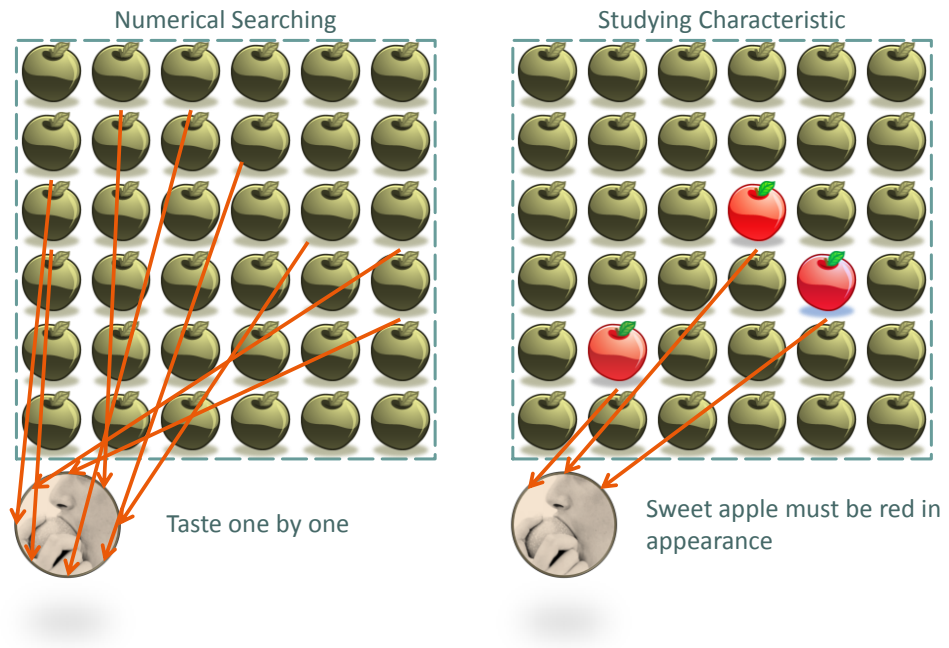


Fig. 2.9. Example of selecting the sweetest apple.

The working path of the IFA is shown in Fig. 2.10. Firstly, the IFA finds one of the balanced configurations (outstanding solutions). Then the minimal line loss configuration (best solution) is searched based on the revision of the balanced configuration. Details on each procedure are explained in the followings.

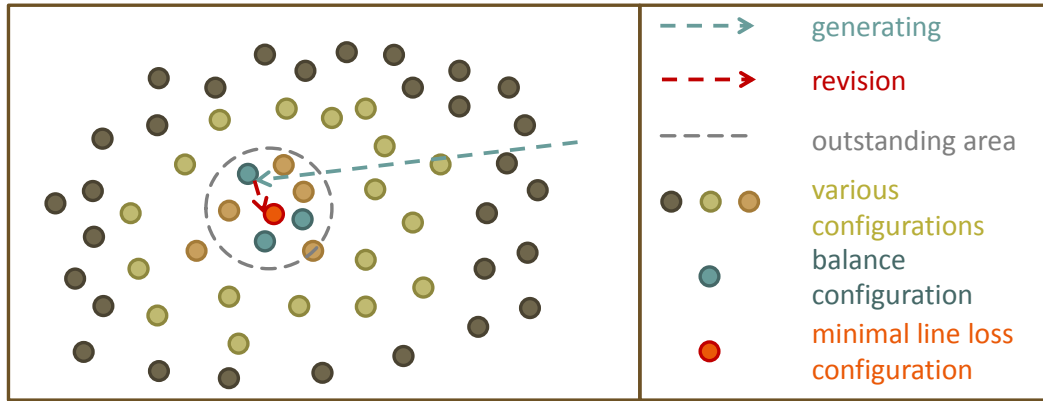


Fig. 2.10. Work path of the IFA.

2.3.1 Flow Generation

The IFA finds the first configuration candidate by the following algorithm. It is called flow generation in this paper because it is based on an analogy to water flowing in pipeline.

- 1) The flows of searching originate from power source, that is, the distribution substation. At the beginning, all the branches (sectionalizing switches) are set as off-state (opened).
- 2) One of the flows can flood towards one of its neighbor nodes through the opened connecting branch. The branch to be passed is decided based on the speed of flow (defined later), that is, the fastest flow (within the voltage constraint conditions) can advance to the neighbor node. When the flow passes the branch, the corresponding sectionalizing switch is decided to be closed.
- 3) The flow can be split into multi-flow when it arrives to “T” nodes.
- 4) Every flow cannot flood to the node which has been already occupied by other flow’s trail. This is the rule to ensure the radial network constraints.

An example of flow generation is illustrated in Fig. 2.11-A to F. The configurations generated by the flow generation always realize the radial topology with supplying to all nodes. Furthermore, all of possible configurations are able to be generated with the combinations of the speed of flows.

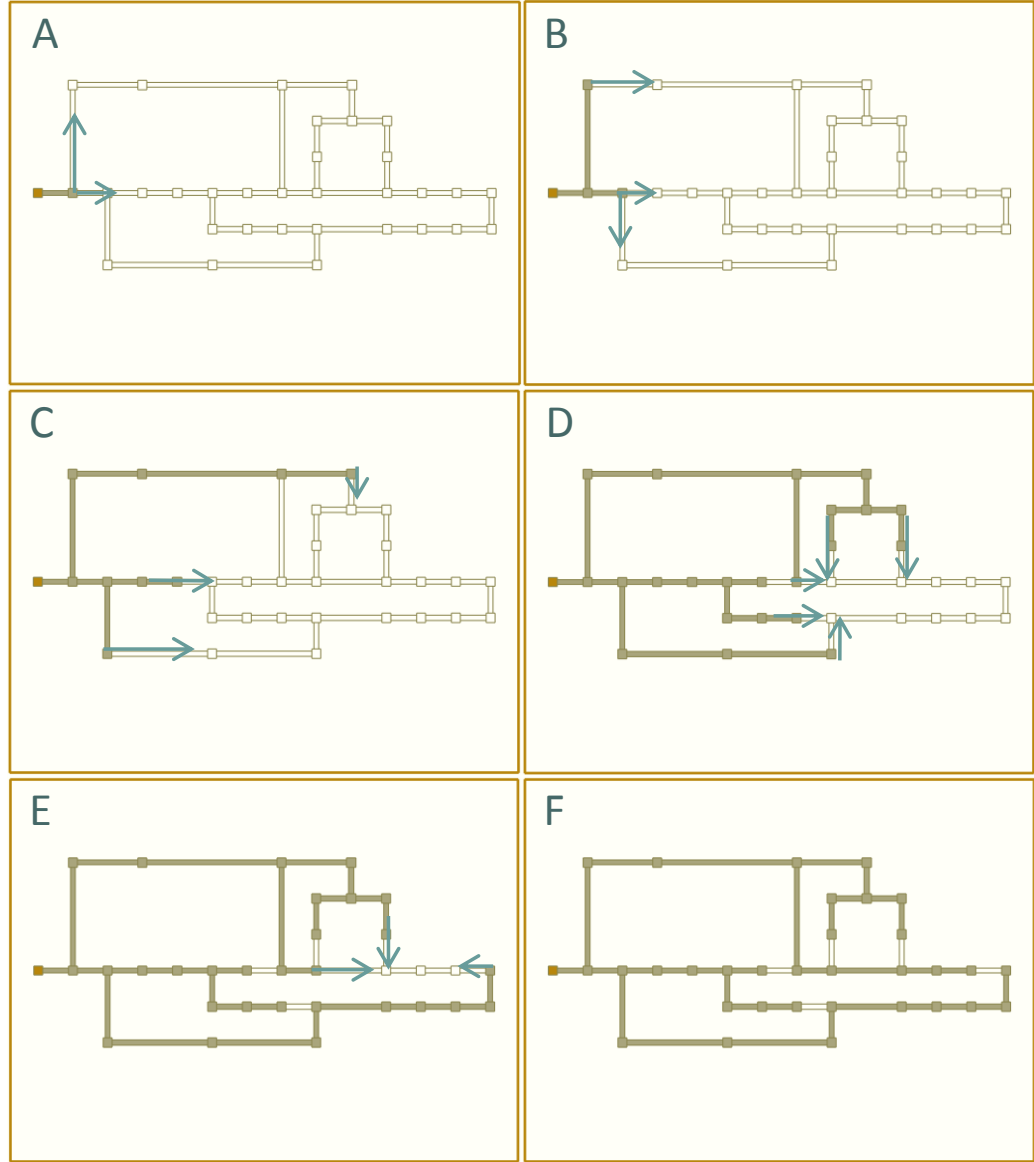


Fig. 2.11. An example of the flow generation in the IFA.

As described above, flow advance is based on the speed of each flow head (referred as v_F), defined as follows:

$$v_F = V_F - \beta \cdot C_b \quad (2.9)$$

Where, β is weight coefficient (constant), V_F is the causing voltage, and C_b is the causing degree of connectivity breaking (DCB). The calculation of V_F and C_b are explained in below:

- 1) The causing voltage, V_F , reflects the supplying weight of candidate flow branches,

where higher value indicates that the branch of flow has more capability for subsequent loads supplying. V_F is calculated as (2.10) approximately,

$$V_F = |V_n - \frac{[P_m R_l + Q_m X_l + j(P_m X_l - Q_m R_l)]}{V_n}| \quad (2.10)$$

Where V_n is the voltage magnitude of node n , obtained by the load flow calculation for the existing configuration of current stage; j is the imaginary unit; P_m and Q_m are the active and reactive load at node m ; R_l and X_l are the resistance and the reactance of branch l ; the position of n , m , l is shown in Fig. 2.12.

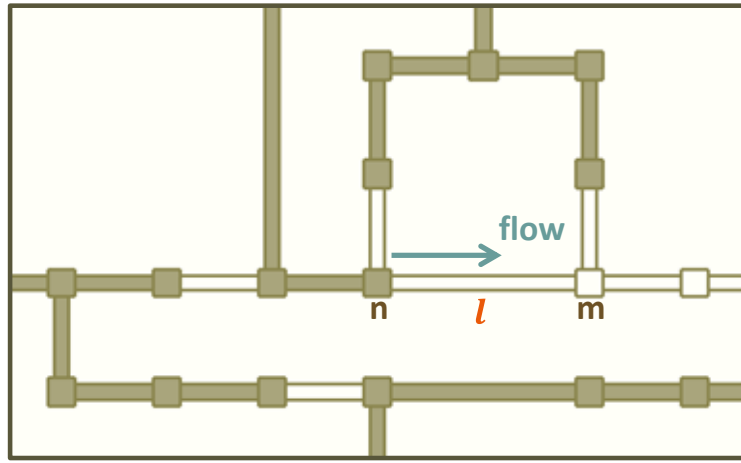


Fig. 2.12. Positions of the parameters in the calculation of V_F .

Voltage estimation by (2.10) is based on an approximation in order to shorten the computation time. Exact load flow calculation is done once only for the fixed configuration in each stage of flow generation.

2) The causing DCB, C_b , reflects the degree of imbalance caused by the advancing of candidate flow branches. C_b is calculated as (2.11)~(2.13).

$$C_b = \frac{\sum_{j=1}^{L_c} (C_{bj} - C_{aj})^2}{\max(1, L_c - 1)} \quad (2.11)$$

$$C_{bj} = \sum_{i=1}^N |\hat{S}_i|, \quad \text{if } i \in N_j \quad (2.12)$$

$$C_{aj} = \sum_{i=1}^N |\hat{S}_i|, \quad \text{if } i \in N_j \quad (2.13)$$

Where C_{bj} , C_{aj} is the degree of connectivity before and after the candidate advancing, respectively; L_c is the amount of candidates; N is the amount of nodes; S_i is the complex load of node i ; N_j is the set of nodes which have not been supplied but have a chance to be supplied from the flow j .

An example of the calculation of C_b is shown in Fig. 2.13. Before advancing the candidate flow branch 13, node 15, 16 and 17 (magnitude of complex loads are assumed as $|S_{15}| = 0.1, |S_{16}| = 0.2, |S_{17}| = 0.3$, respectively) are able to be supplied by flow 1, flow2, and flow 3. Thus, the current degree of connectivity of system, $C_{b1} = C_{b2} = C_{b3} = |S_{15}| + |S_{16}| + |S_{17}| = 0.6$. However, after advancing, flow 2 will be blocked to supply node 16, 17, therefore the causing degree of connectivity of system, $C_{a1} = C_{a3} = |S_{15}| + |S_{16}| + |S_{17}| = 0.6$ and $C_{a2} = |S_{15}| = 0.1$. Then C_b is estimated as

$$C_b = \frac{\sum_{j=1}^3 (C_{bj} - C_{aj})^2}{\max(1, (3-1))} = (0.5)^2 / 2 = 0.125.$$

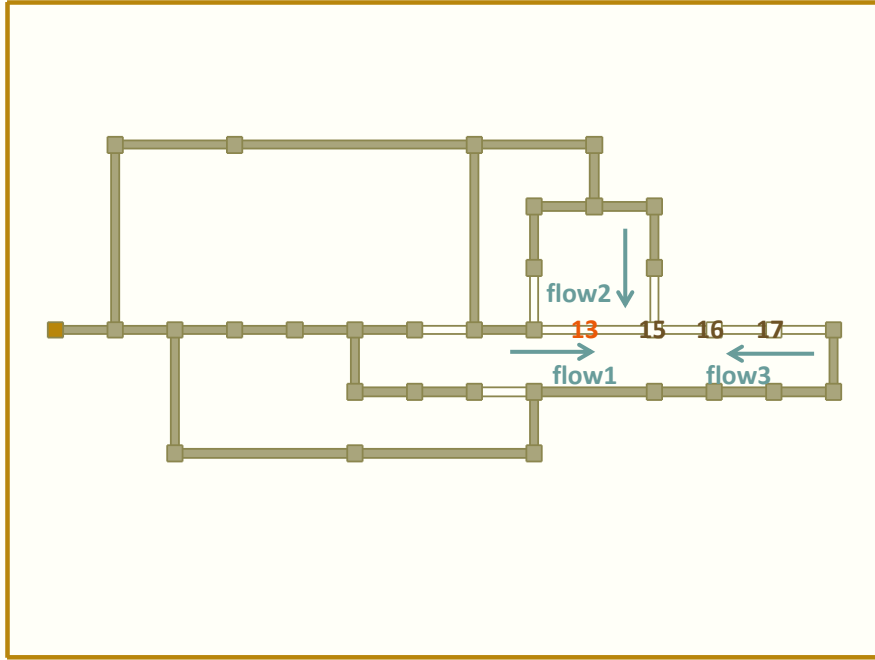


Fig. 2.13. An example of the calculation of C_b .

The balanced configuration, where branches supply loads equably, is expected to obtain in the above flow generation. Node voltages are able to evaluate the amounts of supplying loads of branch (conclusion of section 2.2.2), so the branch with higher V_F should advance faster. DCB will cause the block of topological connectivity, so the

branch with lower C_b should advance faster. The value of V_F and C_b are not comparable in numeric, thus, weighting coefficient β is introduced in (2.9).

2.3.2 Flow Revision

In order to find the better configurations, the configurations obtained by flow generation should be revised by the movement of tie-switches as follows. In each iteration of revision, the positions of tie-switches are moved to adjacent sides by order, which is to satisfy the radial topology constraint. The new configuration will be adopted if it has lower line losses. Revision iteration stops when no movement leads to better configuration.

Fig. 2.14 shows an example of the IFA revision. The arrows in A show the available directions of the movements of tie-switches, graph B shows the configuration after revision.

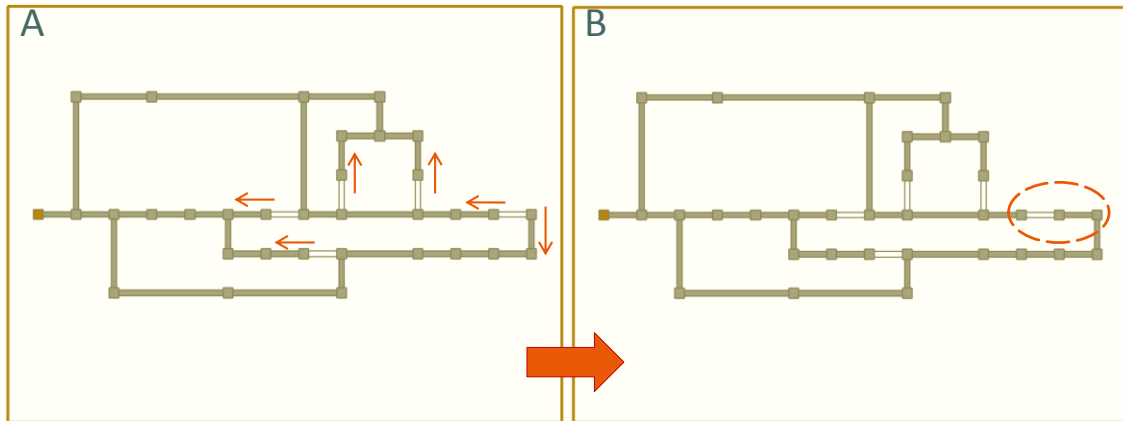


Fig. 2.14. An example of the flow revision in the IFA.

2.4 Numerical Tests of IFA

2.4.1 Model Systems and Conditions

In order to confirm the effectiveness of the proposed method, two test distribution systems were simulated on MATLAB environment. One is a 33-bus test distribution system, shown in Fig. 2.1, consisting of 37 distribution lines under the single feeder. Another, shown in Fig. 2.15, is a 43-bus distribution system [66], which is in practical scale and consists of 18 feeders and 50 distribution lines.

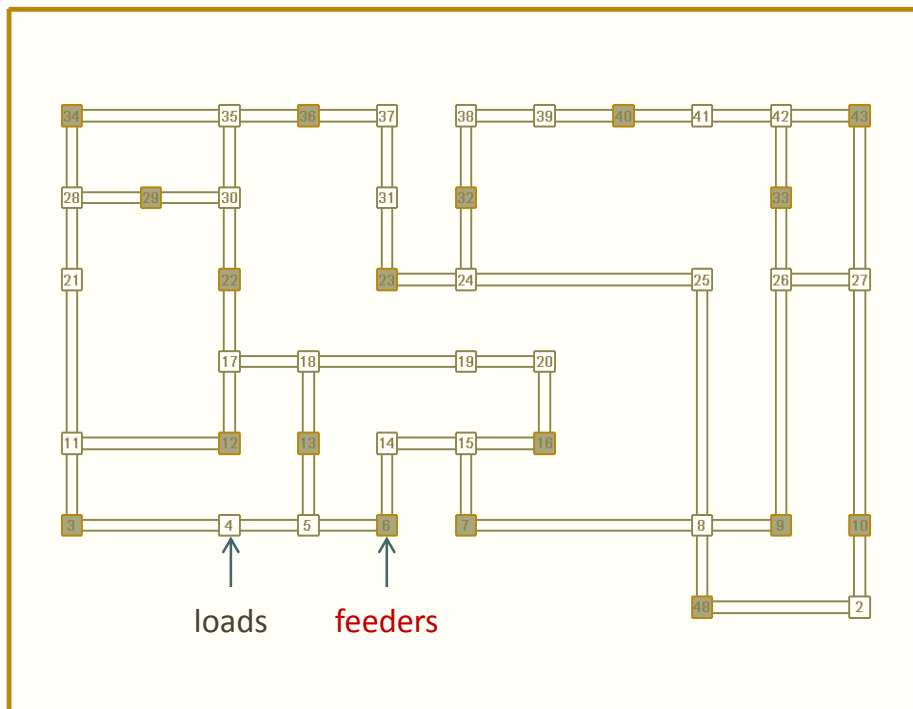


Fig. 2.15. A test 43-bus distribution system in practical scale.

In order to ascertain the validity of IFA under various conditions, different 40 and 20 cases were considered for the 33-bus and 43-bus systems, respectively. The detailed system conditions of cases for two systems are listed in Table 2.1 (detailed bus loads and line impedances of case 1 is shown in Table. A.1 of Appendix A as an example), and the sending voltage for two systems is assumed as 1.0. The global optimal (minimum line loss) configurations for all cases, which are regarded as references, were found by the complete enumeration in advance.

TABLE 2.1
SYSTEM CONDITIONS OF CASES IN THE 33-BUS AND THE 43-BUS SYSTEMS

System Conditions	33-bus system	43-bus system
Random loads distributions	01~09	01~05
Unbalanced loads distributions	10~16	06, 07
Impedance variations	17~30	08~13
Peak and bottom loads	31~40	14~20

2.4.2 Efficiency of IFA

The line losses in two model systems found by the IFA are compared with the globally optimal line losses, and the calculation precisions are shown in Fig. 2.16 (the detailed results for each case are shown in Table. A.2 of Appendix A). Here, the precision is defined as a ratio of the optimal line loss searched by the complete enumeration to the optimized line loss by the IFA.

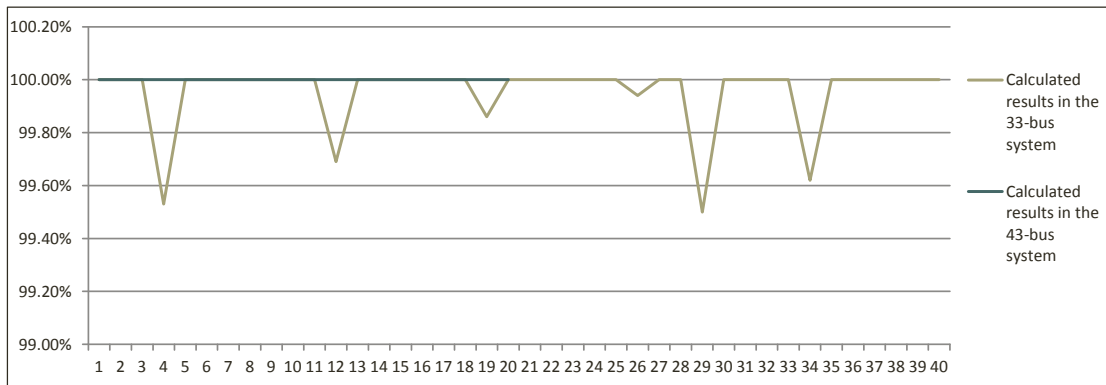


Fig. 2.16. Calculation precision of the IFA method in 40 cases of the 33-bus and 20 cases of the 43-bus distribution system.

In the 33-bus system, the proposed IFA could find the optimal results in 34 of 40 cases (success rate is 85%). In the rest 6 cases, the IFA found sub-optimal configurations, but the most serious deterioration in precision is just 0.48% and is negligible. The average calculation time was only 0.9 seconds (the detailed results for each case are shown in Table. A.3 of Appendix A). In the 43-bus system, 100% of global optimization was realized by the IFA, and the average calculation time for each case was 4.5 seconds (the detailed results for each case are shown in Table. A.4 of Appendix A).

The IFA method performs more precisely in the 43-bus system than in the 33-bus system. Major reason could be the difference of the length of power supply path. The IFA may make wrong selections in the flow generation, and this mistake is difficult to be revised completely in a single feeder system such as the 33-bus system, because it requires relatively longer power supply path. However, this problem doesn't appear in

the 43-bus system since supply path in multi-feeder system becomes shorter.

It is predicted that the nodes voltages can also be improved when the line losses is minimized from the discussion in Section 2.2.2. The lowest node voltages before and after IFA optimizing in the 43-bus system are summarized in Table 2.2. It is observed that configurations with minimal line loss are always within good conditions of voltage profiles (0.95~1.05).

TABLE 2.2

LOWEST NODE VOLTAGES BEFORE / AFTER OPTIMIZATION OF THE IFA IN THE 43-BUS DISTRIBUTION SYSTEM

Case	Before Optimization	After Optimization	Case	Before Optimization	After Optimization
01	0.9741	0.9823	11	0.9594	0.9820
02	0.9707	0.9798	12	0.9377	0.9774
03	0.9756	0.9814	13	0.9587	0.9778
04	0.9812	0.9836	14	0.9439	0.9739
05	0.9793	0.9809	15	0.9687	0.9786
06	0.9696	0.9796	16	0.9646	0.9757
07	0.9779	0.9855	17	0.9706	0.9776
08	0.9681	0.9833	18	0.9846	0.9894
09	0.9540	0.9826	19	0.9826	0.9880
10	0.9614	0.9812	20	0.9855	0.9889

2.4.3 Coefficient Parameter Tuning

Sensitivity of the proposed IFA to the value of β was also investigated to all case study conditions. The relationships between the applied β and the precisions of IFA in both test systems are illustrated in Figs. 2.17 and 2.18. Here, the considered range of β is 0.5~25 in the both systems. For the 33-bus system, the precision of IFA somewhat depends on β , however, the effects are still negligible if β is arranged 1.5~11, as shown in Fig. 2.17. For the 43-bus system, the 100% global optimization can be always achieved to any β as shown in Fig. 2.18. That is, the IFA is robust for the coefficient parameter setting.

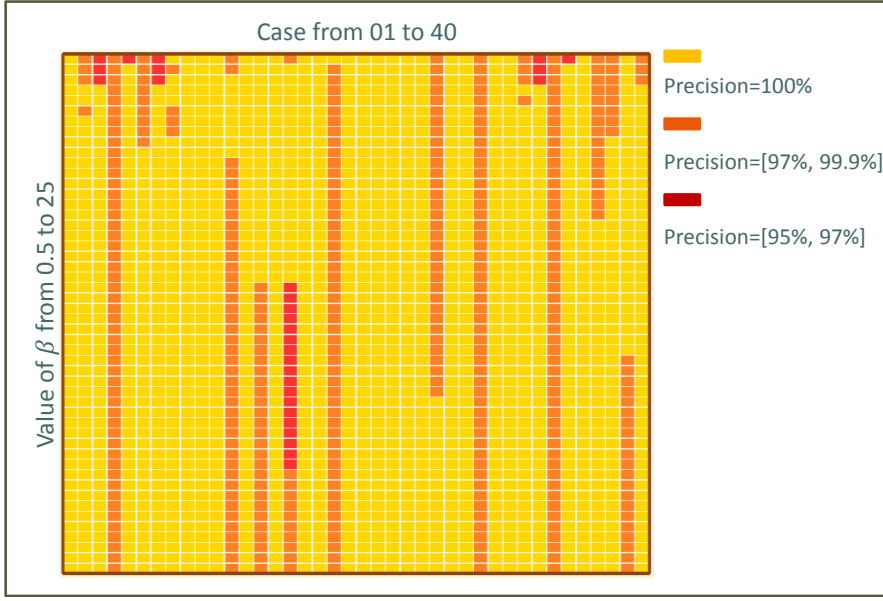


Fig. 2.17. Investigation of β in the 33-bus distribution system.

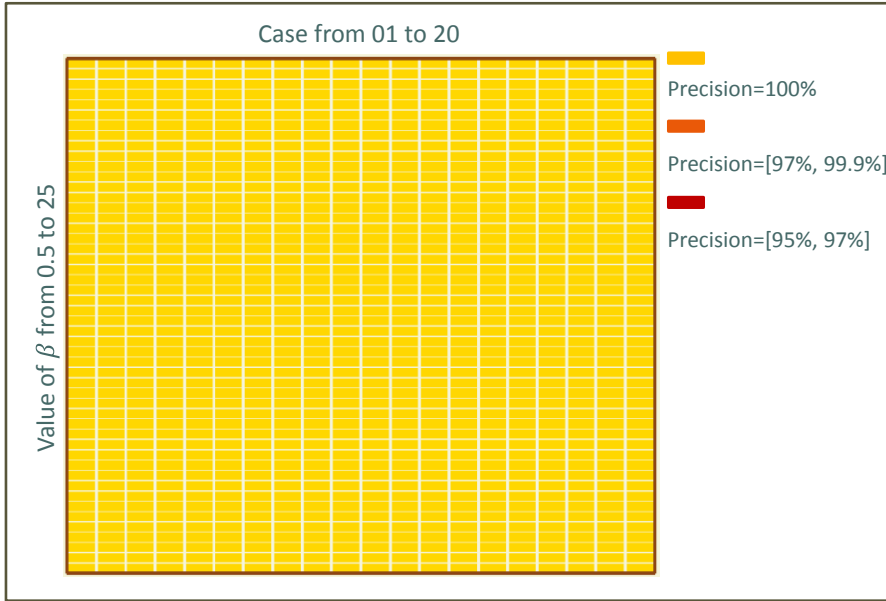


Fig. 2.18. Investigation of β in the 43-bus distribution system.

2.4.4 Comparisons with Meta-heuristic method

The GA based reconfiguration method proposed in [67] was also tested to the test systems for comparison. The applied generation number, crossover rate, and mutation rate are 10, 0.5, and 0.2, respectively. Different population sizes, 5, 10, 20, 30, 50 and 100 were considered because the population size affects the calculation precision and speed.

Fig. 2.19 shows the comparison of the efficiency of the IFA and the GA methods in the

33-bus system. Hereafter, the number after the “GA” indicates the employed population size. As shown in Fig. 2.19, larger population size can obtain better precision, but costs longer calculation time in GA. On the other hand, the IFA can achieve precise results within much shorter calculation time than the GA.

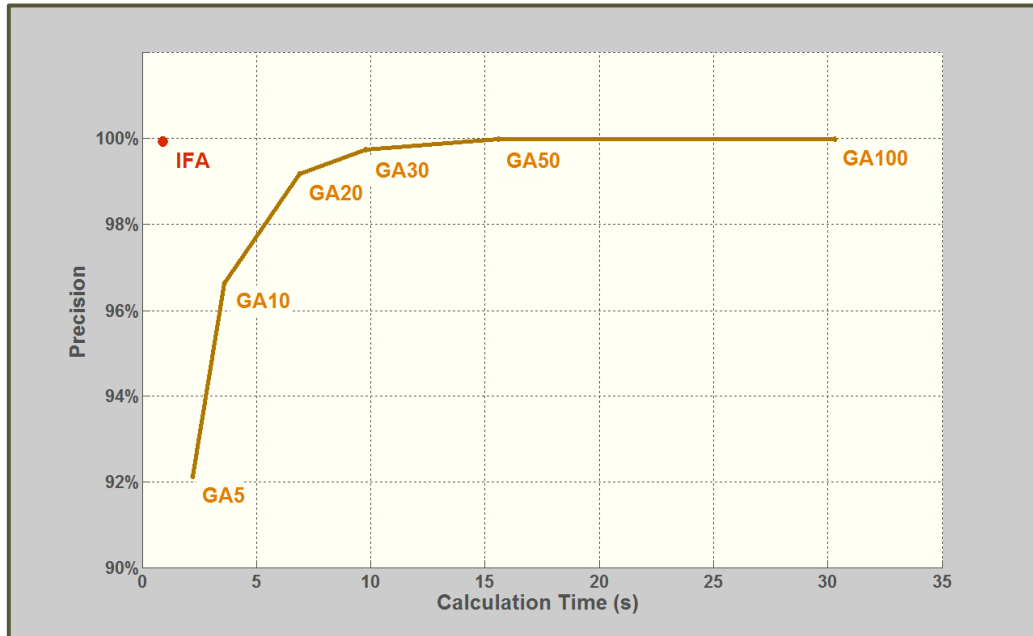


Fig. 2.19. Comparison of the efficiency of the GA and the IFA methods in the 33-bus distribution system.

Another advantage of IFA is stability of algorithm. The GA utilizes probabilistic operation in its mutation process, that is, the final configuration is found in stochastic approach. The results of GA for the same system condition differ. On the other hand, the IFA deterministically decides the configuration, so it can find the same configuration for the same system condition.

The reliability of algorithms requires the optimized results is calculated in the predictable time. The IFA and the GA are also operated in case 01 in the 43-bus system by 2 runs, and results are shown in Table. 2.3.

TABLE 2.3
COMPARISON OF THE RELIABILITY OF THE GA AND IFA METHOD IN CASE 1 IN THE 43-BUS DISTRIBUTION
SYSTEM

Method	1 st Run		2 nd Run	
	Precision	Calculation Time	Precision	Calculation Time
GA5	75%	571.7s	88%	703.8s
GA10	85%	754.5s	92%	583.2s
GA20	96%	543.8s	97%	676.5s
GA30	100%	858.2s	100%	595.3s
GA50	100%	1247.5s	100%	722.5s
GA100	100%	873.7s	100%	1306.1s
IFA	100%	4.8s	100%	4.8s

The validate solutions (radial configurations) in the 43-bus system become rare in the solution space, thus a large quantity of time is spent on the judgment of radial network in the GA method, thus the calculation speed of GA is slow and unpredictable. However, flow generation method guarantees the radial topology of generated configurations, thus, the IFA method performs fast and reliable.

2.5 Multiple Objective Searching

The IFA performs well in the minimization of the line losses in section 2.4, however, in the real system, other indices of power flows, such as voltage drop and loads balancing are also necessary to be accounted. Thus the authors also developed the function of multi-objective optimization of the IFA.

2.5.1 Multi-Folk Function of IFA

In this research, the following 4 objective functions are considered,

- 1) Minimization of line loss:

$$O1 = \min(\text{sum}\Delta P) \quad (2.14)$$

- 2) Minimization of voltage drop:

$$O2 = \min(\text{sum}\Delta V) \quad (2.15)$$

- 3) Minimization of flowing power:

$$O3 = \min(\text{sum}S) \quad (2.16)$$

- 4) Integrated consideration:

$$O4 = b1 * \min(\text{sum}(\Delta P)) + b2 * \min(\text{sum}(\Delta V)) + b3 * \min(\text{sum}(S)) \quad (2.17)$$

It is learned in Section 2.2.2 that not only configuration with minimal line loss, but also configurations in good qualities of power flow, is nearby the balanced configuration. The fork-flow method of IFA is proposed as Fig. 2.20, and detailed process is shown as follows:

- 1) One of balanced configurations is generated.
- 2) The balanced configuration is revised into configurations with minimal line loss, minimal voltage drop and minimal power flow as (2.14), (2.15) and (2.16), respectively.
- 3) Calculate $O4$ as (2.18),

$$\text{Objective} = b1 * \left(\frac{\text{lineloss}}{\text{lineloss}_{\text{optimized}}} \right) + b2 * \left(\frac{\text{voltage}_{\text{drop}}}{\text{voltage}_{\text{drop}}_{\text{optimized}}} \right) + b3 * \left(\frac{\text{flowing_power}}{\text{flowing_power}_{\text{optimized}}} \right) \quad (2.18)$$

Where $\text{lineloss}_{\text{optimized}}$, $\text{voltage}_{\text{drop}}_{\text{optimized}}$, $\text{flowing_power}_{\text{optimized}}$ is the optimized result from objective 1, 2, 3, respectively. And $b1$, $b2$, $b3$ are weight coefficient parameter, set by the operators. The values of line loss, voltage drop, and

flowing power are not comparable, thus these values need to be normalized.

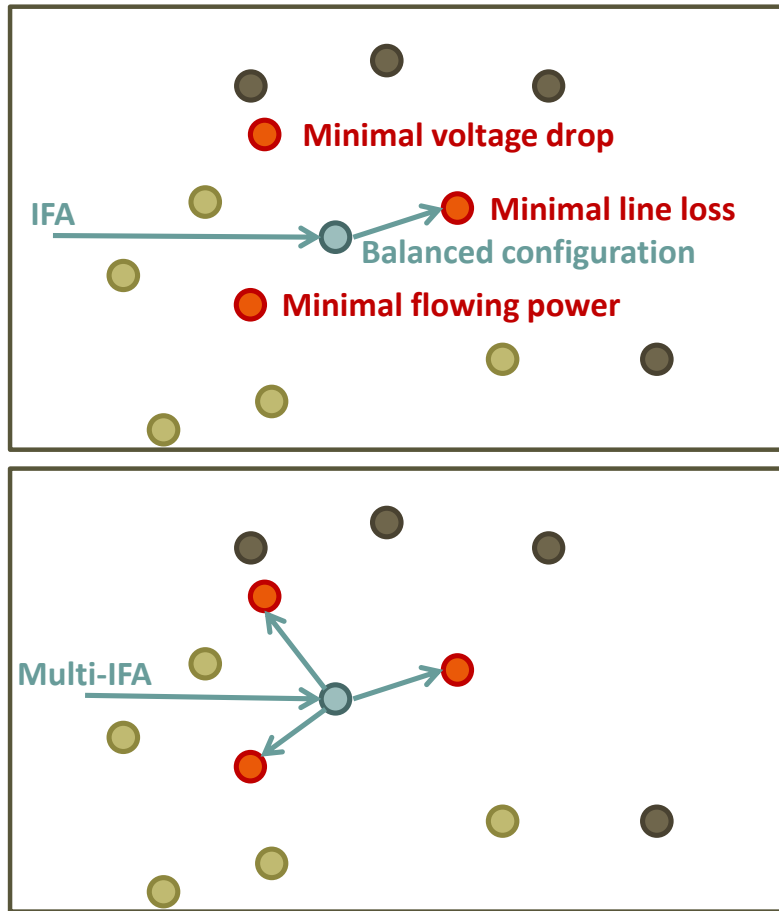


Fig. 2.20. Work path of the multi-fork method in the IFA.

2.5.2 Numerical Tests

The above methods to solve multi-objective reconfiguration are simulated in case 01~20 in the 33-bus system, and results of case 01~05 are shown in Table. 2.4 (more results of case 06~20 are shown Table. A.4 in Appendix A). It is certificated that the improvements can make IFA work effectively in the multi-objective reconfiguration issues.

TABLE 2.4
OPTIMIZED RESULTS OF CASE 01~05 IN THE 33-BUS DISTRIBUTION SYSTEM IN MULTI-OBJECTIVE
RECONFIGURATION

Case	Tie-switch					Line Loss	Voltage Drop	Flowing Power
01	11	15	19	31	35	0.0131	0.1365	2.7861
	15	19	29	31	35	0.0134	0.1354	2.9002
	15	19	29	34	36	0.0153	0.1336	3.0165
	16	18	29	31	35	0.0135	0.1386	2.8674
02	15	19	29	31	35	0.0134	0.1354	2.9002
	16	19	29	31	35	0.0137	0.1388	2.9109
	15	19	29	30	34	0.0142	0.1353	2.9740
	16	18	29	31	35	0.0139	0.1396	2.8929
03	15	19	29	30	35	0.0138	0.1363	2.9430
	15	19	29	31	35	0.0117	0.1256	2.7279
	15	19	29	34	36	0.0127	0.1237	2.8076
	16	18	29	31	35	0.0118	0.1286	2.7034
04	15	19	29	31	35	0.0117	0.1256	2.7279
	16	19	29	31	35	0.0148	0.1439	3.0385
	15	19	29	30	34	0.0162	0.1399	3.1155
	16	18	29	31	35	0.0149	0.1444	3.0326
05	15	19	29	31	35	0.0149	0.1415	3.0550
	16	19	29	31	35	0.0133	0.1339	2.8829
	15	19	29	30	34	0.0141	0.1307	2.9461
	16	18	29	31	35	0.0136	0.1349	2.8646

2.6 Conclusions

In this chapter, the properties of the configurations with low line loss and the collections of power state variables in reconfiguration have been studied. Two practical laws have been concluded:

- 1) Balanced supplying topology leads to configurations with low line loss;
- 2) State variables of power flow are strongly correlated.

Accordingly, the IFA method has been proposed to reduce the line loss of distribution system. The effectiveness of IFA has been demonstrated by a 33-bus test distribution system and a 43-bus distribution system in practical scale respectively. The merits of IFA method can be summarized:

- 1) Direct topological generating is used, rather than unordered numerical searching.
- 2) Flow generation rule guarantees topological validity of candidates.
- 3) Multiple power flow information, such as voltage, active power loss, DCB, is utilized in flow generation.
- 4) No stochastic approach is used.
- 5) Only one coefficient parameter is used, and it has wide range of adaptive values for high precision performance.

Based on above merits, the IFA method performed better than the conventional methods in efficiency, stability, reliability, robustness in the case studies. It can be concluded that the proposed IFA method is effective for online reconfiguration of distribution systems.

Chapter 3. Reconfiguration with DG Installations in Large-scale Systems

The authors have proposed a two-stage heuristic algorithm named IFA, which is used to initially determine the configuration that uniformly distributes the loads, and subsequently revise this configuration to the optimal one by means of a switch revision function in Chapter 2. The algorithm enables the quick determination of the optimal configuration of a power distribution system with few DGs. However, massive DG installations into conventional distribution systems cause geographical unbalance of load distributions and rapid variation of load profiles. In this case the IFA along with other branch-exchange based algorithms [55]–[58], [61] unexceptionally lose computation accuracies, as their computed results might oftentimes have serious errors with the global optimum.

In the present chapter, the authors present an improvement of the IFA, named extended flow algorithm (EFA), for application to a massive power system with several DGs. Because the computation burden increases exponentially with the size of the system, the authors also present simplifications of some of the EFA functions for reducing the computation time. The consequent simplified method is more efficient for reconfiguring large-scale systems.

3.1 Problem Statements

To give a clear illustration on the EFA method, mathematical model of the 33-bus system is represented in this chapter, as shown in Fig. 3.1. A combination of lines that channel resource to the terminal of a tie switch is referred to as a “flow” in this chapter. Each red arrow in Fig. 3.1 indicates a “flow line”, which is further discussed in Section 3.2. It is, however, immediately obvious that each flow corresponds to a flow line.

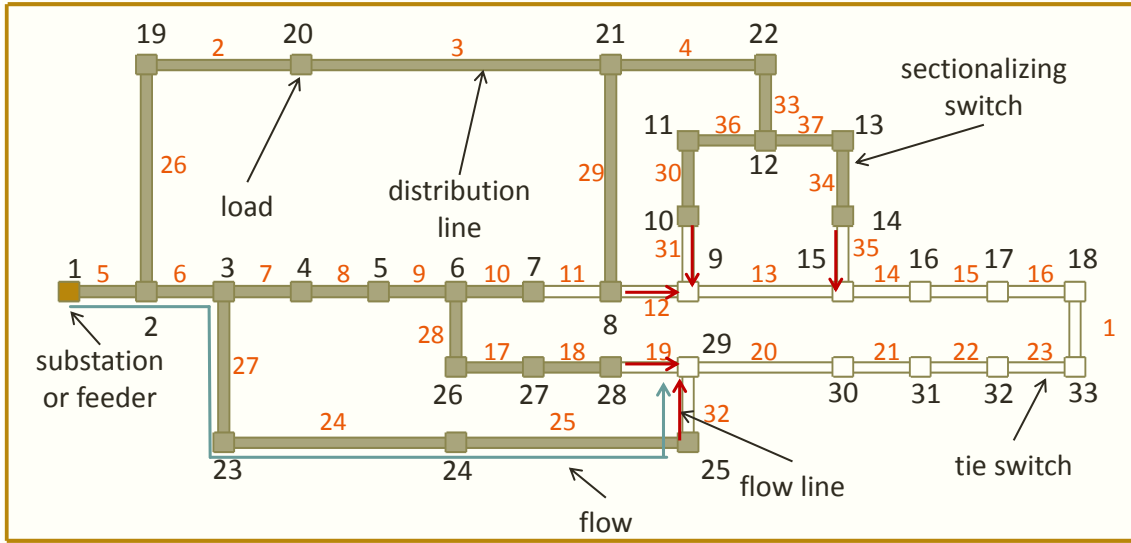


Fig. 3.1. A representation of the symmetric 33-bus test distribution system.

Minimizing voltage deviations formulated as (3.1) is regarded as the objective function for the RODN in this chapter:

(Objective function)

$$\min f = \sqrt{[\sum_{i=1}^N (V_s - V_i)^2] / N} \quad (3.1)$$

where N is the total number of buses, V_s is the magnitude of the sending voltage at a distribution substation [p.u.], and V_i is the voltage at node i [p.u.], which is obtained by load flow calculation for a determined configuration. The constraint conditions are considered same as Section 2.1.

The EFA is an extension of the IFA and therefore also consists of two stages. The first stage, referred to as the flow generation mechanism (FGM), is used to generate a balanced configuration, which has been determined to have lower voltage deviations in Section 2.2.2. However, because the balanced configuration is a rough guide for achieving optimality and may not be sufficiently accurate, the second stage of the EFA,

referred to as the flow revision mechanism (FRM), is used to improve the accuracy through an enhanced branch exchange approach, by which the minimum voltage deviation configuration (the best solution) is determined.

The DGs in this research are treated exactly same as negative load, which however has two critical distinctions with low loading level, 1) buses with high penetration of DGs are possible to present as negative net loads, 2) partial penetrations of DGs extremely increase networks' geographical load distributions. The installation of DGs also changes the voltage profiles of a distribution system. For example, the inverse power flows from the DGs produce a voltage increase.

To give a brief description on the problems of the IFA in the systems with massive DG installations: a balanced configuration is intermediately targeted in the proposed method. However, the determination of an effective balanced configuration in the IFA is considerably difficult as many DGs are installed and load distributions are uneven [65]. As a result, the optimized results in the IFA couldn't be guaranteed within high accuracy in this case. Compared to the original IFA, the improvements afforded by the EFA mainly targeting at coping with installed DGs are explained as follows.

- 1) A new formulation is developed in the FGM to guide the flow generation, which is proved to enhance qualities of the generated balanced configurations.

- 2) A highly efficient branch exchange method, which has higher revision ability on balanced configuration, is developed in the FRM.

3.2 Improvements on IFA: Extended Flow Algorithm (EFA)

3.2.1 Flow Generation Mechanism

Before initiating the FGM, the parts of the distribution system with inherent radial topologies are identified as clusters, and the switches in the clusters are excluded from the off-state candidates in the FGM. For example, the lines connecting nodes 89–97 in Fig. 3.5 are identified as belonging to the same cluster and excluded from the off-state candidates. The FGM is initiated in the status in which all the lines are set to the off-state (opened) and the sending point in the distribution substation is initially activated (colored in Fig. 3.1). The opened lines only connect with the single activated nodes that are defined as flow lines, e.g., lines 12, 19, 31, 32, and 35 in Fig. 3.1, where Line 11 is not a flow line since it connects two activated nodes. In each iteration, the flow line with the lowest flow burden (defined below) is set to the on-state (closed). The lines in a cluster are bundled, which implies that all the lines are immediately closed when any one of them is closed. The iteration is terminated when all the nodes are activated. The flowchart of the FGM is shown in Fig. 3.2. The configuration generated by the above rules also naturally has a radial topology with supply to all the nodes satisfying constraints, which is identical as the IFA.

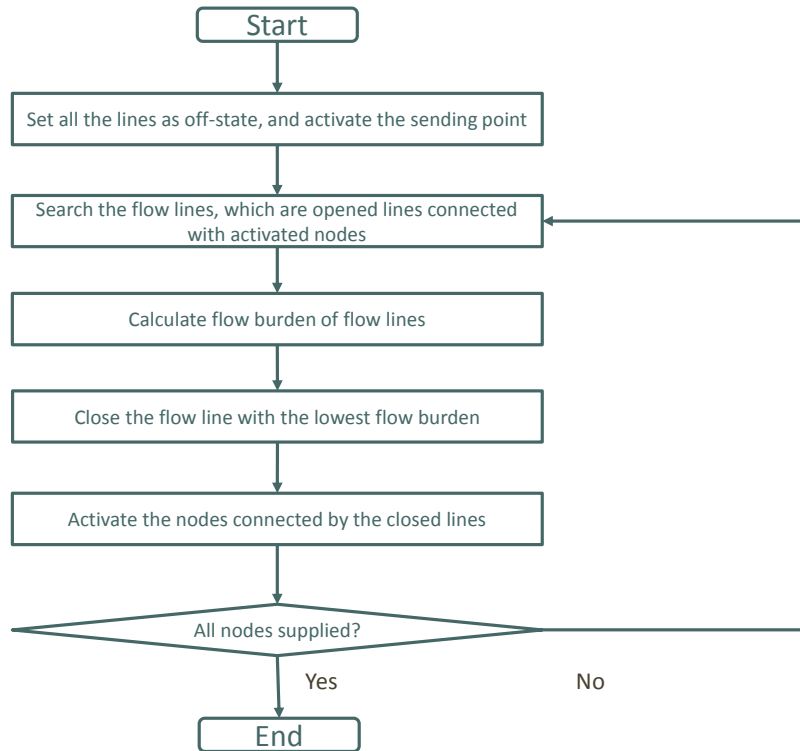


Fig. 3.2. Flow chart of the FGM.

In the iteration described above, the flow line that is to be closed is identified based on the flow burden. The balanced configuration can be realized by closing the flow line (i.e., advancing the flow) with the lowest flow burden in each iteration. The flow burden of the j -th flow (FB_j) is defined as follows:

$$FB_j = (V_S - V_{Fj})^2 + \beta \cdot C_{DCBj} \quad (3.2)$$

Where V_{Fj} is the estimated voltage of the corresponding node to be activated after closing the j -th flow line; e.g., the V_F of flow lines 32 is the voltage of node 29 when flow line 32 in Fig. 3.1 is closed. The simplified calculation of V_{Fj} is identical as the IFA in (2.10). $(V_S - V_{Fj})^2$ gives the voltage loss between the sending point and the flow line, and reflects the actual burden of the j -th flow. A higher value of $(V_S - V_{Fj})^2$ indicates a heavier flow burden on the load, with a flow characterized by a lower $(V_S - V_{Fj})^2$ being more likely to be selected because of the expectation that the total load along the corresponding distribution lines would be relatively small. C_{DCBj} in (3.2) is the degree of connectivity block (DCB), which is the potential burden of the j -th flow. It is a measure of how the advancement of the flow line interferes with other movements; e.g., in Fig. 3.1, the flow in flow line 12 would be incapable of supporting additional load if flow line 31 is closed. The calculation of C_{DCBj} is also identical as the IFA in (2.11)-(2.13). A flow with a higher C_{DCBj} is more likely to experience inhibition of its advance. The values of $(V_S - V_{Fj})^2$ and C_{DCBj} have different dimensions, and a weighting coefficient β also is thus introduced into (3.2). Compared to the “flow speed” proposed in Section 2.3.1 in the IFA, the flow burden proposed can better reflect flows’ load burden in the presence of DGs, irrespective of whether the voltage deviation involves V_{Fj} being higher or lower than V_S .

3.2.2 Flow Revision Mechanism

To determine the suboptimal configuration, the balanced configuration obtained by the FGM should be revised by iteratively moving the positions of the opened switches in the FRM stage. More specifically, the position of one of the opened switches is moved to an adjacent side, and the resultant new configuration is regarded as a sub-optimality candidate. All the possible candidate configurations are compared based on their voltage deviations as defined by (3.1), and the candidate with the lowest deviation is tentatively selected as a suboptimal configuration. The detailed flow chart is shown in Fig. 3.3.

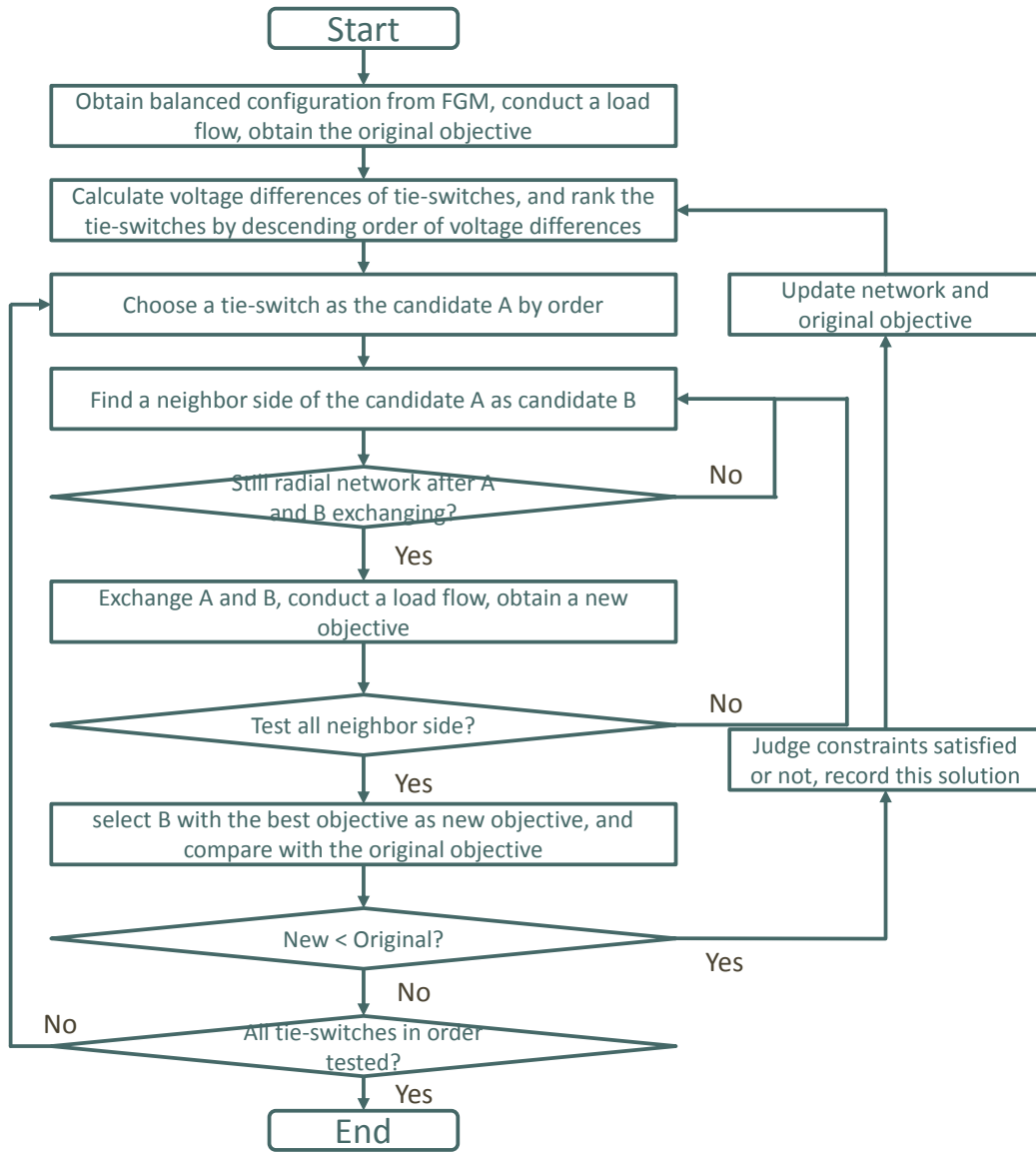


Fig. 3.3. Flow chart of the FRM.

Step 1) In each iteration, the tie switch with the largest voltage difference is chosen as candidate switch “A.” It has been found that the overall voltage deviations can be decreased by reducing the voltage differences of the tie switches [56].

Step 2) The sectionalizing switches adjacent to candidate switch “A” are chosen as candidate switch “B” with the condition that the configuration remains a radial network after the exchange of the on/off statuses of “A” and “B” (i.e., moving the opened switch from “A” to “B”).

Step 3) Voltage deviations are calculated using the new switch states. All the “B” around “A” are tested, and the solution with the smallest voltage deviations is selected and compared with the original solution. The original network is updated if the new

solution is found to be better.

Step 4) Steps 1–3 are repeated until no better objective function is obtained.

In the above process, all the new solutions are evaluated based on whether the voltage constraint condition (2.6) is satisfied or not, and they are then recorded. Finally, the feasible configuration that satisfies the constraints and has the smallest voltage deviations is selected as the final configuration. The steps 1-4 considerably enhance searching range and efficiency in the FRM, compared to common branch exchange approaches used in the IFA or other heuristic methods. As a consequence, the FRM could depress errors of the final results even when the balanced configurations in the FGM are not well established, which will be certified in case studies of Section 3.3.

3.3 Numerical Tests of EFA

3.3.1 Model Systems and Conditions

To confirm the effectiveness of the EFA, two small-scale and two large-scale test distribution systems were simulated in the MATLAB environment. The first small-scale system was the 33-bus distribution system shown in Fig. 2.1, consisting of 37 distribution lines under a single feeder. The second small-scale system was a 43-bus distribution system comprising 18 feeders and 50 distribution lines show in Fig. 2.15. The large-scale test systems were a 118-bus distribution system comprising 132 distribution lines [56] and a 216-bus distribution system comprising 240 distribution lines [57], respectively shown in Figs. 3.4 and 3.5.

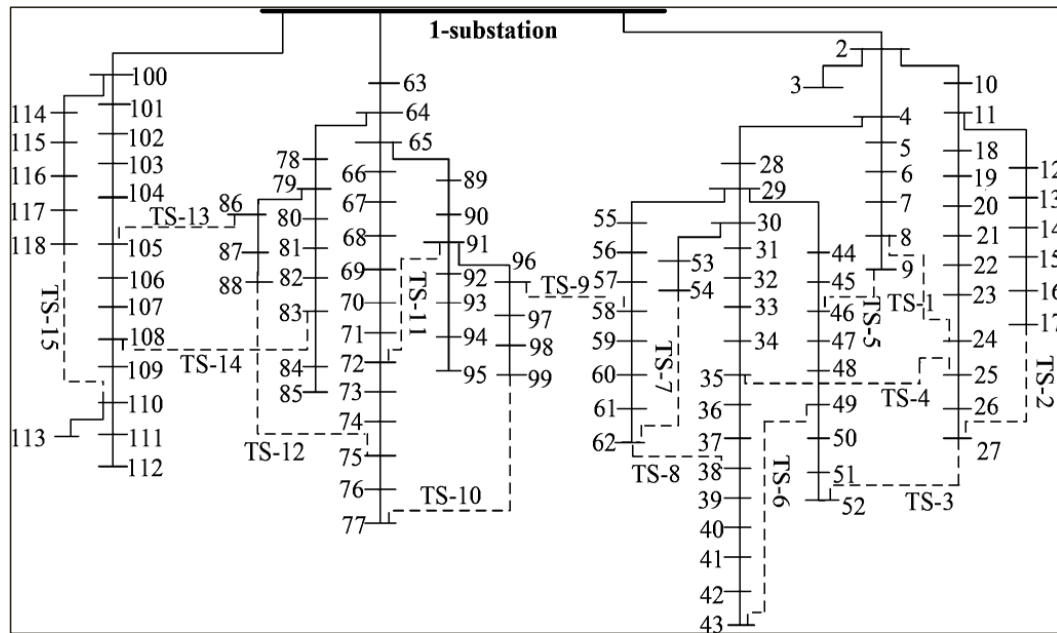


Fig. 3.4. A 118-bus large scale distribution system.

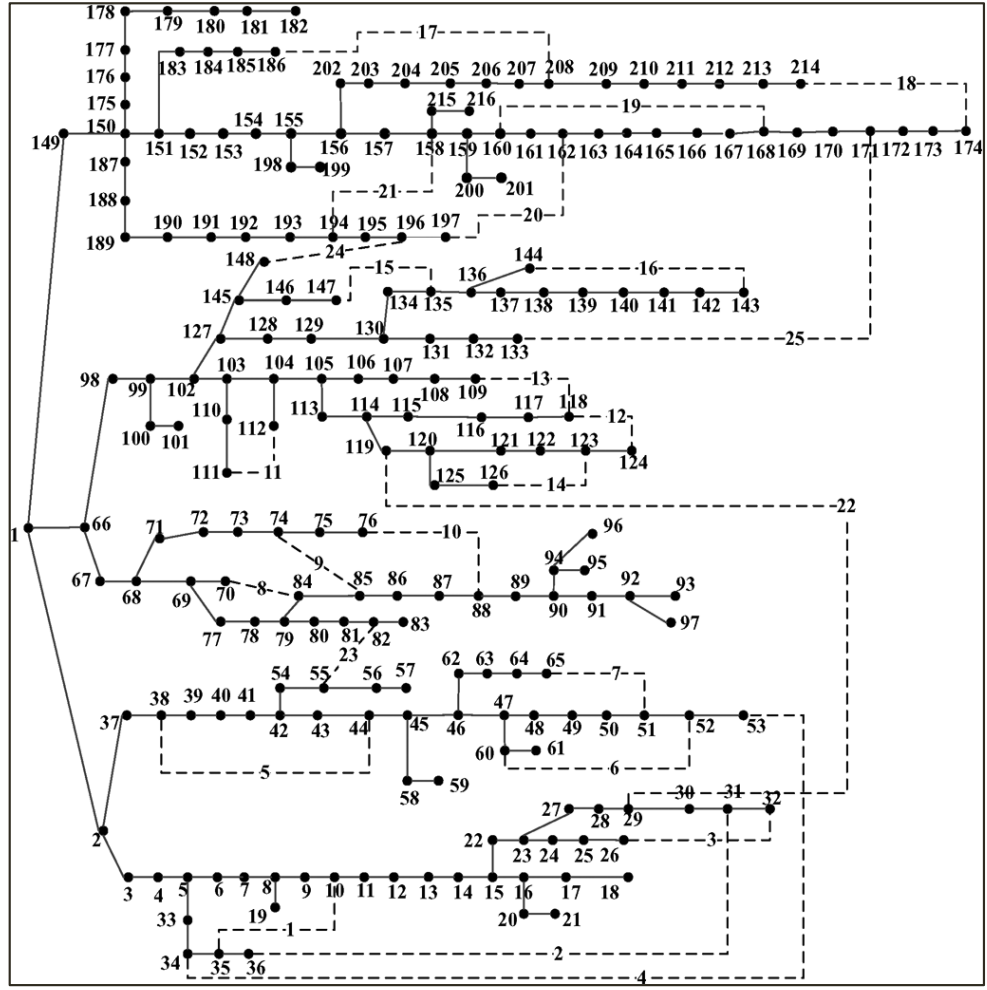


Fig. 3.5. A 216-bus large scale distribution system.

To ascertain the validity of the EFA under various conditions, 80, 40, 20, and 10 cases of the 33-, 43-, 118-, and 216-bus systems were considered, respectively. Each bus was assumed to be connected to 20 consumers, with the probability of a consumer being equipped with a DG denoted by p . The value of p for each case and the load and DG of each consumer are given in Table 3.1. The amplitude of the DG was considered to be two times that of the load, and some nodes therefore behaved as net negative loads with increasing p . ε_1 and ε_2 in Table 3.1 denote random values that vary within 40%–100% and 0–100%, respectively, to imitate the variations of the load and DG, respectively. The sending voltages of the four considered systems were all assumed to be 1.0. β in (3.2) has a wide adaptive value range of 0.1–1 and was set to 0.3 for all the cases of the four systems considered in this study.

TABLE 3.1
CONDITIONS OF THE DIFFERENT CASES OF THE 33-, 43-, 118-, AND 216-BUS SYSTEMS.

System Condition	33-bus system	43-bus system	118-bus system	216-bus system
Load of each consumer	$\varepsilon_1(0.0015 + j0.0005)$	$\varepsilon_1(0.0075 + j0.0040)$	$\varepsilon_1(0.0010 + j0.0004)$	$\varepsilon_1(0.0005 + j0.0002)$
DG of each consumer	$\varepsilon_2(0.0030 + j0.0010)$	$\varepsilon_2(0.0150 + j0.0080)$	$\varepsilon_2(0.0020 + j0.0008)$	$\varepsilon_2(0.0010 + j0.0004)$
$p = 0.1$	Cases 1–10	-	-	-
$p = 0.2$	Cases 11–20	Cases 1–10	Cases 1–5	-
$p = 0.3$	Cases 21–30	-	-	-
$p = 0.4$	Cases 31–40	Cases 11–20	Cases 6–10	Cases 1–5
$p = 0.5$	Cases 41–50	-	-	-
$p = 0.6$	Cases 51–60	Cases 21–30	Cases 11–15	-
$p = 0.7$	Cases 61–70	-	-	-
$p = 0.8$	Cases 71–80	Cases 31–40	Cases 16–20	Cases 6–10

3.3.2 Demonstration of EFA

Case 1 of the 33-bus test system was used to demonstrate the application of the EFA. The globally optimal solution obtained by the complete enumeration is shown in Fig. 3.6-A, where the tie-switches are 16, 19, 29, 31, and 35. The objective function was determined to be $f_{optimal} = 0.0370$. In the EFA method, the lines are closed by comparing their flow burdens in the FGM stage. A snapshot of the process during the FGM stage is shown in Fig. 3.6-C, and the corresponding calculation of the flow burden is illustrated in Table 3.2. Lines 11, 18, 29, 31, 32, and 37 were chosen as the flow lines in this stage. Although lines 29 and 32 have lower voltage loss $(V_S - V_{Fj})^2$ values, their C_{DCB} values, which indicate their potentials to break the network connectivity, were higher. Line 18, which has the lowest flow burden, was finally selected as the line to be closed at this stage. The lines were closed in the order 5, 26, 6, 7, 28, 2, 3, 8, 4, 24, 9, 25, 33, 28, 36, 10, 17, 30, 18, 37, 34, 29, 32, 20, 21, 22, 23, 1, 12, 13, 14, 15, while lines 11, 16, 19, 31, and 35 were kept opened as the tie switches. The obtained balanced configuration is shown in Fig. 3.6-B, where $f_{balanced} = 0.0384$. It can be observed that the topologies of the optimal and balanced configurations are similar, and that the difference between their objective functions are small. The obtained balanced configuration was transferred into the FRM for further improvement, and the status of tie switch 11 was exchanged with that of sectionalizing switch 29. The tie switches of the final configuration are 16, 19, 29, 31, and 35, which are identical to those of the global

optimal configuration.

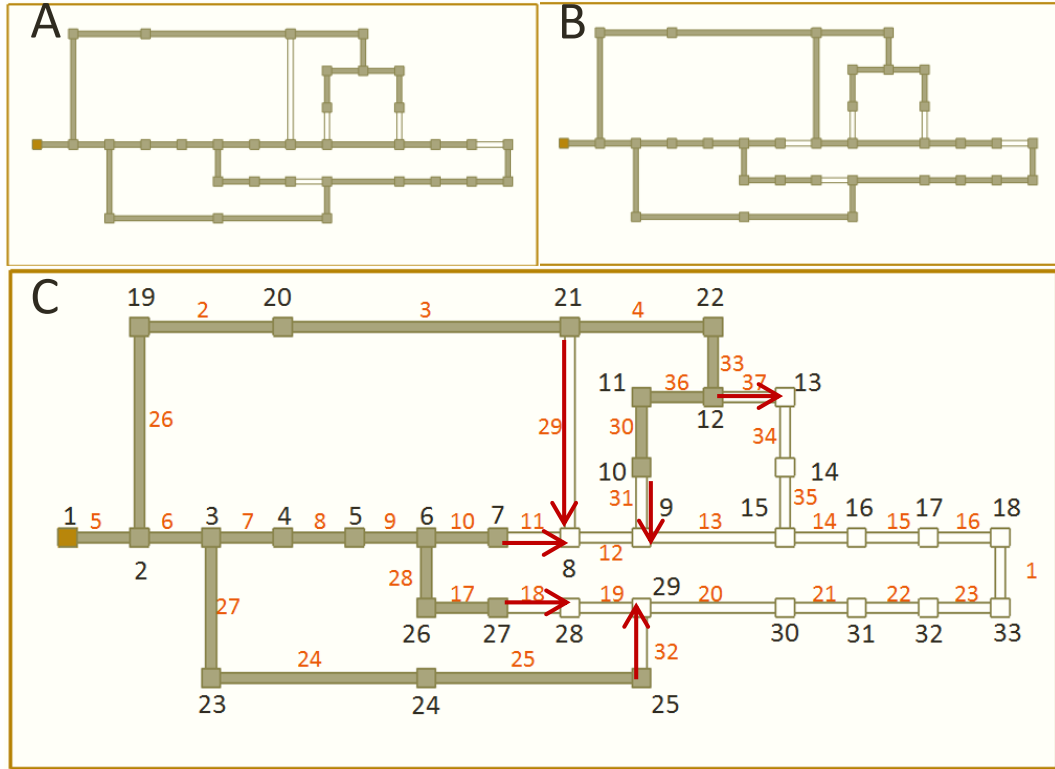


Fig. 3.6. (A) Globally optimal configuration/final configuration; (B) balanced configuration; (C) Snapshot during the FGM stage.

TABLE 3.2

SNAPSHOT OF THE CALCULATION OF THE FLOW BURDEN FOR CASE 1 IN THE 33-BUS SYSTEM.

Candidate line	$(V_S - V_{Fj})^2$	C_{DCBj}	β	FB_j
18	0.00033	0.00000	0.30000	0.00033
37	0.00038	0.00000	0.30000	0.00038
32	0.00018	0.01260	0.30000	0.00396
29	0.00019	0.01282	0.30000	0.00404
11	0.00031	0.01282	0.30000	0.00416
31	0.00037	0.02208	0.30000	0.00700

3.3.3 Tests on Small-Scale Systems

The efficiency of the EFA was also tested on the two small-scale distribution systems. The calculation results for 80 cases of the 33-bus system, and 40 cases of the 43-bus system are summarized in Table 3.3 (the detailed results for two small scale systems in the EFA are shown in Table. A.X of Appendix A). The calculation error in Table 3.3 is

defined as the difference between the voltage deviation determined by the search method and that for the global optimal configuration, which was determined in advance by complete enumeration.

TABLE 3.3
SIMULATION RESULTS OF THE GA, TCUHH, IFA, AND EFA FOR THE TWO SMALL-SCALE DISTRIBUTION SYSTEMS

System	Indices	GA	TCUHH	IFA	EFA
33-bus	Maximum error	0.001138	0.003939	0.002551	0.000870
	Average error	0.000073	0.001326	0.000316	0.000054
	Number of globally optimized cases (success rate)	62 (77.5%)	3 (3.8%)	51 (63.8%)	61 (76.3%)
	Average calculation time	3.80 s	0.17 s	0.20 s	0.28 s
43-bus	Maximum error	0.000200	0.018430	0.000823	0.000235
	Average error	0.000022	0.002245	0.000071	0.000022
	Number of globally optimized cases (success rate)	14 (35.0%)	7 (17.5%)	26 (65.0%)	33 (82.5%)
	Average calculation time	698 s	0.47 s	0.41 s	0.71 s

In the 33-bus system, the proposed EFA could determine the optimal results for 61 out of the 80 cases, which represented 76.3% success rate. In the other cases, the EFA determined the suboptimal configurations, with the most serious deterioration being merely 0.000870, which is negligible. The average calculation time was about 0.3 s. Similarly high calculation accuracy and performance of the EFA were observed for the cases of the 43-bus system, with the average calculation time for each case being 0.7 s. It is also observed by the authors in other numerical tests that high computation efficiencies of the EFA were also guaranteed when objective function in the FRM is defined as others, e.g. minimization of line losses, load balancing or their combinations (multiple objective functions). This result can also be explained by the analysis of complete enumerations in Section 2.2.2 that stable variables of power flows are highly correlated with configurations transferring.

Three other methods proposed in previous works were also implemented in the same computer environment and their results were compared with those of the EFA, as presented in Table 3.3. The population size, generation number, crossover rate, and mutation rate used for the GA [67] were 45, 10, 0.5, and 0.02, respectively. The TCUHH

method is a heuristic method with a high calculation speed [55], while the IFA was previously proposed by the present authors. All four tested methods were found to minimize the voltage deviations in the small-scale systems. The GA utilizes a probabilistic operation in its mutation process, and its final result is therefore instable and dependent on the initial configuration. Higher calculation accuracy can be achieved by increasing the population size or generation number, although this also increases the calculation time. The calculation time of the GA for the 43-bus system was very long, attributable to the rarity of radial configurations in the solution space of the 43-bus system. The GA spent much time filtering the feasible solutions, and this was much more so for the larger systems. As a heuristic method, the TCUHH iteratively opens the switch with the lowest current to determine the initial configuration for “branch exchange.” This approach is simple and fast but not accurate, which causes the TCUHH not be very reliable. The IFA has an adaptive calculation accuracy and speed, but the accuracy of the final results is not as high as that of the EFA in the DG issue. The EFA’s calculation accuracy is comparable to that of the GA, although it has a much faster calculation speed, especially for a 43-bus system. Moreover, the EFA has a reasonably high rate of achieving global optimality. The EFA does not employ a stochastic approach, and its results are therefore stable. The optimal configuration is determined from the balanced configuration, and the results are therefore independent of the initial configuration and there is no need for unordered low-quality iterations (the detailed calculated errors in the 33-bus and 43-bus systems are shown in Table A.5 and A.6 in Appendix A).

Fig. 3.7 shows the errors of the balanced and final configurations obtained by the EFA for the 80 cases of the 33-bus system. In cases 1–40, when fewer DGs were installed, the balanced configurations were quite close to the global optimal configuration, with the balanced configurations of 27 of these cases actually achieving global optimality, representing a 67% success rate. However, in cases 41–80, there was a low probability, namely, 5 out of 40 (success rate of 12.5%), of the balanced configurations achieving global optimality when many DGs were installed, and there were many nodes with negative net loads. The errors were eventually rectified by the improved branch exchange of the FRM, afforded by its high revision ability.

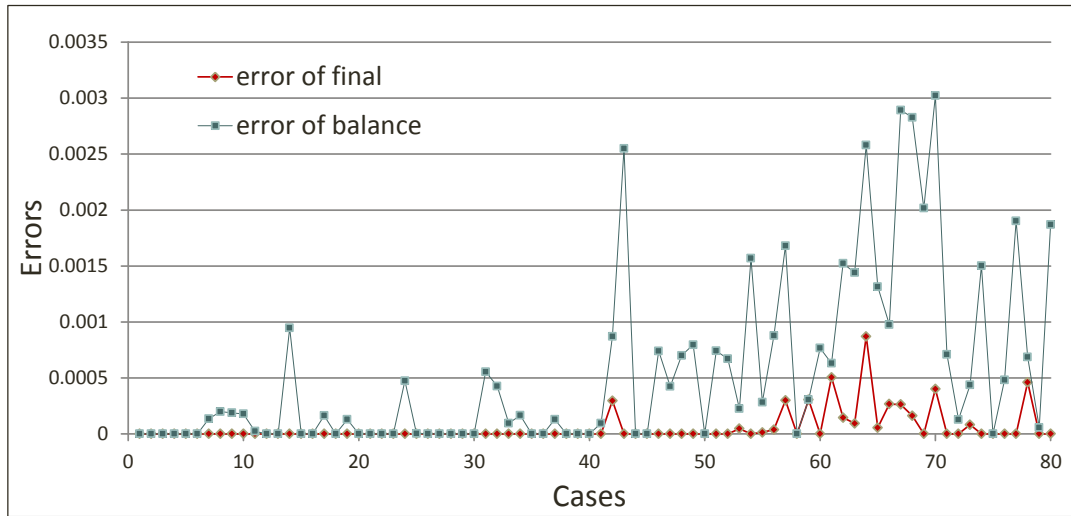


Fig. 3.7. Errors of the balanced configuration and final configuration in the application of the EFA to 80 cases of the 33-bus system.

The errors for all cases of the two systems, obtained by the GA, the TCUHH, the IFA and the EFA, were normalized in Fig. 3.8 with cases' DGs installations rate (capacities of DGs divided by the one of loads). It is observed that with less DG installations, the TCUHH lost its computation accuracies easily, whereas the IFA had lower errors. However accuracy of the IFA couldn't be guaranteed as rate of DGs installations exceeds 60%. The EFA had excellent computation accuracy with less DGs installations, and the errors were also depressed when massive DGs were connected. To deserve to be mentioned that the GA was not obviously affected by DG installation, but its main demerit is relatively long computation time, which has been confirmed above.

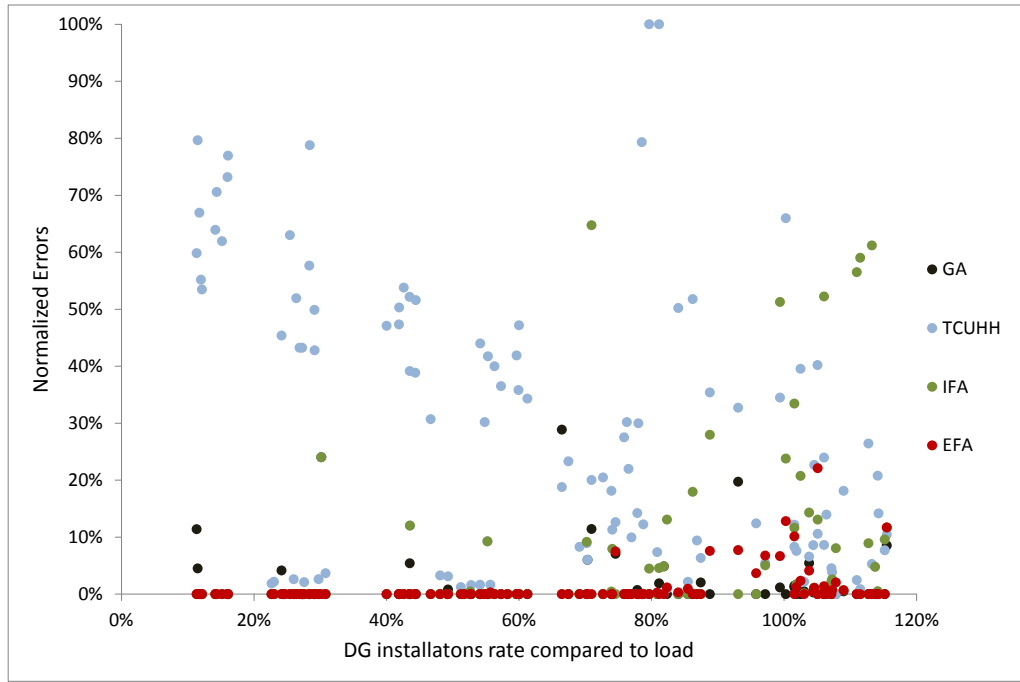


Fig. 3.8. Normalized errors of 80 cases in 33-bus system and 40 cases in 43-bus systems by the GA, TCUHH, IFA and EFA with DG installation rate.

3.3.4 Tests on Large-Scale Systems

The 118- and 216-bus systems were also used to test the validity of the EFA for large-scale systems. The calculation results of the TCUHH, IFA, and EFA for the two systems are shown in Fig. 3.9 and Table. 3.4. Because the globally optimal configurations of the large-scale systems were difficult to determine, the calculation results of the TCUHH were used as reference. The “percentage of voltage deviation” (PVD) in Figs. 3.9-A and B was obtained by dividing the voltage deviation for the EFA or the IFA by that for the TCUHH. It was also found that the EFA performed very much better than the other methods for all the considered cases of the two large-scale systems. In the EFA, the computation time is longer but accuracy is much higher compared to the TCUHH, thus the EFA has better performance since computation accuracy will be major index to evaluate algorithms’ qualities. In the 216-bus system, the IFA experienced severe efficiency degradation, whereas the EFA maintained its high performance with regard to both computation accuracy and speed (the detailed calculated results in the 118-bus and 216-bus systems are shown in Table A.7 and A.8 in Appendix A).

TABLE 3.4.

SIMULATION RESULTS OF THE EFA, IFA, AND TCUHH FOR THE TWO LARGE-SCALE DISTRIBUTION SYSTEMS.

System	Index	EFA	IFA	TCUHH
118-bus	Average PVD	91.3%	94.6%	100.0%
	Average calculation time	6.3 s	4.2 s	2.6 s
216-bus	Average PVD	93.2%	105.8%	100.0%
	Average calculation time	34.6 s	25.8 s	9.9 s

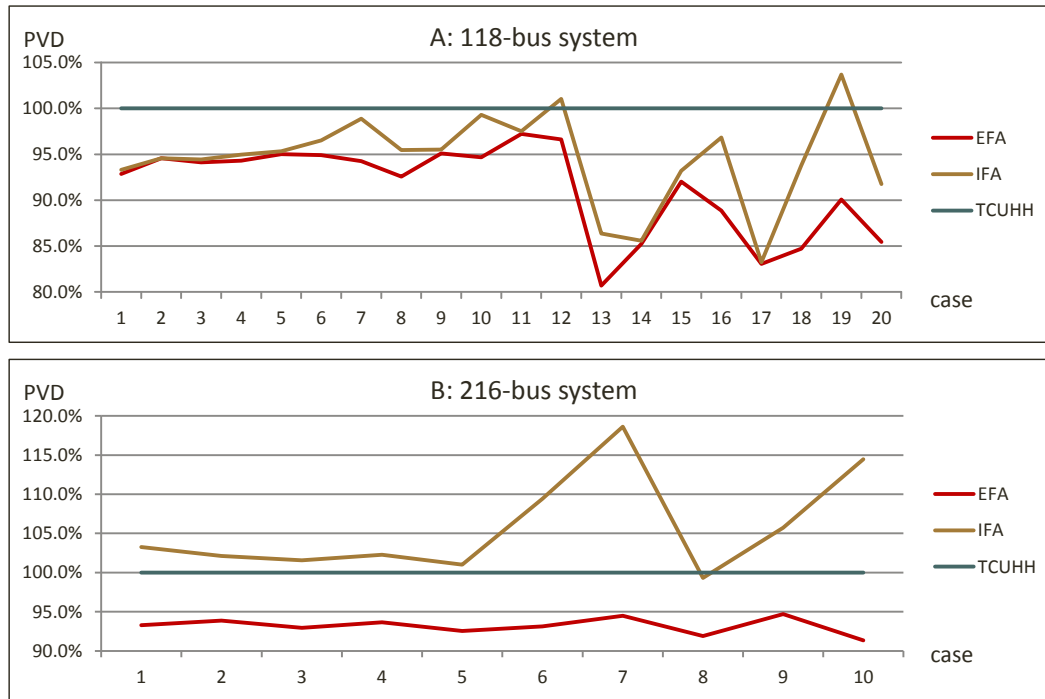


Fig. 3.9. Calculation results of the EFA, IFA, and TCUHH for the 118- and 216-bus systems.

3.4 Simplification of EFA

3.4.1 Simplified EFA

As demonstrated in Section 3.3.4, the EFA can find the better system configuration in a practical computation time. However, the computation time of the EFA for the 216-bus system was a bit longer than the other two methods (IFA and TCUHH). Breakdown of the computation time of EFA is summarized in Table 3.5, which shows both FGM and FRM spent relatively long computation time. Therefore, approximation approaches in FGM and FRM, which can increase the EFA's computation speed for a large-scale system while sacrificing the computation accuracy, are presented here. The EFA with approximations is called Simplified EFA (SEFA) hereafter.

TABLE 3.5
SIMULATION RESULTS OF THE EFA AND THE SEFA IN THE 216-BUS SYSTEM

Index	EFA	SEFA ($Cthr = 0.00001$)	SEFA ($Cthr = 0.000005$)	SEFA ($Cthr = 0.000001$)
Average PVD	93.18%	94.33%	93.84%	93.26%
Average FGM computation time	16.2 s	4.3 s	4.3 s	4.3 s
Average FRM computation time	18.4 s	2.7 s	4.0 s	9.5 s
Average total computation time	34.6 s	7.0 s	8.3 s	13.8 s

1) For the 216-bus system, the FGM required 18.4 seconds, which is almost spent for the computation of the connectivity of the system network. In details, computation of C_{DCBj} defined as (2.11)–(2.13) requires complex cyclic procedures to obtain N_{bjh} , N_{ajh} , which cost computation time mostly. In order to shorten the computation time for C_{DCBj} , the following approximated definition is applied for C_{DCBj} :

$$C_{DCBj} = NF_j \sum_{k \in N_i}^N |Netload_k| \quad (3.3)$$

Where NF_j gives the number of the neighboring flow lines of flow line j ; e.g., in Fig. 3.1, flow line 31 has one neighboring flow line, line 12. N_i is the set of inactivated nodes. Computation of NF_j is much faster than to obtain N_{bjh} , N_{ajh} . As a result, computation time of the FGM is extremely reduced in the SEFA (in Table 3.5). However,

as a rough calculation for C_{DCBj} , Equation (3.3) will sacrifice the computation accuracy.

2) Fig. 3.10 shows the normalized reduction of the voltage deviations in the FRM stage for 10 cases of the 216-bus system (each line corresponds to one of 10 cases). The indices in the vertical axis in Fig. 10 are calculated by (3.4),

$$y = (VD_b - VD_m)/(VD_b - VD_f) \quad (3.4)$$

Where VD_b and VD_f are the voltage deviations of the balanced configurations found by FGM and of the final configurations, respectively, and VD_m are the voltage deviations of configurations in some stage in the FRM. Thus “0” on the vertical axis corresponds to the state of the balanced configuration, while “1” corresponds to the final results.

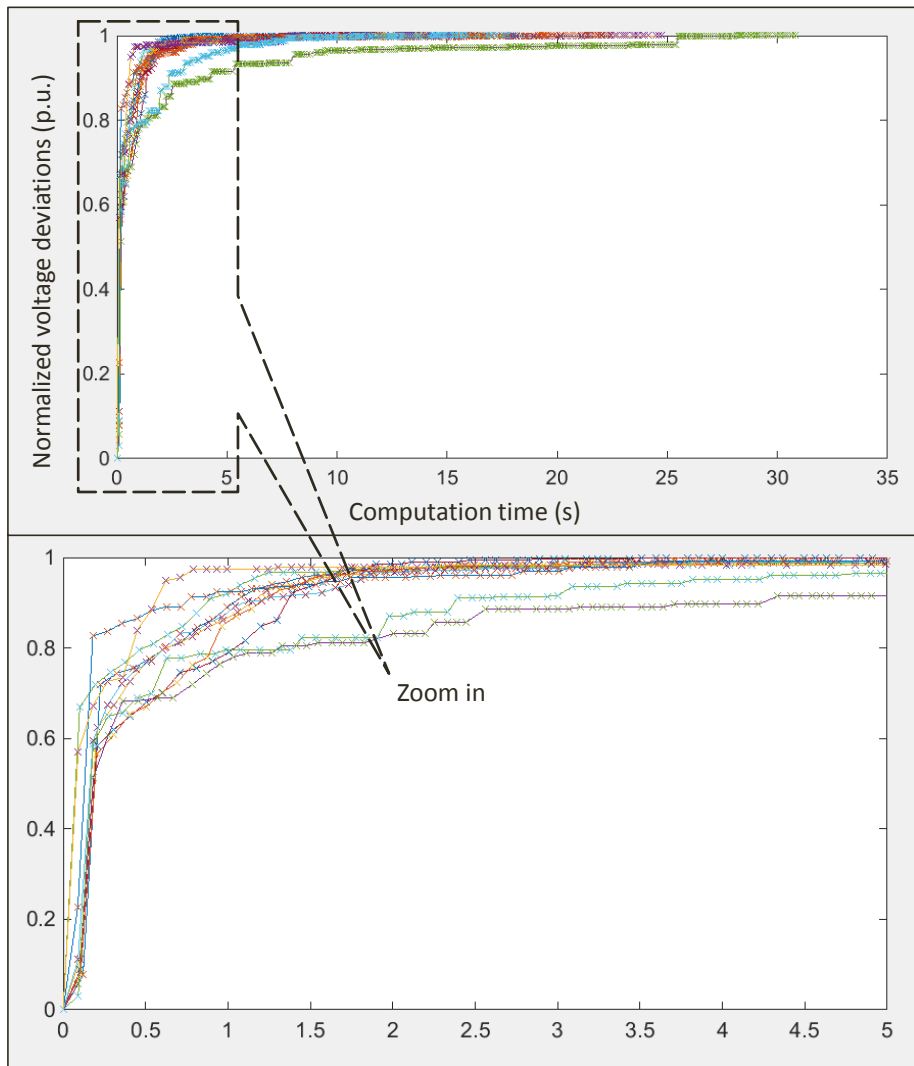


Fig. 3.10. Normalized reduction of the voltage deviations in the FRM stage of the EFA for 10 cases of the 216-bus system.

A rapid decrease during the early iterations can be observed, but the reduction later becomes inefficient. Another condition is thus proposed for terminating the iterations, namely, immediately when the difference between the original solution and a new one, as determined in step 3, becomes lower than a designed compromise threshold, denoted by $Cthr$. A higher $Cthr$ would terminate the iterations earlier, although this would also decrease the accuracy of the final results. Nevertheless, this approach effectively enables avoidance of inefficient iterations to shorten the computation time of the EFA when applied to a large-scale system. Further case studies were conducted to prove that the decrease in the calculation accuracy resulting from these proposed simplifications is negligible while the shortening of the calculation time is considerable.

3.4.2 Tests of SEFA

The SEFA was tested by applying it to the 216-bus system using $Cthr$ values of 0.00001, 0.000005, and 0.000001, respectively. The PVD in Table 3.5 was obtained by dividing the voltage deviation for the EFA or SEFA by that for the TCUHH. The results are presented in Table 3.5. As can be observed, for a $Cthr$ of 0.000005, which is the most adaptive consideration for calculation accuracy and speed, the SEFA shortened the computation time by as much as 76.0% while sacrificing a calculation accuracy of only 0.66% relative to the EFA. Also compared with the TCUHH in Table 3.4, it is observed that the SEFA with $Cthr = 0.000005$ has better performance both in computation accuracy and speed. The authors don't compare the EFA and the SEFA quantitatively, since the computation time and accuracy are in trade-off relationship. This paper leaves choice of EFA or SEFA, and design of $Cthr$, to the system operators who are eligible for practical operations of distribution systems. As a conclusion, the SEFA is particularly effective for large-scale systems that require time-consuming calculations (the detailed calculated results of the SEFA in the 216-bus systems are shown in Table A.9 in Appendix A).

3.5 Conclusion

In this chapter, the previously proposed IFA of the authors was expanded as an EFA, which enables more efficient optimality reconfiguration of power distribution systems containing massive DGs. The main improvements of the EFA are two-fold:

- 1) The concept of flow burden is used to evaluate the power supply branches to generate a balanced configuration.
- 2) The modified configuration revision algorithm tests a wider solution space to guarantee high calculation accuracy.

The effectiveness of the EFA was demonstrated by application to two small-scale distribution systems and two large-scale distribution systems with many installed DGs. It was found that the EFA exhibited a stable performance in systems containing many installed DGs, and a higher efficiency compared to previously proposed methods. The SEFA was also proposed to simplify the DCB calculations of the EFA and use a compromise threshold to terminate inefficient iterations. The SEFA affords compromise between calculation accuracy and speed for application to large-scale systems. It is concluded that the proposed methods are effective for online reconfiguration, especially of large-scale distribution systems with DG installations.

Chapter 4. Daily Optimal Schedule of Reconfiguration

The EFA proposed in Chapter 3 has been proved to be an efficient reconfiguration method especially to cope with large scale systems with DG installations. Further discussion on reasonable arrangement of reconfiguration instants is given in this chapter. The rest of this chapter is organized as follows. In Section 4.1, the optimal daily schedule of reconfiguration is formulated. In Section 4.2, we present the proposed daily schedule combined by the long-term reconfiguration method, the approach to decide the reconfiguration instants and relevant load prediction methods. In Section 4.3, two test distribution systems with PV installations operated on realistic time-varying data were simulated to certificate the proposed methods. Finally, the conclusions drawn from the present work are presented in Section 4.4.

4.1 Problem Statements

4.1.1 Mathematical Model of Daily Schedule of Reconfiguration

A produced sequence of reconfiguration schedule (SRS) is depicted in Fig. 4.1, in which L is the number of lines (switches) of the distribution network and T is the total number of time intervals, equal to 48 in a day. In the horizontal top-row individuals, called sequence of reconfiguration instants (SRI), each individual can have two modes: 0 and 1, which represents the network configuration should keep previous status and is to be changed, respectively. The vertical bottom-row individuals also called sequence of configurations selection (SCS) indicates the selection of the configuration at each time interval based on combination of switches, in which “1” indicates sectionalizing switch and “0” indicates tie switch.

Sequence of reconfiguration instants

	1	0	0	0	0	1	0	0	0
Sequence of configurations selection	0	0	0	0	0	1	1	1	1
	1	1	1	1	1	0	0	0	0
	1	1	1	1	1	1	1	1	1
	0	0	0	0	0	1	1	1	1
	0	0	0	0	0	0	0	0	0
	1	1	1	1	1	0	0	0	0
	1	1	1	1	1	1	1	1	1
	0	0	0	0	0	0	0	0	0

T

L

Fig. 4.1. A produced sequence of reconfiguration schedule.

4.1.2 Objective and Constraints

Minimization of total operating cost of daily reconfiguration schedule is formulated as follows:

(Objective function)

$$f = \sum_{t=1}^T \sqrt{\sum_{i=1}^N (V_s - V_{i,t})^2 / N} + \alpha \cdot \sum_{t=1}^{T-1} \sum_j^L (SS_{j,t+1} - SS_{j,t}) \quad (4.1)$$

Where t is time interval, and considered as 30-minute, which is the most exact accuracy of load measurement in current sensor-embedded sectionalizing switches. N is the total number of buses; V_s is the magnitude of the sending voltage at distribution substation [p.u.]; $V_{i,t}$ is the voltage of node i at time interval t [p.u.]; SS_j^t is the switch state of distribution line j at time interval t ; Balance of reduction of voltage deviations and cost of switch operations is adjustable by the coefficient parameter α in (4.1).

(Constraints)

- 1) Isolation constraint: all the buses should be energized.
- 2) Radial network constraint: distribution networks should have a radial structure without loops.
- 3) Capacity limit: a line cannot be overloaded.
- 4) Voltage limit:

$$V_{min} \leq V_{i,t} \leq V_{max} \quad (4.2)$$

Where V_{min} and V_{max} are voltage constraint, and considered as 0.95 and 1.05 [p.u.] in this paper.

4.2 Solution Algorithms of Reconfiguration Schedule

The authors mainly hired three technologies to manage the above reconfiguration schedule: load and PV prediction, a long-term reconfiguration method which developed based on the EFA, and a novel approach to decide reconfiguration instants. The detailed developments are stated as following sections.

4.2.1 Load and Photovoltaic (PV) Predictions

Future behaviors of loads and DGs are needed to determine the optimal daily schedule of reconfiguration. Two patterns of load predictions are utilized in this paper. The first one is a simplified and rough short-term prediction model given in (4.3).

$$Pre_Data_t = (\sum_{day=1}^D Act_Data_{t-day*T})/D \quad (4.3)$$

Where Pre_Data_t and Act_Data_t is the predicted and actual data for load and PV of time interval t respectively; D is number of past days, and selected as 5 in this chapter. Load and PV data is predicted as the mean value of the past five days' actual data of the same time interval.

The second pattern is the assumption that the errors between predicted and actual data are extremely small and ignorable with highly improvement of prediction techniques, thus the actual data is directly used as predicted data in the case studies.

4.2.2 Long-Term Reconfiguration Method

Configurations between two reconfiguration instants, i.e. two “1” in the SRI, are possible to be fixed for a considerable long period. The proposed long-term reconfiguration method targets on (4.4) which is a compromise optimum for a certain period's time-varying loads.

$$\min f_{vd} = \sum_{t=t_1}^{t_2-1} \sqrt{\sum_{i=1}^N (V_s - V_{i,t})^2 / N} \quad (4.4)$$

Where t_1 and t_2 are time intervals of two neighbor reconfiguration instants. The calculation burden of (4.4) is heavy to solve, thus (4.5) is used to substitute for (4.4) as simplified calculation.

$$\min f_{vd}^* = \sum_{t \in SD} \sqrt{[\sum_{i=1}^N (V_s - V_{i,t})^2] / N} \quad (4.5)$$

Where SD is set of sample load data, obtained by dividing the entire load and DG data into multiple sections evenly, and the mean value of each section is used as sample data. Fig. 4.2 shows an example that daily load and PV data as $t_1=1$ and $t_2 = 48$ (node 20 of case 2 in the 6th day in Section 4.3.1) are divided into 8 of sample data.

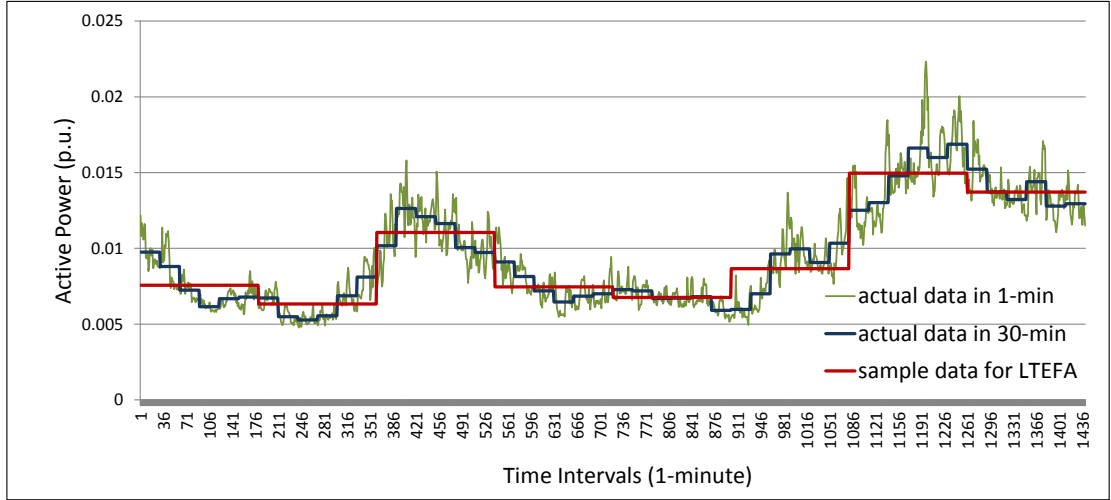


Fig. 4.2. Actual load data in 1-minute and 30-minute, and sample load data for the LTEFA's calculation on node 20 of 33-bus system of case 2 in the 6th day.

Parallel supplying loads will reduce voltage deviations of system, which is the theory mainly followed by the EFA proposed in Chapter 3. The EFA is improved into a long-term reconfiguration method named long-term extended flow algorithm (LTEFA) to solve (4.5) based on the following algorithms in this paper.

An assuming system is established as loads and PVs are the time-average values of SD . In the FGM, one of the balanced configurations is generated based on the assuming system. In the FRM, the balanced configuration is revised into the final result as (4.5) is used as the objective function. As a consequence, the compromise optimal configuration is obtained by the LTEFA achieving the minimal voltage deviations for the multiple sample data, which improve fixed configurations' time-adaptability in a certain period. The corresponding constraints of reconfiguration are guaranteed in the FRM.

4.2.3 Approach to Decide Reconfiguration Instants

Although total voltage deviations over time period T , i.e. (4.4) or (4.5), can be minimized if the optimal network configuration for each time interval is found, the overall cost of numerous switch operations for frequent reconfigurations will be extremely costly, thus network reconfiguration at all time interval is not economical. Another main task of optimal daily schedule of reconfiguration is to arrange the SRI

reasonably to further reduce both voltage deviations and switch costs, which is solved by a novel approach, named accumulation of unbalanced load distribution (AULD) proposed as follows.

The configuration is essentially optimized based on net load distribution of a specific time [65], [64], so the frequent transformation of net load distribution is believed to be the rooted motivation that multiple reconfigurations are needed in a day. So firstly arrays combined by $NLP_{i,t}$, which is the net load percentage (NLP) of node i at time interval t normalized from the net loads, are used to represent distribution of net load. Assuming that a new reconfiguration occurs at t , and its configuration is designed by present $\{NLP_{i,t}\}$ but also continuously operated on later $\{NLP_{i,t}\}$ till another reconfiguration triggers. A special status of NLP at reconfiguration triggering is defined as net load percentage of operating configuration (NLPOC), and the authors mainly evaluate the transformation of net load distribution by comparing $\{NLP_{i,t}\}$ and $\{NLPOC_i\}$ to decide appropriate reconfiguration timing. The SRI is decided by the following iterative process, also shown in Fig. 4.3.

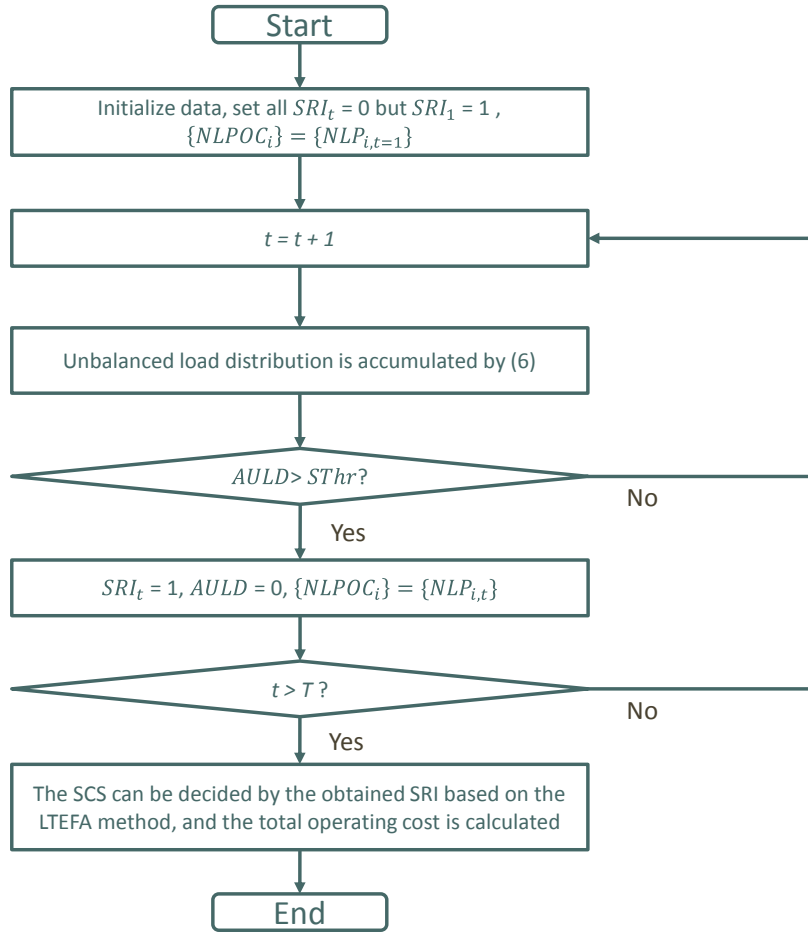


Fig. 4.3. Flow chart of the AULD method.

Step 1) Initialize the SRI as all individuals are “0” but the initial one is “1”. Initial $\{NLP_{i,t}\}$ is recorded as $\{NLPOC_i\}$.

Step 2) Difference between $\{NLPOC_i\}$ and $\{NLP_{i,t}\}$ is accumulated by (4.6) with time interval increasing.

$$AULD_t = AULD_{t-1} + \frac{\sum_{i=1}^N (NLP_{i,t} - NLPOC_i)^2}{N} \quad (4.6)$$

Step 3) If $AULD_t$ exceeds a designed spilled threshold, marked as STh , t individual of SRI is activated as “1”, and $\{NLPOC_i\}$ is substituted by the present $\{NLP_{i,t}\}$.

Step 4) repeat steps 2) and 3) till all time intervals are checked.

Step 5) the whole SRI is obtained, and the SCS could be optimized as the LTEFA is applied between every two reconfiguration instants to decide the optimal configurations. Consequently the SRS is obtained and the total operating cost of system operation is computed.

The STh used in the AULD method is a practical number affected by factors like network topologies, position of DG, selection of α and so on, and different case by case. However, the daily optimal schedule of reconfiguration as the SRC is complicated multiple variable has been transferred into a single variable problem which is much easier to be solved. A hybrid search approach combined by exhaustive sampling and binary search shown in Fig. 4.4 is applied to achieve the most adaptive STh by the following iterative algorithms.

Step 1) Several (set as 20 in this paper) sampling numbers are evenly extracted from maximal and minimal spilled threshold $SThr_{max}$ and $SThr_{min}$. Sampling numbers are applied on the algorithms of Fig. 4.3, and their results are marked as $AULD(SThr)$. $SThr$ which achieves minimal $AULD(SThr)$ and its neighbor one are set as new $SThr_{max}$ and $SThr_{min}$.

Step 2) The new $SThr_{max}$, $SThr_{min}$ and their middle number, marked as $SThr_{mid}$, are applied into Fig. 4.3 to calculate $AULD(SThr_{min})$, $AULD(SThr_{max})$ and $AULD(SThr_{mid})$.

Step 3) if $AULD(SThr_{mid})$ is not maximum of the three, the two STh which achieve lower $AULD(SThr)$ are set as new $SThr_{max}$ and $SThr_{min}$, and repeat steps 2)~3). Otherwise, the final result of STh is decided as the one which achieves the minimal $AULD(SThr)$.

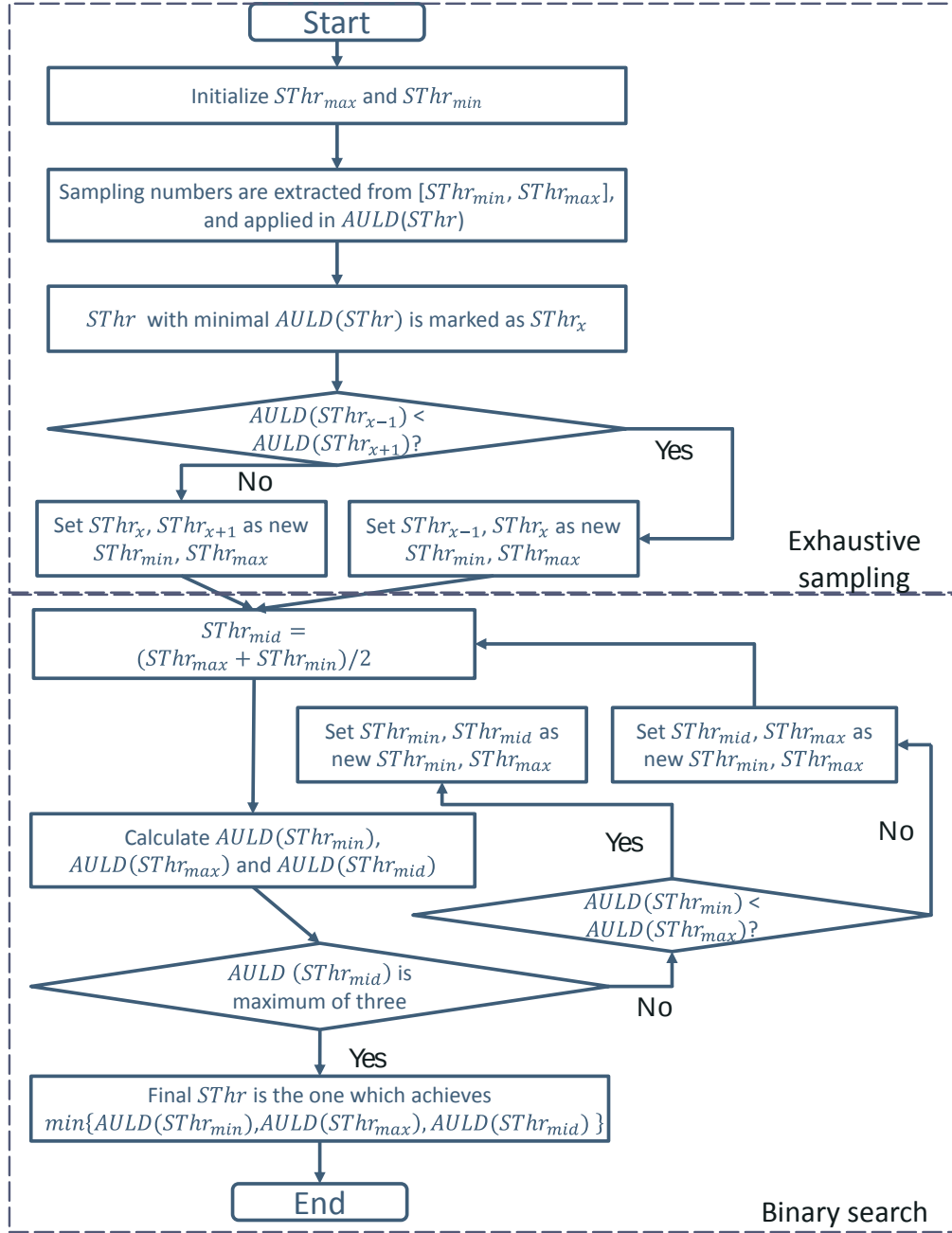


Fig. 4.4. Flow chart of the hybrid search approach.

4.2.4 Proposed Daily Optimal Schedule

The proposed optimal daily schedule of reconfiguration is shown schematically in Fig. 4.5. The load and PV data are initially predicted by the method proposed in Section 4.2.1. The SRI is decided by the AULD method proposed in Section 4.2.3, and transferred into the LTEFA proposed in Section 4.2.2 to decide the corresponding SCS accordingly. The proposed hybrid search in Section 4.2.3 will rerun the AULD method and the LTEFA by

adjusting $SThr$ till the most adaptive one appears. The functions in Fig. 4.5 are divided into stages of judgement and operation. Calculations to make schedule is based on the predicted data (prediction pattern 1) or the actual data (prediction pattern 2) in 30-minute time interval, while the actual total operating cost on real system operation is tested on the actual data in 1-minute one.

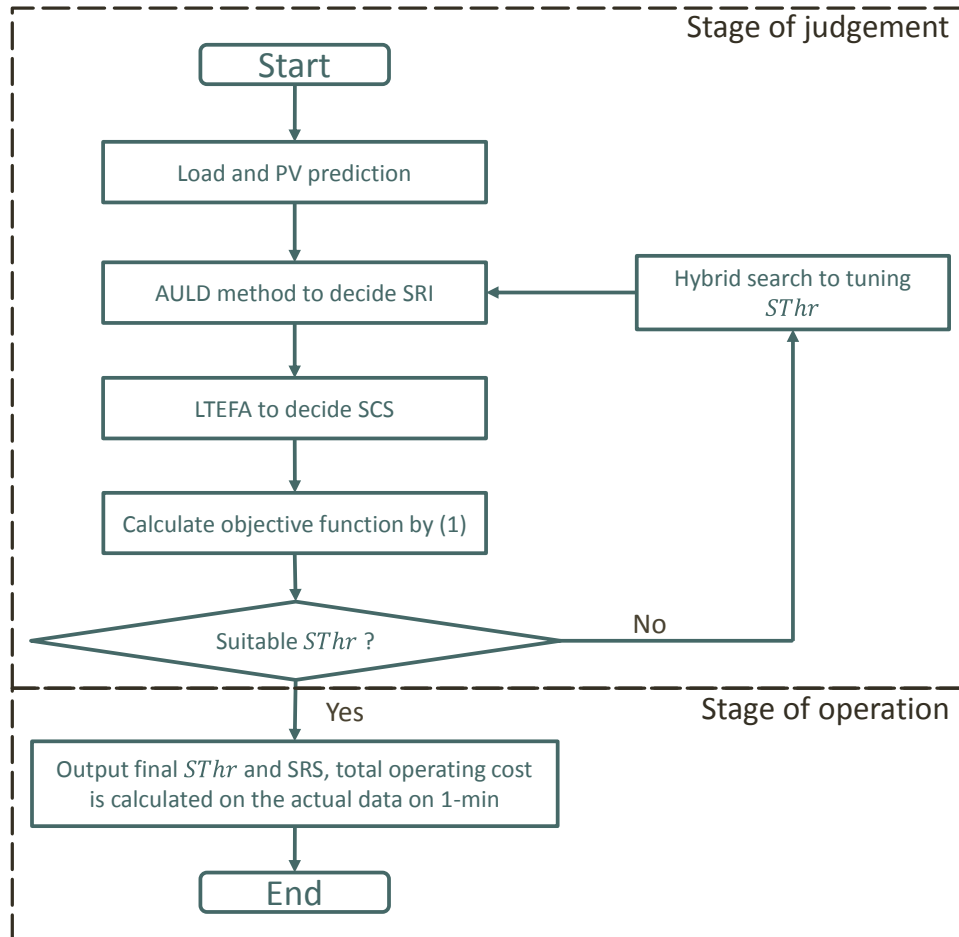


Fig. 4.5. Flow chart of the proposed daily optimal schedule of reconfiguration.

4.3 Numerical Tests

4.3.1 Conditions of Systems and Methods

To confirm the effectiveness of the proposed method, two test distribution systems were simulated in the MATLAB environment. The first system is the 33-bus distribution system shown in Fig. 2.1, consisting of 37 distribution lines under a single feeder. The second system is a 118-bus distribution system comprising 132 distribution lines [57], as shown in Fig. 3.4. The two test systems under study are both equipped by the remotely operated switches for the purpose of optimal daily schedule of reconfiguration. The actual load and PV data observed from a demonstration research on grid-interconnection of clustered PV power generation systems in Ota, Gunma, Japan, promoted by the New Energy and Industrial Technology Development Organization (NEDO) [68] is modified as load data of test consumers. 600 consumers with independent time-varying loads are distributed into the two systems' buses randomly and evenly. The data under study is analyzed at 30-min interval, and the length of simulation period is considered as 288×30 minutes (6 days). The 1st ~5th days, which are the past days, are used to predict the future 6th day's behaviors. 12 cases with varied load and PV, position of PV and data period are considered for the 33-bus and 118-bus system in Table 1.1, in which case 1, 4, 7, 9 are considered without PV installation, and others are installed with PV installations. As an example, the actual active power of load and PV and their predicted ones based on (4.3) on node 20 of the 33-bus system of case 2 are shown in Fig. 4.6.

TABLE 4.1
CASES CONDITIONS OF THE 33- AND 118-BUS SYSTEMS

Case	System	Maximal node load	Maximal node PV	Nodes with PV	Period of data
1	33-bus	$0.0335 + 0.0016i$	$0.0000 + 0.0000i$	None	2007.06.01~2007.06.06
2	33-bus	$0.0335 + 0.0016i$	$0.0755 + 0.0002i$	1~22	2007.06.01~2007.06.06
3	33-bus	$0.0205 + 0.0020i$	$0.0445 + 0.0014i$	23~33	2007.06.01~2007.06.06
4	33-bus	$0.0335 + 0.0016i$	$0.0000 + 0.0000i$	None	2007.06.21~2007.06.26
5	33-bus	$0.0335 + 0.0016i$	$0.0755 + 0.0002i$	1~22	2007.06.21~2007.06.26
6	33-bus	$0.0205 + 0.0020i$	$0.0445 + 0.0014i$	23~33	2007.06.21~2007.06.26
7	118-bus	$0.0133 + 0.0026i$	$0.0000 + 0.0000i$	None	2007.06.01~2007.06.06
8	118-bus	$0.0133 + 0.0026i$	$0.0278 + 0.0011i$	31~90	2007.06.01~2007.06.06
9	118-bus	$0.0125 + 0.0002i$	$0.0352 + 0.0004i$	1~30 & 91~118	2007.06.01~2007.06.06
10	118-bus	$0.0133 + 0.0026i$	$0.0000 + 0.0000i$	None	2007.06.21~2007.06.26
11	118-bus	$0.0133 + 0.0026i$	$0.0278 + 0.0011i$	31~90	2007.06.21~2007.06.26

12	118-bus	$0.0125 + 0.0002i$	$0.0352 + 0.0004i$	1~30 & 91~118	2007.06.21~2007.06.26
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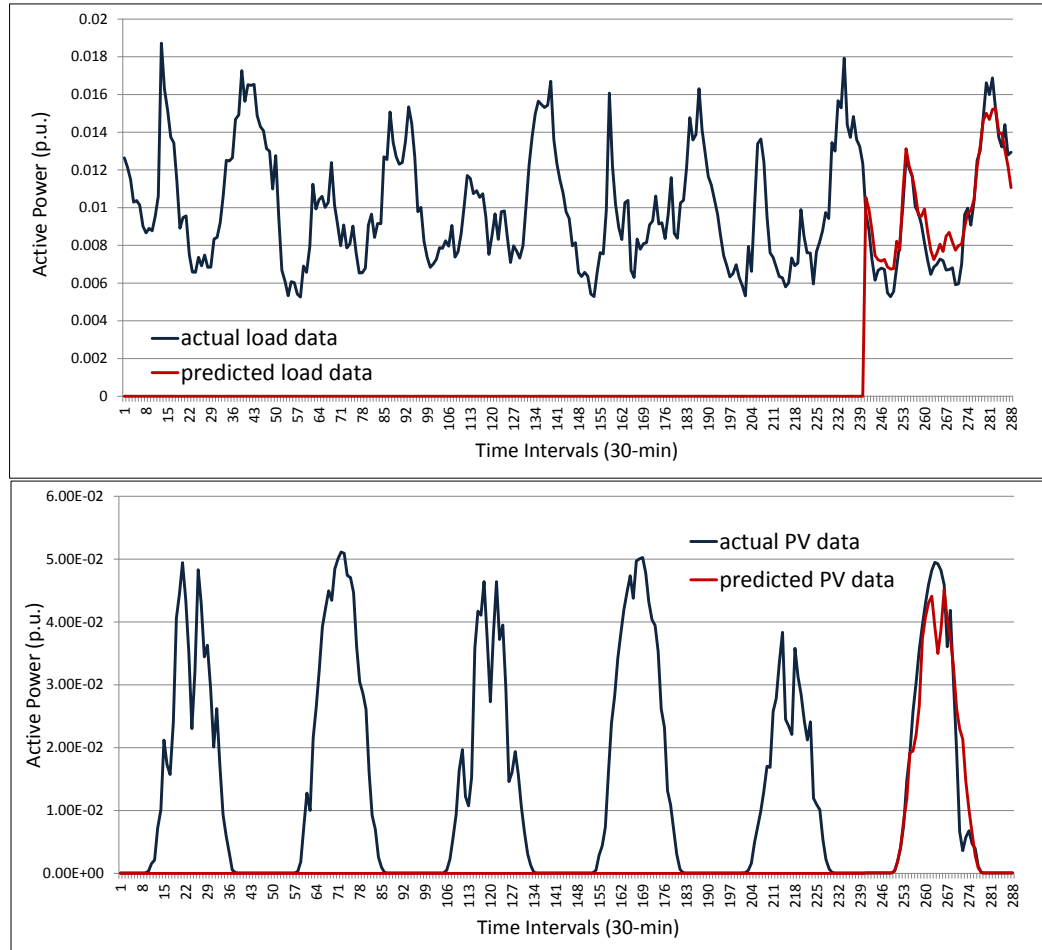


Fig. 4.6. Actual and predicted time-varying load and PV data on node 20 of 33-bus system of case 2 in 6 days.

Besides the proposed methods, other policies for daily schedule of reconfiguration are also implemented in the same computer environment as comparisons, and their abbreviations are shown in Table 4.2.

TABLE 4.2
CONDITIONS OF THE POLICIES

Method	Calculated data	Reconfiguration method	Approach to decide SRI
1st_EFA_ac / 1st_LT_ac / 1st_LT_pre	Actual / predicted data	EFA / LTEFA	Only 1st time interval
Online_EFA_ac	Actual data	EFA	Every time interval

AULD_LT_ac / AULD_LT_pre	Actual / predicted data	LTEFA	AULD optimization
GA_BE_pre	Predicted data	Improved branch exchange	GA optimization
GA_LT_ac / GA_LT_pre	Actual / predicted data	LTEFA	GA optimization

The “1st_EFA_ac” is a conventional consideration that the one fixed configuration optimized by load data of the initial time interval is used for the whole day, as load prediction is not needed. The “1st_LT_ac” and “1st_LT_pre” are also applying fixed configuration for the whole day, however the fixed configuration is optimized by the whole day’s actual or predicted data based on the LTEFA, respectively. The “Online_EFA_ac” is an online short-term reconfiguration which specifies configurations by each time interval with load varying, where decisions are made by detecting real-time data so load prediction is either not needed. The “AULD_LT_pre” is the proposed method which implements the AULD method to decide the SRI, and apply the LTEFA to decide the SCS based on the predicted data. The “AULD_LT_ac” directly uses the actual data to make reconfiguration schedule to show the effectiveness of the proposed method without effect of prediction errors. The “GA_BE_pre” is the optimal daily schedule proposed by [45], which combined the GA and an improved branch exchange reconfiguration method, which is also a short-term one, to decide the SRS. The “GA_LT_ac” and “GA_LT_pre” are similar policies with the “AULD_LT_ac” and “AULD_LT_pre”, but the GA is used to decide SRI instead of the AULD, which could show the high efficiency of the AULD method compared to the GA solely. The population size, generation number, crossover rate, and mutation rate used for the above GAs were set as 50, 10, 0.5, and 0.02, respectively. The back/forward sweep algorithm [71] was used for the load flow calculation for all of simulations.

4.3.2 Tests on LTEFA

To ascertain the advantage of the proposed LTEFA compared to the short-term reconfiguration method, the 1st_EFA_ac, the 1st_LT_ac and the 1st_LT_pre was firstly tested on case 1~3 on the 33-bus system. The above three policies are implemented on the condition that the reconfiguration is only permitted at the initial time interval, and the obtained configuration will be fixed in a day. The optimized total operating cost (actually only voltage deviations existing) of systems are shown in Table 4.3, where results of the 1st_EFA_ac were used as the reference and the “percentage of total cost (PTC)” was obtained by dividing the total operating cost of the related policies by that for the 1st_EFA_ac. The number of sample data (NSD) used in the LTEFA was selected

as 8.

TABLE 4.3

CALCULATION RESULTS OF THE 1st_EFA_AC, 1st_LT_AC AND 1st_LT_PRE ON CASE 1~3 OF THE 33-BUS SYSTEM

Method	Case 1	Case 2	Case 3
1st_EFA_ac	43.6963	50.2743	28.3148
PTC	100.0%	100.0%	100.0%
1st_LT_ac	43.6963	49.0931	26.8043
PTC	100.0%	97.6%	94.7%
1st_LT_pre	43.6963	49.0931	28.5158
PTC	100.0%	97.7%	100.7%

In case 1 which are installed without PV installation, neither the 1st_LT_ac or the 1st_LT_pre reduce more total operating cost than the 1st_EFA_ac. The reason is that load data has the similar power flow patterns during a day if no PV is interconnected, thus the configuration decided by the EFA at the 1st time interval is also adaptable for further load data. On the other hand, the two 1st_LT policies have better results than 1st_EFA_ac in case 2 with PV installation, where the power flow patterns are varied due to highly uneven penetration of PV generations. The detailed voltage deviations analyzed in 1-min time interval observed in the 1st_EFA_ac and the 1st_LT_ac on case 2 are shown in Fig. 4.7.

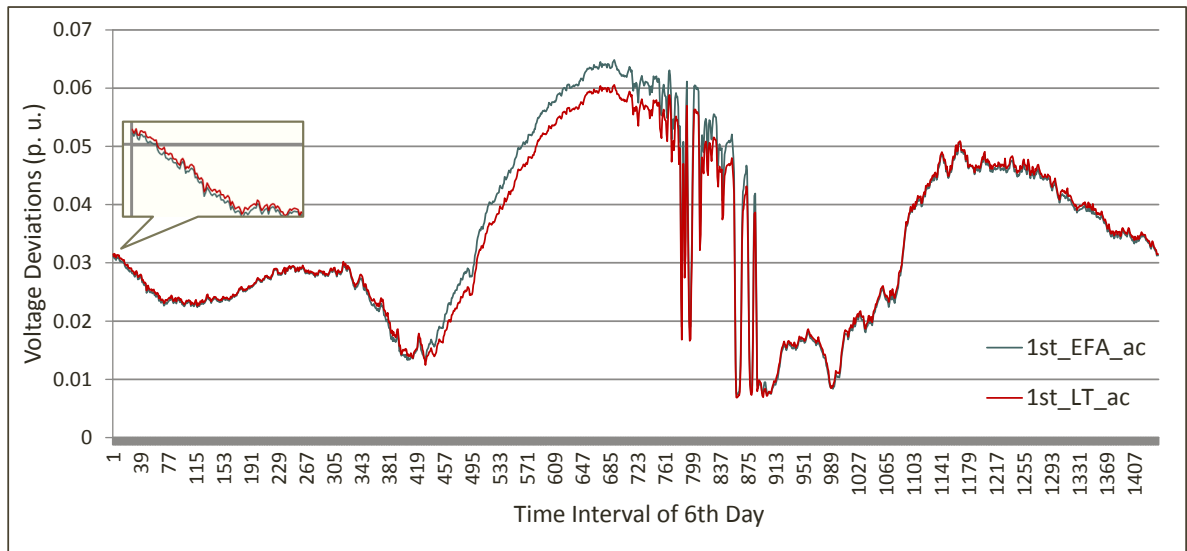


Fig. 4.7. Detailed voltage deviations analyzed at 1-min time interval in the 1st_EFA_ac and the 1st_LT_ac on case 2.

In early periods, the 1st_EFA_ac had lightly lower voltage deviations, since this policy

designed the configuration specifically for the initial time periods. However at middle periods, output of PV increased due to high solar radiation in the daytime, the net loads of node 1~22 with PV installations decrease and even present as negative values, while other node 23~33 behave as relatively heavy loads. This transformations of load distribution were adapted by the 1st_LT_ac rather than the 1st_EFA_ac. As a consequence, the 1st_LT_ac has much more reduction on voltage deviations in the middle periods, and its total voltage deviations are lower than the 1st_EFA_ac, that is to say, the long-term reconfiguration can design configuration with higher time-adaptability compared to the past short-term ones, especially in the networks with highly varied DG installations. The 1st_LT_ac also has lower results than the 1st_EFA_ac in case 3, but the 1st_LT_pre occasionally has worse results which is resulted from prediction errors.

4.3.3 Tests on Single Case

Case 2 which is partially installed with PV was firstly used to demonstrate the advantage of the proposed optimal daily schedule. The calculation results of the AULD_LT_ac, AULD_LT_pre, GA_BE_pre, 1st_EFA_ac and Online_EFA_ac are shown in Table 4.4 with $\alpha = 0.05$, $NSD = 5$, $SThr_{max} = 0.05$, $SThr_{min} = 0.001$.

TABLE 4.4

TEST OF CASE 2 BY AULD_LT_AC, AULD_LT_PRE, GA_BE_PRE, 1ST_EFA_AC AND ONLINE_EFA_AC

Method	Total voltage deviations	Reconfiguration n times	Switch operation times	Total operating cost	Calculation time
AULD_LT_ac	47.0824	2	12	47.6824	68.8 s
AULD_LT_pre	47.3022	4	18	48.2022	68.7 s
GA_BE_pre	48.5957	4	16	49.3957	1433.2 s
1st_EFA_ac	50.2743	0	0	50.2743	0.6 s
Online_EFA_ac	46.6102	15	52	49.2102	13.2 s

Although with inaccuracy of the predicted data, the AULD_LT_pre and the GA_BE_pre could arrange the SRI more reasonably and consequently reduce 4.1% and 1.7% more total operating cost than the 1st_EFA_ac. Also attributed to application of the LTEFA, the total operating cost was further reduced by the AULD_LT_pre compared to the GA_BE_pre. Furthermore, the AULD_LT_pre has more than 20 times shorter computation time than the GA_BE_pre, which is the main advantage of the proposed AULD method. The total operating cost was 5.2% further reduced by the AULD_LT_ac compared to the 1st_EFA_ac, as prediction error ignored. The SRI and the SCS of the AULD_LT_ac's result are listed in Table 4.5. Fig. 4.9 also shows fluctuated variation of

total operating cost as S_{thr} varying from 0.001 to 0.05.

TABLE 4.5
RECONFIGURATION INSTANTS AND REGARDING SEQUENCES OF CONFIGURATION SELECTIONS OF THE
AULD_LT_AC'S RESULT ON CASE 2

Reconfiguration instants	Configuration (lines with switch-off)				
1	11	19	23	31	35
15	11	14	28	31	34
30	1	11	19	31	35

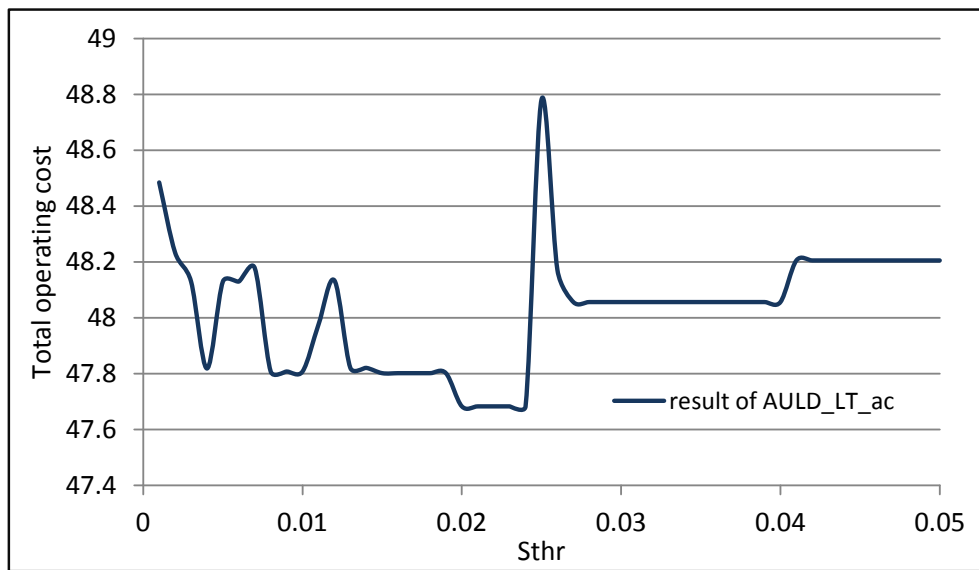


Fig. 4.8. Variation of total operating cost with S_{thr} varying from 0.001 to 0.05 in the AULD_LT_ac.

4.3.4 Tests on 33-bus system

The AULD_LT_ac, AULD_LT_pre, GA_LT_ac, GA_LT_pre, GA_BE_pre, 1st_EFA_ac and Hourly_EFA_ac are applied on case 1~6 on the 33-bus system as setting of α , NSD , $S_{thr_{max}}$ and $S_{thr_{min}}$ is exactly same with Section 4.3.3, and their calculated results are shown in Table 4.6.

TABLE 4.6
TEST OF THE AULD_LT_AC, AULD_LT_PRE, GA_LT_AC, GA_LT_PRE, 1ST_EFA_AC AND ONLINE_EFA_AC
ON CASE 1~6
ON THE 33-BUS SYSTEM IN CONDITION OF $\alpha = 0.05$

Method	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Average calculation time
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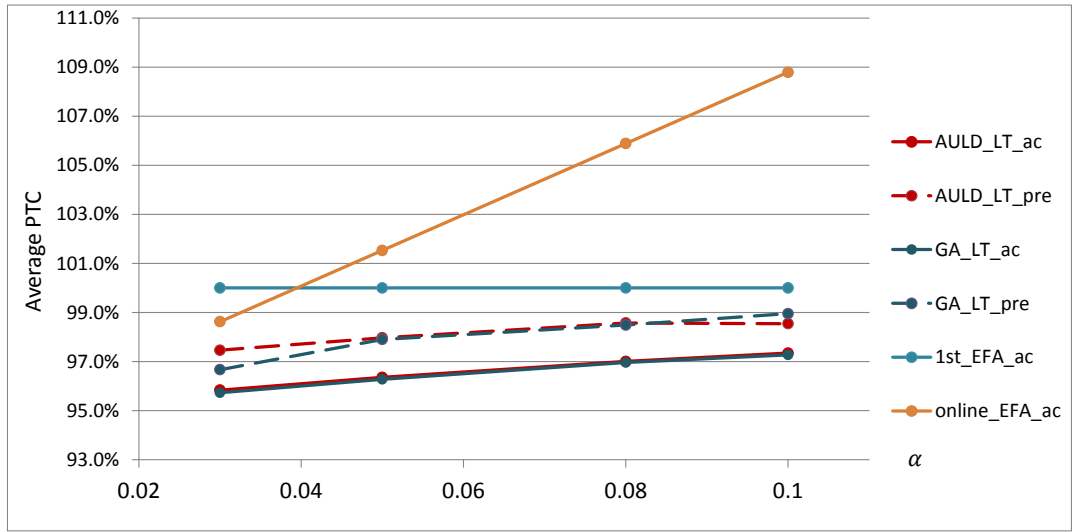
							/ PTC
AULD_LT_ac	43.6963	47.6824	25.9369	45.8050	43.6282	25.8372	49.0 s
PTC	100.0%	94.8%	91.6%	100.0%	96.7%	95.0%	96.4%
AULD_LT_pre	43.6963	48.2022	26.3525	45.8050	44.4629	27.2822	51.2 s
PTC	100.0%	95.9%	93.1%	100.0%	98.6%	100.3%	98.0%
GA_BE_pre	43.6963	49.3957	27.8415	45.8050	45.3993	28.0146	1447.6 s
PTC	100.0%	98.3%	98.3%	100.0%	100.6%	103.0%	100.0%
1st_EFA_ac	43.6963	50.2743	28.3148	45.8050	45.1145	27.2050	0.43 s
PTC	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Online_EFA_a							19.1 s
c	43.6963	49.2102	28.8192	45.8050	45.1893	29.7462	
PTC	100.0%	97.9%	101.8%	100.0%	100.2%	109.3%	101.5%

It was also observed that the fixed configuration, i.e. 1st_EFA_ac, can achieve the minimal voltage deviations without imposing any extra switch operations, and consequently minimal total operating cost is attained in case 1 and 4 without PV installation. Whereas reasonable arrangements of reconfiguration instants by the GA or AULD are efficient to reduce more total operating cost in case 2, 3, 5 and 6 which are installed with PV. By summarizing average PTC and calculation time, the higher computation accuracy and extremely shorter computation time of the AULD_LT_pre is also confirmed in 6 cases' studies compared to the GA_BE_pre.

The authors also tested the AULD_LT_ac, AULD_LT_pre, GA_LT_ac, GA_LT_pre, 1st_EFA_ac and Online_EFA_ac with α varying in 0.03, 0.05, 0.08 and 0.1, and the calculation results are shown in Table 4.7 and Fig. 4.9.

TABLE 4.7
TEST OF α ON CASE 1~6 ON THE 33-BUS SYSTEM

Method / α	0.03	0.05	0.08	0.10
AULD_LT_ac	95.8%	96.4%	97.0%	97.3%
AULD_LT_pre	97.5%	98.0%	98.6%	98.5%
GA_LT_ac	95.7%	96.3%	97.0%	97.3%
GA_LT_pre	96.7%	97.9%	98.5%	99.0%
1st_EFA_ac	100.0%	100.0%	100.0%	100.0%
Online_EFA_ac	98.6%	101.5%	105.9%	108.8%

Fig. 4.9. Test of α on case 1~6 on the 33-bus system.

The proposed AULD_LT_ac and AULD_LT_pre could always trade off reduction of voltage deviation and cost of switch operations, and stably more reduce total operating cost of system with α varying than 1st_EFA_ac or Online_EFA_ac. In practical applications, α will be decided by the power company operators based on actual worth of voltage deviation reduction compared to cost of switch operations. If fairly using the LTEFA as the reconfiguration method, the AULD_LT_ac has extremely similar computation accuracy with the GA_LT_ac if prediction errors are ignored, while AULD_LT_pre and GA_LT_pre have different performance as α varied. As observed, to achieve approximate results, it costs 500 times of iterations in the GA optimizations to specify the SRI, while only 13~15 times of iterations are needed in the AULD, therefore the AULD has much shorter computation time than the GA.

4.3.5 Tests on 118-bus system

The 118-bus system was also used to test the validity of the proposed methods on larger scale systems. The calculated results of the AULD_LT_ac, AULD_LT_pre, 1st_EFA_ac and Online_EFA_ac of case 7~12 are shown in Table 4.8 with $\alpha = 0.01$ and other parameters are exactly same as in Section 4.3.4.

TABLE 4.8

TEST OF THE AULD_LT_AC, AULD_LT_PRE, 1ST_EFA_AC AND ONLINE_EFA_AC ON CASE 7~12 ON THE 118-BUS SYSTEM IN CONDITION OF $\alpha = 0.01$

Method	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12	Average calculation time
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							/ PTC
AULD_LT_ac	22.3182	20.2948	18.9965	22.7415	19.2684	17.6494	713.2 s
PTC	99.2%	95.6%	95.3%	100.0%	98.3%	97.5%	97.7%
AULD_LT_pre	22.4284	20.6577	19.1484	22.7493	19.5924	17.8891	629.8 s
PTC	99.7%	97.3%	96.1%	100.0%	100.0%	98.8%	98.8%
1st_EFA_ac	22.4870	21.2227	19.9306	22.7415	19.5998	18.0993	5.5 s
PTC	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Online_EFA_a							283.2 s
c	26.2543	24.0230	23.7736	26.0783	23.4091	22.7118	
PTC	116.8%	113.2%	119.3%	114.7%	119.4%	125.5%	118.1%

It was found that the AULD_LT_ac and AULD_LT_pre could averagely reduce more 2.3% and 1.2% total operating cost compared to the 1st_EFA_ac in this system. The further reductions of the AULD_LT_ac and AULD_LT_pre compared to the 1st_EFA_ac existed not only in case 8, 9, 11 and 12 with PV installations but also in case 7 which are without PV installations, since flow patterns of loads are assumed more severe in 118-bus system than the 33-bus one. It is certificated that the optimal daily schedule of reconfiguration is mainly significant to the networks with severe flow patterns of loads no matter DG is installed or not. The average calculation time the AULD_LT_ac and AULD_LT_pre in 118-bus system is available for system management since daily schedule of reconfiguration is made one day ahead.

4.4 Conclusions

In this chapter, a joint optimal daily schedule of reconfiguration has been proposed to minimize the total operating cost of the distribution system, instead of the optimum fixed configuration or online/hourly reconfiguration policies. The reduction of voltage deviations and cost of switch operations is achieved into balance by applying the proposed method which decides reconfiguration instants based on detecting transformation of load distributions. Furthermore, a long-term reconfiguration technology is adopted to extend timeliness of the obtained configurations. The proposed methodologies are certified on two test distribution systems under the real-time measured time-varying load and PV. It is revealed from the simulation results that daily schedule of reconfiguration is inevitable to minimize the operating costs of the network, especially distribution systems with PV installations with intermittent nature. The proposed joint optimal daily schedule can obtain accurate results within considerably shorter computation time, compared to the methods proposed in other publications.

Chapter 5. Conclusion and Perspectives

5.1 Conclusion of Researches

The main target of this thesis is a study of modern reconfiguration techniques to cope with new challenges, such as online management, interconnection of distributed generators (DG), scale increasing and time varying load files, on electrical distribution system.

The properties of the configurations of good power state variables in reconfiguration were studied, and the concept called “balanced configuration” is proposed firstly. Accordingly, a highly efficient reconfiguration method, named intelligent flow algorithm (IFA) has been proposed to reduce the line losses of distribution system. The effectiveness of IFA was demonstrated by two test distribution systems, and it was proved that the IFA is effective for online reconfiguration with better performance than the conventional methods in efficiency, stability, reliability and robustness.

Secondly, the IFA was expanded as an extended flow algorithm (EFA), which enables more efficient optimality reconfiguration of power distribution systems containing massive DGs. The effectiveness of the EFA was also demonstrated by application to two small-scale distribution systems and two large-scale distribution systems with many installed DGs. It was found that the EFA exhibited a stable performance in systems containing many installed DGs, and a higher efficiency compared to previously proposed methods.

Finally, a joint optimal daily schedule of reconfiguration has been proposed to minimize the total operating cost of the distribution system. The proposed daily schedule is certified on two test distribution systems under the real-time measured time-varying load and PV, which also reveals that daily schedule of reconfiguration is inevitable to minimize the operating costs of the network, especially distribution systems with PV installations with intermittent nature.

To make a general observation, the “balanced configuration” was a critical theoretical support for developments of new algorithms, as the IFA, the EFA and the AULD method. Applications of “balanced configuration” give indispensable contributions on efficiency of the proposed algorithms, which make the IFA, the EFA, the LTEFA and the AULD be effective for online reconfiguration, reconfiguration installed with DG and reasonable reconfiguration schedule.

- 1) The IFA is developed as a fast reconfiguration method, which is mostly simple to be applied for online reconfiguration.
- 2) The EFA is an expansion of the IFA, which has higher efficiency especially in case

of massive DG installations. Its application is a solution to cope with interconnected DG increasing on distribution systems.

- 3) The proposed reconfiguration schedule brings big benefits on system operations, which is effective in the condition to high developments of load prediction techniques and highly stable distribution system operations.

5.2 Perspectives

Subsequent researches of this thesis can be divided into two main aspects: 1) further improvements on the efficiency of the proposed reconfiguration algorithms; 2) development of reconfiguration schedule regarding probabilistic system conditions, illustrated as follows.

5.2.1 Further Improvements on Flow Algorithms

1) The reconfiguration algorithms developed is heuristic methods as mentioned, mainly due to incomplete knowledge of “balanced configurations”. As a result, the proposed methods could not guarantee the global optimizations. During investigations of the balanced configurations in Section 2.2, there are still plenty of unanswerable knowledge:

1) Although it was observed load balancing configuration led to good operation qualities, we didn’t propose accurate power flow indices to evaluate the so-called “balance” which is actually affected by not only node injected load but also line impedances. We reasonably infer that the balanced configurations generated in the IFA or the EFA could be directly used as the optimal solutions in the condition that available power flow indices are developed to guide the generation of balanced configurations. In another word, the numerical revision approach applied in the IFA or the EFA is a temporary expedient in case that knowledge of balanced configuration is not completely studied.

2) It is observed that state variables of power flow are strongly correlated as configurations varying, we failed to reveal the correlation affected by the system inherent conditions as injected load, impedances and inherent topologies. It is known to the readers that the conclusion in Section 2.2.2 is widely used though this thesis, however we could not define the categories of flow algorithms, which might lose efficiency in some extreme system conditions.

3) Massive DG installations mislead effective generation of the balanced configurations in the IFA, as studied in Chapter 3. Although the EFA was proposed as an expansion of the IFA to cope with massive DG installations, the flow chart or programming is relatively complicated. As mentioned above, better solution will be given if complete knowledge of balanced configuration is learned.

In next stage of researches, deeper investigations on topological properties configurations with high operation qualities (e.g. lower line losses and lower voltage deviations) will be given, we expect to develop the existed heuristic methods into mathematic ones based on deeper knowledges of balanced configurations. As an ideal expect therefore, future flow algorithms will perfectly performs in varieties of conditions

of reconfiguration on distribution system with absolutely higher efficiency (computation accuracy and speed), stability and reliability than any other heuristic or meta-heuristic methods.

5.2.2 Probabilistic Reconfiguration

The previous researches of the reconfiguration problem have been studied based on deterministic approaches. Subsequent researches also aim to study the reconfiguration problem with uncertainties in both load and DG using the point estimate method (PEM) [63], which is generally simple and flexible to deal with complex models. As an example, the issue to maximize DG equipment by favor of reconfiguration function is considered under probabilistic distribution system, where load prediction is insignificant in long-term timeliness of DG equipment. Some predicted techniques to solve probabilistic reconfiguration problem are planned as follows,

- 1) In order to achieve realistic system performance, probabilistic approaches are expected to be employed to model the random variation of load demand and DG.
- 2) The uncertainties involved in the reconfiguration problem will be handled through an effective probabilistic power flow based on the PEM.
- 3) The discrete nature of the tie and sectionalizing switches make the stochastic reconfiguration problem a complex nonlinear optimization problem with discrete variables.
- 4) Load flow patterns are expected to be classified to reduce computation burden in the probabilistic load flow calculation.
- 5) Reconfiguration schedule should also be considered as probabilistic model, as system operators could have multiple schedules to cope with uncertain scenarios.

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Appendix A: Detailed Calculated Results in Numerical Tests

TABLE A.1
SIMULATION CONDITIONS OF CASE 1 IN THE 33-BUS DISTRIBUTION SYSTEM

Number of Line / Node	Load of Node	Impedance of Line
01	0.0045 + 0.0106i	0.03119 + 0.03119i
02	0.0090 + 0.0009i	0.09385 + 0.08456i
03	0.0032 + 0.0073i	0.02554 + 0.02984i
04	0.0147 + 0.0065i	0.04423 + 0.05848i
05	0.0210 + 0.0059i	0.00575 + 0.00293i
06	0.0150 + 0.0077i	0.03075 + 0.01566i
07	0.0097 + 0.0089i	0.02283 + 0.01162i
08	0.0181 + 0.0064i	0.02377 + 0.01211i
09	0.0128 + 0.0074i	0.05109 + 0.04411i
10	0.0002 + 0.0024i	0.01167 + 0.03860i
11	0.0106 + 0.0040i	0.04438 + 0.01466i
12	0.0117 + 0.0062i	0.06426 + 0.04617i
13	0.0141 + 0.0068i	0.12478 + 0.12478i
14	0.0105 + 0.0041i	0.04656 + 0.03400i
15	0.0172 + 0.0038i	0.08042 + 0.10737i
16	0.0047 + 0.0091i	0.02321 + 0.03581i
17	0.0236 + 0.0077i	0.01773 + 0.00902i
18	0.0181 + 0.0114i	0.06607 + 0.05825i
19	0.0101 + 0.0089i	0.05017 + 0.04371i
20	0.0127 + 0.0038i	0.03166 + 0.01612i
21	0.0069 + 0.0006i	0.06079 + 0.06008i
22	0.0066 + 0.0077i	0.01937 + 0.02257i
23	0.0117 + 0.0066i	0.02127 + 0.03345i
24	0.0162 + 0.0090i	0.05602 + 0.04424i
25	0.0159 + 0.0100i	0.05590 + 0.04374i
26	0.0220 + 0.0067i	0.01023 + 0.00976i
27	0.0097 + 0.0077i	0.02815 + 0.01923i
28	0.0102 + 0.0051i	0.01266 + 0.00645i

29	$0.0024 + 0.0109i$	$0.12478 + 0.12478i$
30	$0.0098 + 0.0075i$	$0.01226 + 0.00405i$
31	$0.0120 + 0.0057i$	$0.06513 + 0.04617i$
32	$0.0115 + 0.0059i$	$0.03119 + 0.03119i$
33	$0.0081 + 0.0128i$	$0.12478 + 0.12478i$
34	-	$0.03379 + 0.04447i$
35	-	$0.03687 + 0.03281i$
36	-	$0.02335 + 0.00772i$
37	-	$0.09159 + 0.07206i$

TABLE A.2
CALCULATION RESULTS OF THE IFA IN THE 33-BUS DISTRIBUTION SYSTEM

Case	Global Result	IFA Result	Precision
case 01	0.0131	0.0131	100.00%
case 02	0.0134	0.0134	100.00%
case 03	0.0137	0.0137	100.00%
case 04	0.0116	0.0117	99.53%
case 05	0.0148	0.0148	100.00%
case 06	0.0133	0.0133	100.00%
case 07	0.0130	0.0130	100.00%
case 08	0.0115	0.0115	100.00%
case 09	0.0114	0.0114	100.00%
case 10	0.0118	0.0118	100.00%
case 11	0.0121	0.0121	100.00%
case 12	0.0188	0.0189	99.69%
case 13	0.0125	0.0125	100.00%
case 14	0.0113	0.0113	100.00%
case 15	0.0155	0.0155	100.00%
case 16	0.0101	0.0101	100.00%
case 17	0.0210	0.0210	100.00%
case 18	0.0215	0.0215	100.00%
case 19	0.0220	0.0221	99.86%
case 20	0.0190	0.0190	100.00%
case 21	0.0246	0.0246	100.00%
case 22	0.0218	0.0218	100.00%
case 23	0.0216	0.0216	100.00%
case 24	0.0189	0.0189	100.00%

case 25	0.0184	0.0184	100.00%
case 26	0.0199	0.0199	99.94%
case 27	0.0211	0.0211	100.00%
case 28	0.0286	0.0286	100.00%
case 29	0.0213	0.0214	99.50%
case 30	0.0192	0.0192	100.00%
case 31	0.0193	0.0193	100.00%
case 32	0.0196	0.0196	100.00%
case 33	0.0202	0.0202	100.00%
case 34	0.0170	0.0171	99.62%
case 35	0.0218	0.0218	100.00%
case 36	0.0020	0.0020	100.00%
case 37	0.0020	0.0020	100.00%
case 38	0.0021	0.0021	100.00%
case 39	0.0018	0.0018	100.00%
case 40	0.0022	0.0022	100.00%

TABLE A.3

CALCULATION RESULTS OF THE IFA IN THE 43-BUS DISTRIBUTION SYSTEM

Case	Global Result	IFA Result	Precision
case 01	0.0240	0.0240	100.00%
case 02	0.0256	0.0256	100.00%
case 03	0.0246	0.0246	100.00%
case 04	0.0207	0.0207	100.00%
case 05	0.0214	0.0214	100.00%
case 06	0.0178	0.0178	100.00%
case 07	0.0169	0.0169	100.00%
case 08	0.0226	0.0226	100.00%
case 09	0.0241	0.0241	100.00%
case 10	0.0213	0.0213	100.00%
case 11	0.0261	0.0261	100.00%
case 12	0.0285	0.0285	100.00%
case 13	0.0260	0.0260	100.00%
case 14	0.0219	0.0219	100.00%
case 15	0.0346	0.0346	100.00%
case 16	0.0370	0.0370	100.00%
case 17	0.0355	0.0355	100.00%

case 18	0.0086	0.0086	100.00%
case 19	0.0092	0.0092	100.00%
case 20	0.0088	0.0088	100.00%

TABLE A.4
OPTIMIZED RESULT OF CASE 06~20 IN THE 33-BUS DISTRIBUTION SYSTEM IN THE MULTI-OBJECTIVE
RECONFIGURATION

Case	Tie-switch					Line Loss	Voltage Drop	Flowing Power
06	16	19	29	31	35	0.0133	0.1339	2.8829
	15	19	29	31	35	0.0130	0.1308	2.8352
	15	19	29	34	36	0.0141	0.1288	2.9161
	16	18	29	31	35	0.0132	0.1324	2.8188
07	15	19	29	31	35	0.0130	0.1308	2.8352
	15	19	29	31	35	0.0115	0.1254	2.7406
	15	19	29	34	36	0.0133	0.1233	2.8438
	16	18	29	31	35	0.0117	0.1288	2.7082
08	15	19	29	31	35	0.0115	0.1254	2.7406
	15	19	29	31	35	0.0114	0.1239	2.6603
	15	19	29	34	36	0.0130	0.1220	2.7472
	16	18	29	31	35	0.0116	0.1260	2.6399
09	15	19	29	31	35	0.0114	0.1239	2.6603
	14	19	29	34	36	0.0118	0.1232	2.7023
	15	19	29	34	36	0.0119	0.1221	2.6741
	16	18	29	31	35	0.0131	0.1272	2.5602
10	15	19	29	35	36	0.0119	0.1227	2.6546
	1	11	19	31	35	0.0121	0.1289	2.5790
	11	15	19	31	35	0.0126	0.1228	2.6183
	1	11	18	30	35	0.0131	0.1310	2.5508
11	11	16	19	31	35	0.0123	0.1254	2.5884
	11	16	19	31	35	0.0189	0.1768	3.1336
	11	15	19	31	35	0.0200	0.1679	3.2381
	1	11	18	30	35	0.0218	0.1926	3.1031
12	11	16	19	31	35	0.0189	0.1768	3.1336
	11	14	19	31	35	0.0125	0.1295	2.7762
	11	14	19	31	35	0.0125	0.1295	2.7762
	1	11	18	30	35	0.0133	0.1386	2.6550
13	11	15	19	31	35	0.0125	0.1297	2.7286
	15	19	29	31	34	0.0113	0.1259	2.6696

	15	19	29	34	36	0.0118	0.1245	2.7379
	16	18	29	31	35	0.0117	0.1295	2.6139
14	15	19	29	31	34	0.0113	0.1259	2.6696
	1	11	19	31	35	0.0155	0.1598	2.8995
	11	15	19	31	35	0.0170	0.1470	2.9803
	1	11	18	30	35	0.0164	0.1612	2.8825
	11	16	19	31	35	0.0159	0.1511	2.9278
15	13	17	29	34	36	0.0101	0.1163	2.5789
	15	19	29	34	36	0.0107	0.1099	2.4604
	16	18	29	31	35	0.0120	0.1151	2.3265
	14	18	29	35	36	0.0104	0.1116	2.4308
16	1	11	19	31	35	0.0210	0.1625	2.7012
	1	11	18	30	34	0.0215	0.1614	2.6894
	1	11	18	30	35	0.0213	0.1622	2.6881
	1	11	19	30	35	0.0210	0.1624	2.7001
17	11	16	19	31	35	0.0215	0.1657	2.7244
	1	11	18	30	34	0.0224	0.1623	2.6858
	1	11	18	30	35	0.0221	0.1633	2.6841
	1	11	19	30	35	0.0218	0.1634	2.6981
18	1	11	19	31	35	0.0221	0.1647	2.7527
	1	11	18	30	34	0.0227	0.1631	2.7232
	1	11	18	30	35	0.0225	0.1643	2.7210
	1	11	19	30	35	0.0221	0.1643	2.7378
19	11	16	19	30	35	0.0190	0.1552	2.5900
	1	11	19	30	34	0.0193	0.1523	2.5832
	1	11	18	30	35	0.0193	0.1536	2.5647
	1	11	19	30	35	0.0191	0.1535	2.5821
20	11	15	19	31	35	0.0131	0.1365	2.7861
	15	19	29	31	35	0.0134	0.1354	2.9002
	15	19	29	34	36	0.0153	0.1336	3.0165
	15	19	29	34	36	0.0153	0.1336	3.0165

TABLE A.5

CALCULATION ERRORS OF THE GA, THE TCUHH, THE IFA AND THE EFA IN THE 33-BUS DISTRIBUTION
SYSTEM

Case	GA	TCUHH	IFA	EFA
01	0.000449	0.002357	0	0
02	0	0.002106	0	0
03	0	0.003031	0	0
04	0	0.002174	0	0

05	0	0.002518	0	0
06	0	0.002637	0	0
07	0	0.00244	0	0
08	0	0.00278	0	0
09	0	0.002883	0	0
10	0.000178	0.003138	0	0
11	0	0.00227	0	0
12	0	0.001966	0	0
13	0	0.003104	0	0
14	0.000946	0.000946	0.000946	0
15	0	0.001704	0	0
16	0	0.002046	0	0
17	0.000163	0.001788	0	0
18	0	0.001704	0	0
19	0	0.001685	0	0
20	0	0.002482	0	0
21	0	0.002032	0	0
22	0	0.001855	0	0
23	0	0.001982	0	0
24	0	0.000474	0.000474	0
25	0	0.001209	0	0
26	0	0.002119	0	0
27	0	0.00153	0	0
28	0	0.002056	0	0
29	0	0.001865	0	0
30	0.000214	0.001543	0	0
31	0	0.001189	0	0
32	0	0.000365	0.000365	0
33	0	0.001351	0	0
34	0	0.001651	0	0
35	0	0.001411	0	0
36	0	0.001439	0	0
37	0	0.001858	0	0
38	0	0.001644	0	0
39	0	0.001733	0	0
40	0	0.001576	0	0

41	0	0.000917	0	0
42	0.000279	0.000497	0	0.000295
43	0.00045	0.000789	0.002551	0
44	0	0.000327	0	0
45	0	0.000807	0	0
46	0.001138	0.00074	0	0
47	0	0.000352	0.000361	0
48	0.000237	0.000237	0	0
49	0	0.000445	0.000313	0
50	0	0.000866	0	0
51	0	0.00037	0	0
52	0	0.002039	0.000707	0
53	0	3.78E-05	0.000515	4.58E-05
54	0.000192	0	0.000192	0
55	0	0.001978	0	1.21E-05
56	0	8.49E-05	0	3.68E-05
57	0	0.001394	0.001102	0.000299
58	7.50E-05	0.003939	0.00018	0
59	0.000777	0.001289	0	0.000305
60	8.09E-05	0.00025	0	0
61	0	0.002599	0.000937	0.000504
62	0	0.000489	0	0.000145
63	0	0.001558	0.000817	9.28E-05
64	0	0.000417	0.000515	0.00087
65	0	0.000943	0.002058	5.43E-05
66	0	0.000215	0.000199	0.000267
67	4.62E-05	0.001359	0.00202	0.000263
68	0.000214	0.00026	0.000563	0.000162
69	4.57E-05	0.000327	0.001317	0
70	5.80E-05	0.00048	0.000458	0.0004
71	0	9.75E-05	0.002225	0
72	0	0.000208	0.00241	0
73	0	0	0.000318	8.09E-05
74	0	3.43E-05	0.002325	0
75	0	0.000558	0	0

76	0	0.000819	2.07E-05	0
77	0	0.000303	0.000378	0
78	0.000336	0.000411	0.000461	0.000461
79	0	0	0.000188	0
80	0	0.001041	0.000352	0

TABLE A.6

CALCULATION ERRORS OF THE GA, THE TCUHH, THE IFA AND THE EFA IN THE 43-BUS DISTRIBUTION SYSTEM

Case	GA	TCUHH	IFA	EFA
01	1.73E-18	0.00E+00	0.00E+00	0.00E+00
02	0	0.000674	0	0
03	0	0.000482	0	0
04	-1.73E-18	0.0004	0.00E+00	0.00E+00
05	0	0	0	0
06	1.73E-18	0.00E+00	0.00E+00	0.00E+00
07	0	0	0	0
08	1.73E-18	0.000345	0.00E+00	0.00E+00
09	1.73E-18	0.00048	0.00E+00	0.00E+00
10	0	0.00039	0	0
11	1.73E-18	0.00E+00	0.00E+00	0.00E+00
12	0	0	0	0
13	0	0.000296	0	0
14	8.67E-19	0.000226	0.00E+00	0.00E+00
15	0.00015	0.000576	0	0
16	-1.73E-18	0.000603	0.00E+00	0.00E+00
17	8.67E-19	0.000304	0.00E+00	5.35E-05
18	0	0.000307	0	0
19	0	0	0	0
20	8.67E-19	8.19E-05	8.19E-05	0.00E+00
21	8.67E-19	0.001358	0.00E+00	4.95E-05
22	0	0.005526	0	0
23	0.000131	0.002622	0	0
24	8.67E-19	0.01843	0.000823	0.00E+00
25	8.67E-19	0.00334	8.53E-05	0.00E+00
26	0	0.005566	0	0
27	8.67E-19	0.005068	0.00E+00	0.00E+00

28	0	0.001836	0	0
29	4.34E-19	0.002258	1.36E-05	0.00E+00
30	0	0.01462	0	0
31	0.00013	0.000707	0.000478	0.000121
32	9.04E-05	0.000402	2.49E-05	0.00E+00
33	2.17E-19	0.000836	0.000403	0.00E+00
34	2.09E-05	0.007407	2.58E-05	0.00E+00
35	5.77E-05	0.001583	9.28E-05	8.91E-05
36	3.05E-06	0.00257	0.000125	0
37	0	0.001589	1.61E-05	0.00E+00
38	8.87E-05	0.003343	0.000123	0.000126
39	-2.17E-19	0.001396	0.000321	0.000235
40	0.000200	0.004180	0.000212	0.000200

TABLE A.7

OPTIMIZED VOLTAGE DEVIATIONS OF THE TCUHH, THE IFA AND THE EFA IN THE 118-BUS DISTRIBUTION
SYSTEM

Case	TCUHH	IFA	EFA
01	0.04462	0.04164	0.04143
02	0.04598	0.04348	0.04348
03	0.04498	0.04248	0.04233
04	0.04414	0.04192	0.04163
05	0.04450	0.04242	0.04228
06	0.02605	0.02514	0.02472
07	0.02344	0.02318	0.02209
08	0.02492	0.02378	0.02306
09	0.02633	0.02515	0.02504
10	0.02395	0.02378	0.02267
11	0.00745	0.00727	0.00724
12	0.01076	0.01087	0.01040
13	0.00955	0.00825	0.00771
14	0.00910	0.00779	0.00776
15	0.00823	0.00767	0.00758
16	0.00898	0.00870	0.00798
17	0.00864	0.00719	0.00718
18	0.01109	0.01040	0.00940
19	0.00810	0.00840	0.00730

20	0.00945	0.00868	0.00808
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TABLE A.8

OPTIMIZED VOLTAGE DEVIATIONS OF THE TCUHH, THE IFA AND THE EFA IN THE 216-BUS DISTRIBUTION SYSTEM

Case	TCUHH	IFA	EFA
01	0.02580	0.02665	0.02407
02	0.02457	0.02509	0.02306
03	0.02363	0.02401	0.02196
04	0.02597	0.02655	0.02432
05	0.02554	0.02580	0.02363
06	0.00781	0.00855	0.00727
07	0.00795	0.00943	0.00751
08	0.01033	0.01026	0.00950
09	0.00804	0.00850	0.00761
10	0.00980	0.01122	0.00895

TABLE A.9

OPTIMIZED VOLTAGE DEVIATIONS OF THE SEFA IN THE 216-BUS DISTRIBUTION SYSTEM

Case	SEFA ($Cthr = 0$)	SEFA ($Cthr = 0.00001$)	SEFA ($Cthr = 0.000005$)	SEFA ($Cthr = 0.000001$)
01	0.024073	0.024178	0.024178	0.024073
02	0.023063	0.023173	0.023091	0.023063
03	0.021965	0.022039	0.022039	0.021965
04	0.024319	0.024319	0.024319	0.024319
05	0.023632	0.023664	0.023639	0.023632
06	0.007273	0.007486	0.007438	0.007328
07	0.007511	0.007823	0.007532	0.007511
08	0.009497	0.009596	0.009592	0.009505
09	0.007612	0.007646	0.007637	0.007612
10	0.008952	0.009159	0.009159	0.008952

TABLE A.10

DETAILED RESULTS OF THE TEST OF α ON CASE 1~6 ON THE 33-BUS SYSTEM

Total operating cost / PTC	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
$\alpha = 0.1$						

AULD_LT_ac	43.69627 100.0%	48.28238 96.0%	26.27779 92.8%	45.80498 100.0%	44.22819 98.0%	26.43723 97.2%
AULD_LT_pre	43.6963 100.0%	48.9869 97.4%	26.9525 95.2%	45.8050 100.0%	44.5066 98.7%	27.1983 100.0%
GA_LT_ac	43.6963 100.0%	48.4170 96.3%	26.3180 92.9%	45.8050 100.0%	44.1601 97.9%	26.2433 96.5%
GA_LT_pre	43.6963 100.0%	49.1695 97.8%	27.6257 97.6%	45.8050 100.0%	44.3682 98.3%	27.2050 100.0%
1 st _EFA_ac	43.6963 100.0%	50.2743 100.0%	28.3148 100.0%	45.8050 100.0%	45.1145 100.0%	27.2050 100.0%
Online_EFA_ac	43.6963 100.0%	51.8102 103.1%	33.0192 116.6%	45.8050 100.0%	47.6893 105.7%	34.6462 127.4%
$\alpha = 0.08$						
AULD_LT_ac	43.6963 100.0%	48.0424 95.6%	26.2378 92.7%	45.8050 100.0%	43.9882 97.5%	26.1972 96.3%
AULD_LT_pre	43.6963 100.0%	48.7469 97.0%	26.7125 94.3%	45.8050 100.0%	44.3466 98.3%	27.7022 101.8%
GA_LT_ac	43.6963 100.0%	47.9608 95.4%	26.2276 92.6%	45.8050 100.0%	43.8607 97.2%	26.2537 96.5%
GA_LT_pre	43.6963 100.0%	48.3883 96.2%	26.4020 93.2%	45.8050 100.0%	45.1463 100.1%	27.5751 101.4%
1 st _EFA_ac	43.6963 100.0%	50.2743 100.0%	28.3148 100.0%	45.8050 100.0%	45.1145 100.0%	27.2050 100.0%
Online_EFA_ac	43.6963 100.0%	50.7702 101.0%	31.3392 110.7%	45.8050 100.0%	46.6893 103.5%	32.6862 120.1%
$\alpha = 0.05$						
AULD_LT_ac	43.6963 100.0%	47.6824 94.8%	25.9369 91.6%	45.8050 100.0%	43.6282 96.7%	25.8372 95.0%
AULD_LT_pre	43.6963 100.0%	48.2022 95.9%	26.3525 93.1%	45.8050 100.0%	44.4629 98.6%	27.2822 100.3%
GA_LT_ac	43.6963 100.0%	47.5839 94.6%	25.9389 91.6%	45.8050 100.0%	43.5118 96.4%	25.8272 94.9%
GA_LT_pre	43.6963 100.0%	48.2701 96.0%	26.8023 94.7%	45.8050 100.0%	43.6340 96.7%	27.2050 100.0%
1 st _EFA_ac	43.6963 100.0%	50.2743 100.0%	28.3148 100.0%	45.8050 100.0%	45.1145 100.0%	27.2050 100.0%
Online_EFA_ac	43.6963 100.0%	49.2102 97.9%	28.8192 101.8%	45.8050 100.0%	45.1893 100.2%	29.7462 109.3%
$\alpha = 0.03$						

AULD_LT_ac	43.6963	47.4180	25.6022	45.8050	43.3882	25.5972
	100.0%	94.3%	90.4%	100.0%	96.2%	94.1%
AULD_LT_pre	43.6963	47.9605	26.1125	45.8050	44.7124	26.6704
	100.0%	95.4%	92.2%	100.0%	99.1%	98.0%
GA_LT_ac	43.6963	47.2486	25.4313	45.8050	43.3596	25.6964
	100.0%	94.0%	89.8%	100.0%	96.1%	94.5%
GA_LT_pre	43.6963	47.7144	26.0431	45.8050	43.3140	26.4206
	100.0%	94.9%	92.0%	100.0%	96.0%	97.1%
1 st _EFA_ac	43.6963	50.2743	28.3148	45.8050	45.1145	27.2050
	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Online_EFA_ac	43.6963	48.1702	27.1392	45.8050	44.1893	27.7862
	100.0%	95.8%	95.8%	100.0%	97.9%	102.1%