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Optimization of Distribution Network with Distributed Generation Based on an Improved Genetic Algorithm

Xiaoyu Sun [1], Jinsong Liu [2], Xin Sun [2], Jingwei Hu [1]

1 Shenyang Institute of Engineering, Shenyang, China.
2 Electric Power Research Institute, State Grid Liaoning Electric Power Supply Co. Ltd., Shenyang China
hjw_sie@163.com

Abstract

The system of distribution network with distributed generation is analyzed, and dynamic optimization based on an improved genetic algorithm is presented in this paper. First, the mathematical model of distribution network can be established by using constraints and objective function, which contains the network loss, the DGs investment and reliability of power supply. Then, according the construction of distribution network, this paper presents a design of improved genetic algorithm. Finally, IEEE 14 nodes system is adopted to realize the design of the algorithm.

Keywords*: genetic algorithm, optimization, distribution network, distributed generation.*

1. Introduction

Distribution network is a bridge which connects users and power plants, allocating power to users. Electric energy is produced from power plants, then through transmission lines and transformers, finally assigned to users by distribution network. With the development of modern society and the wide application of digital high-tech equipment, power quality required by users is getting higher and higher.

Table 1 is the ratio of Investment in Generation, Transmission line and Distribution network in 1995. From the table, the distribution network investment was more than a half of generation investment in developed countries, while in China, the investment in the distribution network accounts for 20 percent of generation, far less than developed countries. In recent years, the investment in power grid has increased rapidly in China, and in 2009 it was the first time that power grid investment exceeded generation investment. But due to the rapid increase of loads meanwhile in China, the matter of lagging construction on power grid is not settled at all.

Table 1. Ratio of Investment in Generations, Transmission lines and Distribution Network in 1995

Nation	Generation investment	Transmission line investment	Distribution network investment
America	1.00	0.43	0.70
Britain	1.00	0.45	0.78
Japan	1.00	0.47	0.68
France	1.00	0.67	0.60
China	1.00	0.23	0.20

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At present, distribution network has been developing drastically in China. There are several development tendencies of distribution network:

(1) Distributed generation is connected with distribution network directly to supply power to users;

(2) Coordinating with loads, flexible AC distribution technology is applied for special power quality required by users;

(3) Active network is designed for the distribution network with high penetration of distributed generations (DGs);

(4) Micro-grid technology is put into use through connecting with conventional distribution network;

(5) Construction of smart grid has been promoted heavily.

Among developments above, distributed generation is applied generally. Distributed generation is a layout which puts generation system around users by small (the power is between several kilowatts to 50 MW) and distributed blocks [1]. The characteristic that position is flexible and distributed not only makes distribution generations adapt to the demand for electricity and resource distribution extremely, but also alleviates the huge investment which is needed by upgrade of transmission lines and distribution network [2].

Therefore, a model of distribution network with distributed generations is designed and optimized in the paper. The distributed generations supply power not only in normal condition but also during AC grid outage, where from generator to step-down transformer.

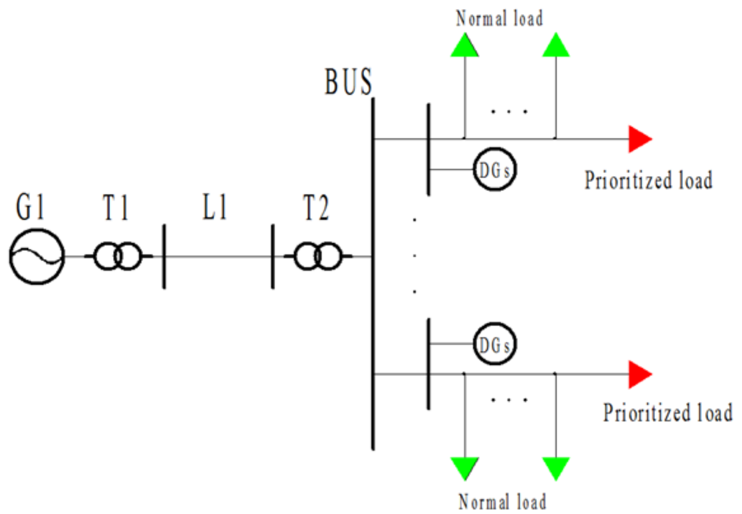

Figure 1. Distribution System with DGs.

Figure 1 shows a typical scheme of the distribution system with distributed generations, which distributes power to various loads. Generally, power plant G1 may be large coal-fired power plant, hydropower plant and nuclear power plant. T1 is a step-up transformer, and T2 is a step-down transformer. High voltage transmission line L1 is between T1 and T2. Loads are divided prioritized loads and normal loads based on the load priority.

At present, gradually mature technology promotes diversification of distributed generation that it can be small wind turbine, photovoltaic power generation, fuel cell or gas turbine [3]. Compared with wind energy, solar energy is widely distributed and resourceful. In the paper, the structure of photovoltaic power generation is shown as Figure 2.

In the Figure 2, if capacity of photovoltaic arrays is enough to supply power to users, photovoltaic arrays will charge to energy storage devices directly. To keep constant power supply, the control system can coordinate output of energy storage devices and photovoltaic arrays. Converter converts direct current produced by photovoltaic arrays into alternating current that corresponds with power quality required by distribution network.

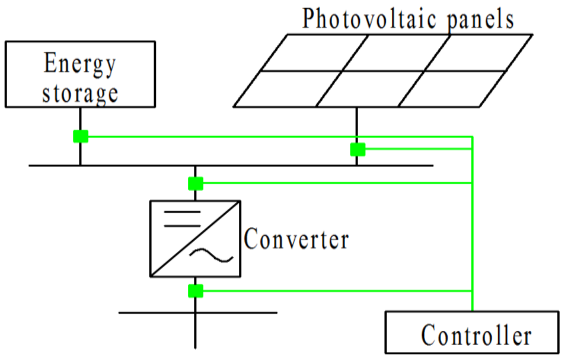

Figure 2. Structure of Photovoltaic Power Generation

2. Model of Distribution Network

In order to optimize distribution network with distributed generation more fully, the network loss, the DG investment and reliability of power supply are contained in the objective function. Reference [4] presents a new planning model for distribution system, which not only contains capital investment, but also considers the factor of distribution system reliability. Reference [5] develops a generalized systematic reliability evaluation method for active distribution system. Reference [6] optimizes distribution network by taking minimum equipment investment costs, system power losses, interruption costs and power purchasing costs as objective function.

2.1 Reliability of Power Supply

Reliability of power supply represents ability that electric system supplies sustainable power to users. In the paper, reliability of power supply is evaluated by conventional indexes, which include average interruption hours of customer, average interruption times of customer and average interruption number of customer.

The average interruption hours of customer can be expressed as follows:

$$H_{AI} = \frac{\sum_{j=1}^{k} (D_{AI} \times N_{AI})}{N_T} \qquad (1)$$

where H_{AI} represents the average interruption hours of customer, k the total times of interruption, D_{AI} the average interruption duration, N_{AI} the average interruption users, and N_T is the total number of users. When a fault occurs, if an isolated grid with distributed generation and loads can be created, the isolated grid will be supplied by distributed generations and energy storage devices [7]. So compared with conventional distribution network, the every time interruption duration declines, and the average interruption hours of customer will decline accordingly.

If the capability of distributed generations and energy storage devices is large enough to supply some prioritized loads during the whole power outage, the every time interruption users will decrease. Therefore, according to the following formula, average interruption times of customer decrease.

$$T_{AI} = \frac{\sum_{j=1}^{k} N_{EI}}{N_T} \tag{2}$$

where T_{AI} is the average interruption times of customer, and N_{EI} is the number of every time interruption users. Correspondingly, average interruption number of customer N_{AI} can be expressed by the interruption times T_I and the number of every time interruption users N_{EI} as follows:

$$N_{AI} = \frac{\sum_{j=1}^{k} N_{EI}}{T_I} \tag{3}$$

where N_{AI} is proportional to $\sum N_{EI}$. According to the above formula 1, 2, 3, reliability of power supply R_{PS} can be expressed as follows:

$$R_{PS} = (1 - \frac{H_{AI}}{T_S}) \times 100\% \tag{4}$$

where T_S is statistical time, and H_{AT} is determined in the formula 1. If the total number of users and the statistical time are constant, with the H_{AT} declining, the reliability of power supply R_{PS} increases.

2.2 Objective Function

In the distribution network with distributed generation, the more distributed generations distribution network put, the less the power transmitted from power plants. Therefore, according formula 5, active power loss and reactive power loss will reduce.

$$\Delta S = (\frac{S_2}{U_2})^2 \times Z = \frac{P_2^{\ 2} + Q_2^{\ 2}}{U_2} \times (R + jX) \tag{5}$$

where $S_2=P_2+Q_2$ is the terminal power, U_2 the terminal voltage, and $Z=R+ jX$ is the impedance power went through.

Although distributed generation can reduce the power loss, the investment of distributed generation is costly, so distributed generation cannot be put into use without limit. Reference [8] puts forward economic analysis in rooftop solar photovoltaic generation system, listing the total investment of the photovoltaic power generation systems as follows:

$$B_C = \sum_{i=1}^{n} (\gamma_i K_i C_0 + A_1 \gamma_i K_i C_0 + A_2 \gamma_i K_i C_0 + A_3 \gamma_i K_i C_0 + A_4 \gamma_i K_i C_0) = (1 + A) \times \sum_{i=1}^{n} \gamma_i K_i C_0 \tag{6}$$

where K is the peak power of the photovoltaic array, C_0 the price of photovoltaic cells per watt, γ_i the weight factor as the capacity of distributed generation, A_1 the investment coefficient of storage battery, A_2 the investment coefficient of charge controller and inverter, A_3 the investment coefficient of auxiliary facilities included bracket and cable, A_4 the investment coefficient of other fees included construction and transportation, and A_1, A_2, A_3 and A_4 are all relative to photovoltaic cells.

So, there exist a best proportion between the investment of distributed generations and the power loss, and the balance can achieve maximum interests. In the paper, the objective is written as follows:

$$\min F = \lambda_1 \sum_{i=1}^{n} \gamma_i K - \lambda_2 \sum_{i=1}^{n} (\Delta S_1 - \Delta S_2) - \lambda_3 \sum_{i=1}^{n} \gamma_i K \quad (7)$$

where λ_1 represents the annual price of photovoltaic power generation systems per kilowatt, λ_2 the cost that power plants generate electricity per kilowatt, λ_3 the subsidy of photovoltaic power generation generate electricity per kilowatt, and n is the total number of distributed generation in the distribution network.

Here,

$$\lambda_1 = \frac{(1+A)C_0}{N}$$
$$\Delta S_1 - \Delta S_2 = \frac{P_2^{\ 2} + Q_2^{\ 2}}{U_2}(R + jX) - \frac{(P_2 - K)^2 + Q_2^{\ 2}}{U_2}(R + jX) \quad (8)$$

where N is service life photovoltaic power generation, and ΔS_1 is power loss without distribution generations, ΔS_2 the power loss without distribution generations. Therefore, formula 7 can transform as follows:

$$\min F = \frac{\lambda_2}{U_2} \sum_{i=1}^{n} \gamma_i^{\ 2} K^2 - (\frac{2P_2}{U_2}\lambda_2 + \lambda_3 - \lambda_1) \sum_{i=1}^{n} \gamma_i^{\ 2} K \quad (9)$$

2.3 Constraint Condition

Based on the objective function, the following constraints are considered in the paper.

(1) Equality constraint

Power balance constrain:

$$\Delta P_i = P_i - U_i \sum_{j=1}^{n} U_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij})$$
$$\Delta Q_i = Q_i - U_i \sum_{j=1}^{n} U_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) \quad (10)$$

where P_i and Q_i are the active and reactive power respectively, U_i and U_j the voltage amplitude for i and j respectively, G_{ij} and B_{ij} the real part and imaginary part of system admittance matrix respectively, δ_{ij} voltage phase angle difference between i and j.

(2) Inequality constraints

Inequality constraints contain node voltage constrain which should be between minimum and maximum voltage, branch power which contributed to DGs should lie on minimum and maximum loads, capacity of DGs which should compensates remained loads at least but not exceed minimum loads, and the number of DGs installation position which should not exceed the number of nodes.

$$U_{\min} \le U_i \le U_{\max}$$
$$S_{L\min} \le S \le S_{L\max}$$
$$S_{L\max} - S_{L\min} \le S_{DG} \le S_{L\min} \quad (11)$$
$$0 \le N_{ip} \le k$$

where U_i is the voltage of low-voltage bus. On request of power quality, the $U_{\min}$ is (1-5%) U_N and the $U_{\max}$ is (1+5%) U_N. $S_{L\min}$ is the minimum load power, and $S_{L\max}$ maximum load power. The k is number of main line in distribution network.

3. Design of Genetic Algorithm

Genetic Algorithm (GA) is an adaptive optimized algorithm of probability search which simulates heredity and evolution of biology in environment. [9]. Based on the search algorithm of natural selection and genetic mechanism, GA simulates breeding, hybridization and mutation phenomenon in the process of natural selection and genetic [10]. Generally, GA codes parameters of a problem as chromosomes, and exchanges information of chromosomes through selection, crossover and mutation in iterative way, forming the final chromosome that meets optimized objects [11].

At present, many of improved genetic algorithms are used in the distribution network optimizing field. Reference [12] established the optimal algorithm of power distribution network rehabilitation based on improved genetic algorithm based on constraint condition. Reference [13] designs a method based on loop circuit to avoid the infeasible solutions in the operations of genetic algorithm. Reference [14] considers that improved GA adopting the TS mutation operation is suitable for optimizing the complex distribution network planning.

In the paper, if the optimized result is judged to not meet GA termination conditions, weight factor γ_i is needed to modify. For example, if the optimized result exceed the constrain conditions or the investment of distributed generations, weight factor will be down. Therefore, the improved GA implementation scheme is as follows:

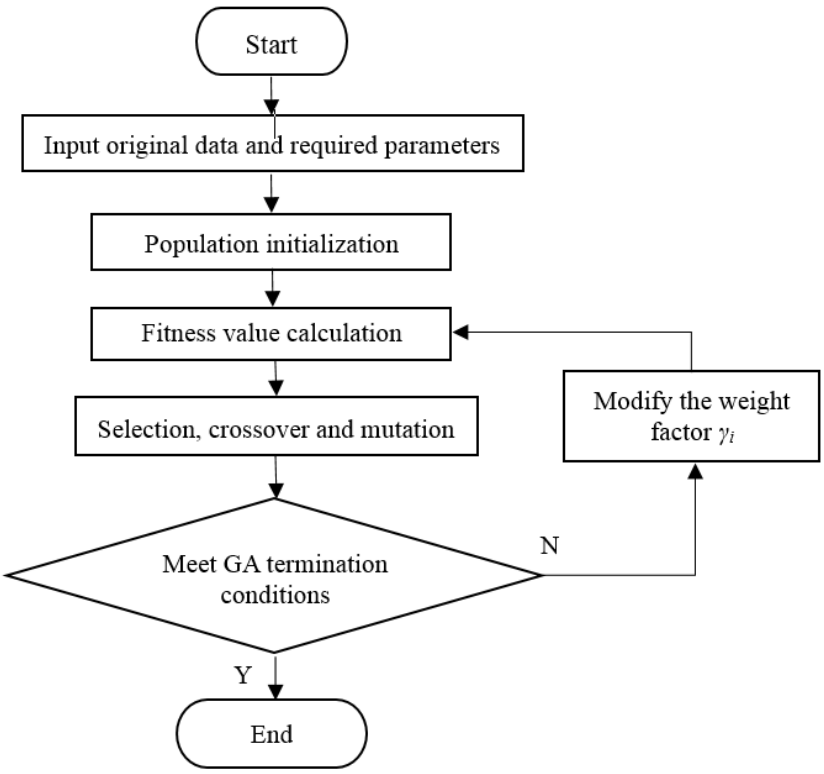

Figure 3. Flowchart of Genetic Algorithm

3.1 Population Initialization

A population is composed of a number of individuals, which are called chromosomes. When initialize a population, we need to choose some individuals randomly according to objective function and constraint conditions. Due to the reason that GA cannot deal with parameters of a problem space directly, these desirable individuals must be converted into chromosomes by coding. In this way, all point in the problem space (candidate solutions) can be as point in the space of GA (chromosomes). And each candidate solution corresponds to a chromosome.

In the paper, binary coding is adopted. For a chromosome, the distributed generation of each branch corresponds to a string of genetic value [15]. The 1 represents a point of distributed generation, and 0 is on behalf of no distributed generation in the distribution network. The corresponding relationship between the chromosome coding and optimization scheme is shown as table Table 2.

Table. 2. Scheme of Chromosome Encoding

Optimization Plan of Distribution Network	Chromosome Coding
Plan *k*	Chromosome *k*
Number of main branches in the distribution network (m)	Number of gene (m)
Number of nodes on each branch (n)	Length of coding (n)
Node with distributed generation	1
Node without distributed generation	0

In order to get a nature solution, each of optimization plans of distribution network namely chromosome coding randomly is independent.

3.2 Fitness Function

In a population that the good and bad are intermingled, fitness is proposed to distinguish excellent individuals from random population. The individuals with high fitness are more likely to inherit to next generation, and the individuals with low fitness may be abandoned. In order to describe fitness visually, fitness function is put forward.

In the paper, minimum value of objective function is required, so reciprocal value of the function is as the individual fitness value. The less function value is, the bigger fitness value is, namely more excellent the individual is.

$$f = \frac{1}{F} = \frac{1}{\frac{\lambda_2}{U_2}\sum_{i=1}^{n}\gamma_i^2 K^2 - (\frac{2P_2}{U_2}\lambda_2 + \lambda_3 - \lambda_1)\sum_{i=1}^{n}\gamma_i^2 K} \tag{12}$$

3.3 Genetic Operation

In the genetic algorithm, after population initialization, genetic operations need to impose certain operations on individuals according to their fitness to the environment (fitness evaluation) in a population, so as to realize the evolutionary process of evolution. Genetic operations include selection crossover and mutation, three kinds of operator. Undergoing operation of these operators circularly, the coded individuals will produce several excellent offspring finally.

(1) Selection operation

Selection operation is to select excellent individuals from a population at a certain probability, and eliminate inferior individuals. In the paper, roulette wheel selection is adopted that choice probability of each individual is proportional to its fitness value.

The probability that the individual is selected is as follows:

$$p_i = \frac{f_i}{\sum_{j=1}^{n} f_j} \tag{13}$$

(2) Crossover operation

Crossover operation refers to breaking two chromosomes at a point randomly, and then combining them crosswise. According to binary coding, the single-point crossover of binary valued crossover is adopted in the paper. The method of crossing chromosome h and chromosome is a follows:

$$\begin{cases} g_{hi} = g_h(1-\frac{i}{n}) + g_l\frac{i}{n} \\ g_{li} = g_l(1-\frac{i}{n}) + g_h\frac{i}{n} \end{cases} \tag{14}$$

where i represents that the chromosome h and chromosome l cross at i point. In order to ensure randomness, i is a random number in (0, n). Taking an example is as shown as Figure 4.

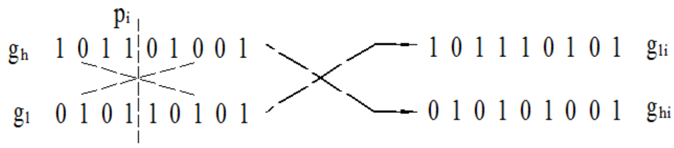

Figure 4. Schematic of Crossover Operation

(3) Mutation operation

The main purpose of mutation operation is to keep population diversity. After selection operation, some inferior individuals are eliminated. In order to maintain integrity of population and global search, it is necessary to mutate some chromosomes and judge them whether meet the terminal conditions.

Due to binary coding, when a gene mutates, it must be 1 to 0 or 0 to 1. In the paper, mutation operation of gene j in chromosome i is expressed as follows:

$$g_{ij}' = 1 - g_{ij} \tag{15}$$

where g_{ij} is the genetic value before mutation operation, and g_{ij}' is genetic value after mutation operation.

4. Analysis of Example

In the paper, IEEE 14 nodes system is adopted to analyze AG as shown as Figure 5. Due to node 7 and node 8 without loads, distribution network contains node 6 to node 14 except 7 and 8. The distribution network belongs to loop network, so the number of main branches is 1, and number of nodes is 7. According to the coding method of Table 2, there are 2^7 kinds of optimization plan in distribution network, namely 128 chromosomes. The 128 chromosomes contains all of the designs of the distributed generations, keeping the integrity of population and global search without selection, crossover and mutation operation, and they are independent of each other. Actually, the code 1010101 and code 0101010 can generate all the 128 chromosomes through crossover and mutation operation. These chromosomes are filtrated via fitness function and selection operation. Therefore, the two codes are vital object for the population and can be as first generation to compute.

In order to reduce the amount of calculation and improve the speed of operation, the length of distribution line and the size of load are added in the fitness function.

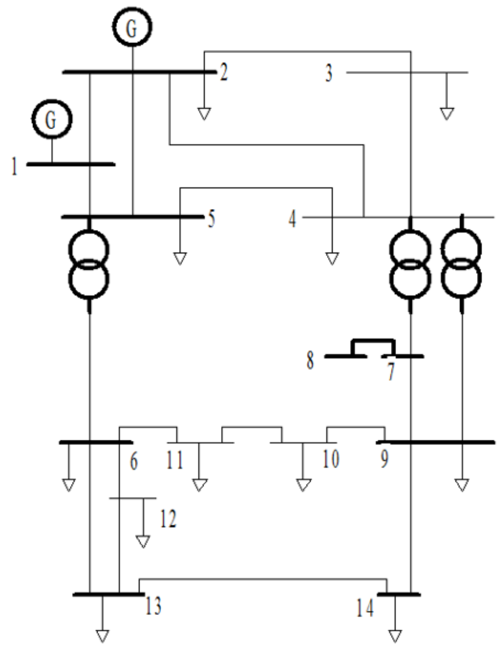

Figure 5. IEEE 14 Nodes System Connection

According to system data of IEEE 14 nodes standard test, active power on 14 is more than 13, 6 more than 9, and line parameter of branch 6 to 11 is bigger than 9 to 10. If the capacities of distributed generations are same, the node 6, 11 and 14 are better with distributed generations.

5. Conclusion

Compared with conventional distributed network, distribution network with distributed generation not only makes full use of renewable energy and decreases the use of fossil fuel, but also increases reliability of power supply.

In the paper, reliability distribution network with distributed generation is evaluated and proved to be true. Based on the reliability, in order to optimize power flow and distribute power more reasonably, model of distribution network is designed. Then, an improved genetic algorithm based on distribution network with distributed generation is proposed. Compared with general genetic algorithm, the improved genetic algorithm adds a section that modify weight factor of distributed generations. Finally, IEEE 14 nodes system is adopted to realize the design of the algorithm. In loop network, the capacity and location of distributed generation are determined by layout of distribution network and the size of load.

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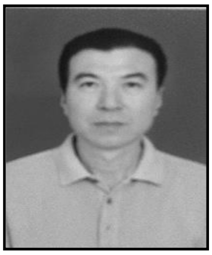
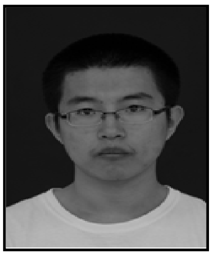
Authors



Xiaoyu Sun, He received the MBA degree from Liaoning University, mainly engaged in electrical device with intelligent controlling based on FPGA and soft core CPU.

Jinsong Liu, He received his Master degree in Electric power system and automation course from Harbin Institute of Technology in 2005.He is currently the director of Technology Department in State Grid Liaoning Electric Power Research Institute. His professional and technical fields include calculation of power system simulation and research of intelligent power grid.

Xin Sun, He was born in 1974. He received the master degree. He is currently a senior engineer with State Grid Electric Power Research Institute of Liaoning Provincial Power. His current research interest is power system relay protection.



Jingwei Hu, He received the B.E. degree in Electrical Engineering and Automation from Shenyang Institute of Engineering, Liaoning, China in 2013. He is currently working towards the Master in Electrical Engineering in Shenyang Institute of Engineering.