Research on Three-phase Unbalance Control of Distribution Area Based on Intelligent Fusion Terminal

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Abstract. As the three-phase four-wire system is used in power transmission and distribution in our country, the single-phase load is the most part of power consumption. The three-phase imbalance of voltage and current on the outlet side of transformers may occur due to the unexpectedly increase or decrease of the load in a certain phase of the low-voltage distribution network. This phenomenon will reduce the service time of the equipment and the power quality of the power supply. A multiple population genetic algorithm (MPGA) is proposed in this paper to treat this problem. Intelligent fusion terminal (IFT) is used as the hardware application platform to communicate with phase-change switch in order to execute the optimal strategy, the three-phase current of the load side would be balanced after the strategy is executed. An example is simulated with MATLAB to show the effectiveness of MPGA.

1. Introduction

In recent decades, due to the rapid development of the economy and industry, the demand to power quality in low-voltage distribution networks is increasing. The voltage and frequency deviation of the power industry's standards for evaluating the quality of power cannot meet the existing needs, so standards such as voltage fluctuation and flicker, voltage sag, harmonics and simple harmonics, and three-phase unbalance are added. In these standards, three-phase unbalance is an important indicator that affects power quality. Usually, due to the unbalance of the three-phase voltage or current in the power grid, other indicators will appear abnormal. Since the low-voltage distribution network is a terminal network directly facing the users, the power quality of the low-voltage distribution network affects the user's power quality directly [1], so the management of three-phase unbalance is crucial to State Grid and users.

The three-phase current imbalance control system based on the intelligent fusion terminal can ensure that the power grid does not have to be powered off and does not impact the power grid when the commutation is executed. The control algorithm in intelligent fusion terminal is very important to ensure fast action, quick response and stable system. In this paper, we propose to use a multi-group genetic algorithms to achieve optimal commutation purposes. The multi-group genetic algorithms can avoid the precocious phenomenon that a single population genetic algorithm is prone to fall into the local optimal solution and improve its search efficiency in the later stage of evolution [2]. Multi-group genetic algorithm is a randomization search algorithm based on probability transition rules, which is widely used to solve multi-objective complex optimization problems [3]. Three-phase unbalance
control is a multi-objective problem which must consider the three-phase current unbalance and the minimum number of commutation. Multi-group genetic algorithms are reasonable and feasible for managing three-phase unbalance.

As an edge IoT agent device in the cloud-pipe-side-end system [4], the intelligent fusion terminal is installed at the exit line of the secondary side of the distribution transformer and is the core of the low-voltage intelligent distribution Internet of Things. Smart distribution equipment, smart meters and other local networking complete the intelligent transformation of the station area, which can realize the homogenous collection of data in the low-voltage distribution station area and the integration of the distribution business. This article uses the intelligent fusion terminal as the application platform, adopts the three-phase balanced optimized commutation method, and deploys the optimized commutation control strategy multi-group genetic algorithm software to the intelligent fusion terminal. The intelligent fusion terminal is successfully networked with each commutation execution switch through a high-speed power line carrier (HPLC) communication module, and then collects power data information such as voltage and current of each phase of the distribution transformer and receives each commutation execution switch to collect and upload users. The electrical energy data of the load and the current phase sequence of the commutation execution switch are used to calculate the three-phase unbalance of the low-voltage distribution network through the intelligent fusion terminal commutation switch APP. If the calculation result exceeds the specified upper limit, it can be genetically optimized according to multiple groups. The commutation control strategy is calculated to achieve an optimal commutation scheme for three-phase balance, and sent to the commutation execution switch via the HPLC communication module for commutation action.

2. Establish a three-phase load imbalance model
The intelligent fusion terminal controls the commutation execution switch to operate, the purpose is to evenly distribute the load on the three phases of the low-voltage distribution network. In order to achieve the purpose of studying and controlling three-phase unbalance, a multi-objective mathematical model of three-phase load unbalance must be established. According to the national power quality standard GB/T15543-2008 "the three-phase voltage allowable imbalance degree of power quality "document and reality, the current imbalance must not exceed 10%. At the same time, in order to increase the service life of the commutation switch, the minimum number of switching actions required for each commutation is required.

2.1. Three-phase current unbalance model
Suppose N commutation execution switch is installed in the distribution area and the N execution switch is binary coded, then the current phase sequence of an execution switch is represented by a column vector L.

\[
L = \begin{bmatrix}
[1 0 0]^T, & \text{A phase} \\
[0 1 0]^T, & \text{B phase} \\
[0 0 1]^T, & \text{C phase}
\end{bmatrix}
\]

(1)

Assuming that the current phase sequence current measured by each commutation executive switch before the commutation of the low-voltage distribution network is I, the current phase sequence of the N commutation switches is expressed by a matrix \( \mathbf{L}^0 \)

\[
\mathbf{I} = [I_1, I_2, I_3, \ldots, I_N]
\]

(2)

\[
\mathbf{L}^0 = [L_1^0, L_2^0, L_3^0, \ldots, L_N^0]
\]

(3)
Then, the sum of the three-phase currents A, B, and C of each load branch collected by the intelligent fusion terminal before commutation is expressed as the difference multiplication of the switch phase sequence state matrix and the current vector [5], namely:

\[
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} = \mathbf{L} \times \mathbf{I}
\]

(4)

Assuming that after the intelligent fusion terminal passes the judgment, after adjusting the phase sequence of each commutation execution switch, the current phase sequence of the N commutation execution switches is represented by a matrix \(\mathbf{L}'\), and each load branch A, B, C three phases collected by the intelligent fusion terminal. The sum of currents is

\[
\mathbf{L} = [L_1, L_2, L_3, \ldots, L_N]
\]

(5)

\[
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} = \mathbf{L}' \times \mathbf{I}
\]

(6)

The three-phase current unbalance of the power grid is expressed by MAX (phase current-three-phase average current/three-phase average current).

\[
\lambda_\alpha = \frac{I_\alpha - I_{av}}{I_{av}} \times 100\%
\]

(7)

In the formula: \(\lambda_\alpha\) represents the phase current unbalance degree of a phase, \(I_\alpha\) represents the real-time current value of a phase at the current moment, and \(I_{av}\) represents the average value of the three-phase current at the current moment.

The calculation of the three-phase unbalance of the user-side current of the distribution network transformer is calculated by formula (8).

\[
\lambda_i = \frac{I_i - I_{av}}{I_{av}} \times 100\%
\]

\[
\lambda_\alpha = \frac{I_\alpha - I_{av}}{I_{av}} \times 100\%
\]

(8)

\[
\lambda_\beta = \frac{I_\beta - I_{av}}{I_{av}} \times 100\%
\]

\[
\lambda_\gamma = \frac{I_\gamma - I_{av}}{I_{av}} \times 100\%
\]

\[
\lambda_{max} = \max(\lambda_\alpha, \lambda_\beta, \lambda_\gamma)
\]

(9)

In formula (8): the parameters \(\lambda_\alpha, \lambda_\beta\) and \(\lambda_\gamma\) represent the values of the current unbalance of the three phases A, B, and C; the parameters \(I_\alpha, I_\beta\) and \(I_\gamma\) represent the phase current values of the three phases of A, B, and C, respectively, which \(I_{av}\) represent the three phases Average current. In formula (9) \(\lambda_{max}\) is the maximum value of the three-phase current unbalance value of A, B and C.

2.2. Least Commutation Action Model

In order to extend the service life of the commutation execution switch, it is necessary to reduce the number of commutations on the premise of meeting the commutation requirements. The minimum number of commutations required for each action needs to be taken as one of the objective functions.
A certain commutation execution switch is represented by \( \mathbf{L}(x_{\text{Ai}}, x_{\text{Bi}}, x_{\text{Ci}}) \in \{0,1\} \) two states, when no commutation operation is performed, it is represented by 0, and when a commutation operation is performed, it is represented by 1. Establish the commutation matrix model of \( N \) commutation executive switches:

\[
D = \left[ \mathbf{L}(x_{\text{Ai}}, x_{\text{Bi}}, x_{\text{Ci}}), \mathbf{L}(x_{\text{Aj}}, x_{\text{Bj}}, x_{\text{Cj}}), \ldots, \mathbf{L}(x_{\text{An}}, x_{\text{Bn}}, x_{\text{Cn}}) \right]
\]

(10)

Then, the total number of action adjustments for each commutation execution switch on all load branches on the entire low-voltage distribution station area is expressed as

\[
D(L) = \sum_{j=1}^{N} D_j
\]

(12)

The objective function in the low-voltage distribution area indicating that all commutation switches require the least number of commutation:

\[
\delta_2 = \min(D(L))
\]

(13)

2.3. Three-phase load imbalance model

According to the actual situation, it can be concluded that the current flowing through each phase access line cannot be greater than the allowable load current of the wire. In summary, in order to realize the optimal commutation strategy, a three-phase load imbalance mathematical model is established [6].

Objective function:

\[
\begin{aligned}
\delta_1 &= \min(\lambda_{\text{max}}) \\
\delta_2 &= \min(D(L))
\end{aligned}
\]

(14)

Constraints:

\[
\begin{aligned}
\lambda_{\text{max}} &\leq \lambda_{\text{limit}} \\
I_A, I_B, I_C &< I_{\text{max}}
\end{aligned}
\]

(15)

The maximum load current \( I_{\text{max}} \) is allowed for in formula (15).

3. Multi-population genetic algorithm

The MPGA algorithm is improved on the basis of the standard genetic algorithm (SGA) and introduces the concept of multiple populations, which expands a single population into a structure of multiple populations, and each population has its own crossover probability and mutation probability. Meanwhile, the genetic operation between the elite individuals of each population is carried out by setting the migration operator. After several generations of evolution, the optimal evolution results of all populations are obtained [7]. MPGA artificial selection operator is added to the algorithm to select the optimal individuals for each population. The MPGA algorithm structure diagram is shown in figure 1.
Figure 1. MPGA algorithm structure diagram.

The standard genetic algorithm for each population in Figure 1 usually selects the operator to use the roulette method, the crossover operator uses the single-point crossover method, and the mutation operator uses the site mutation to ensure the normal genetic evolution of each population [8]. In the multi-group genetic algorithm, we assign different cross probability $P_c$ and mutation probability $P_m$ to each different population. The value of the cross probability affects the size of the SGA's global search ability, and the size of the mutation probability affects the SGA's local search ability. Therefore, it is recommended to choose larger $P_c$ (0.7~0.9) and smaller $P_m$ (0.001~0.05). However, there can be countless different combinations of values for $P_c$ and $P_m$, and the evolutionary results corresponding to the different combinations of values are also very different. MPGA algorithm can solve the difference caused by different values, and the global search and local search of the algorithm are realized by different control parameters set by each population. For example, the control parameters in the existing three populations have different values. In order to enhance the global search ability of MPGA, the $P_c$ and $P_m$ of population 1 can be assigned a larger value; in order to enhance the local search ability of MPGA, the $P_c$ and $P_m$ of population 3 can be assigned a smaller value. At the same time, in order to balance the global and local search capabilities of the MPGA algorithm, the $P_c$ and $P_m$ of population 2 can be assigned an intermediate value.

Each population in the multi-population genetic algorithm architecture is not completely independent of each other. Fig. 1 shows that the population with input side of migration operator is called source population, the population with output side is called target population, and the function of migration operator is to replace the worst individual with the best individual. The connection between each population is to pass the best evolved individuals in one population into another through the migration operator, so that the fine individuals in each population will transfer to each other in other populations, and the contact interaction between the population and the population is realized. If the multi-group genetic algorithm does not exist immigration operators, then it is equivalent to several SGA algorithms to calculate individuals in different populations, thus losing the characteristics of MPGA [9].

The elite populations that exist in the framework of the multi-group genetic algorithm process are relatively special. On the one hand, the elite population is specifically used to store the optimal individuals that have been retained by artificial operators after evolution of each population, and in order to ensure the integrity and existence of the optimal individuals preserved in the elite population, no Genetic evolution operation; on the other hand, the multi-group genetic algorithm cannot be iterated without limit. When the excellent individuals in the elite population do not change after several iterations, it can be used to judge the multi-group genetic algorithm.
4. Three-phase unbalance model solution
According to the established three-phase load unbalanced multi-objective commutation switch model, it can be known that the three-phase unbalanced problem is a nonlinear discrete multi-objective optimization problem. The intelligent optimization algorithm can find the optimal solution through the objective function well. In this paper, the multi-group genetic algorithm (MPGA) can be used to solve the immature convergence of the genetic algorithm.

The steps of applying MPGA algorithm to the optimal solution of commutation switch commutation [10]-[11]:

(1) Encoding operation. Abstract a specific problem into chromosomal variables, and then perform the corresponding gene evolution operation. In order to control the three-phase imbalance problem in the low-voltage distribution area, according to the current phase sequence of the commutation execution switch, the A-phase gene is expressed as \([1, 0, 0]^T\), the B-phase gene is expressed as \([0, 1, 0]^T\), and the C-phase gene is expressed as \([0, 0, 1]^T\) encoded.

(2) Initial population. Determine the number of populations \(P\) is 3 and the population size \(N\) is 100, and start to randomly generate populations related to chromosome sequence. Use the creation population function \(crtbp()\) to arbitrarily initialize the discrete random population, the three randomly generated phase sequence populations after the initial commutation switch, the first generation population size generation, and then undergo the genetic evolution operation of MPGA.

(3) Define the fitness function and calculate the fitness value. The fitness function \(\text{ranking}()\) is used to calculate the fitness value of all individuals in all populations, which is used to evaluate the probability of individual inheritance. The higher the fitness value, the greater the probability of being selected. In this paper, the objective function of the calculated current three-phase unbalance is used as the fitness function, and the size of the unbalance is calculated by the three-phase unbalance function to determine whether to inherit the chromosome.

(4) Genetic evolution operation. Each population uses standard genetic algorithm SGA to optimize iterative chromosomes. In the process of genetic evolution operation, it constantly goes through the process of selection operation, cross operation and mutation operation.

(5) Immigration operator and artificial operator. The immigration operation realizes the co-evolution of individuals, which can accelerate the propagation speed of good individuals among populations, and improve the convergence speed and the accuracy of solutions. Manual selection ensures that the best elite individuals are manually selected and saved.

(6) Iteration termination condition. Iterative termination uses the double convergence criterion as the termination condition. First, when various groups have evolved to the specified number of iterations, the algorithm can be terminated; second, when the fitness value of the best individual of all individuals in multiple populations keeps the specified number of times continuously, the algorithm can be terminated. The two can satisfy one. When searching for the optimal commutation sequence, we set the maximum number of iterations and the population iteration of the commutation sequence stipulates that the algorithm is terminated when several generations remain unchanged, and the optimal commutation sequence is obtained.
5. Simulation and result analysis
In the distribution station area of a typical urban community, the three-phase four-wire system is used for power supply in the low-voltage distribution network of the community. The installation method of the intelligent commutation system device is to install an intelligent fusion terminal on the outlet side of the 10/0.4kv distribution transformer, and install a commutation execution switch on the user side. The commutation execution switch is A, B, C three-phase incoming line, and the outgoing side is single-phase [12]. The user's load is mainly concentrated at the end of the line, assuming that 15 commutation executive switches are installed, as shown in the topology diagram of Figure 3.
can be obtained, \( I_a = 118 \text{A}, I_b = 67 \text{A}, I_c = 72 \text{A} \). Through calculation, the three-phase current unbalance degree is \( \lambda_{\text{max}} = \max(\lambda_a, \lambda_b, \lambda_c) = 37.7\% \) and the waveform diagram of the three-phase current before commutation can be obtained. It can be seen that there is a large three-phase current unbalance in the load area.

Table 1. Phase sequence and current of each commutation execution phase before phase change

| Numbers | Phase sequence | Current |
|---------|----------------|---------|
| 1       | C              | 12      |
| 2       | B              | 14      |
| 3       | A              | 16      |
| 4       | C              | 14      |
| 5       | A              | 14      |
| 6       | B              | 10      |
| 7       | C              | 18      |
| 8       | C              | 18      |
| 9       | A              | 25      |
| 10      | C              | 10      |
| 11      | A              | 28      |
| 12      | B              | 18      |
| 13      | A              | 15      |
| 14      | B              | 25      |
| 15      | A              | 20      |

After detecting the three-phase imbalance in the low-voltage distribution network, the intelligent fusion terminal starts the multi-group genetic algorithm to calculate the optimal commutation instruction. Because there are 15 commutation execution switches, we are divided into \( P = 3 \) initial populations, and the number of chromosomes in each initial population is \( N = 50 \). We stipulate that the multi-group genetic running in the intelligent fusion terminal terminate the iteration condition if the maximum iteration of a single population to 100 times, or the fitness values calculated by all the fine individuals that iterate out in three populations reach 5 times without changing continuously.

Population 1 \( P_c = 0.9, P_m = 0.05 \); Population 2 \( P_c = 0.8, P_m = 0.025 \); Population 3 \( P_c = 0.7, P_m = 0.001 \);

Before the commutation, the switching state of each commutation execution switch is coded to form a matrix as follows:

\[
\mathbf{L}^c = \begin{bmatrix}
0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\
1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

(16)

According to the control parameters of the multi-group genetic algorithm given above, MPGA was used to solve the three-phase unbalance mathematical model with three-phase unbalance and minimum number of commutation as the goal, and MATLAB was used for simulation. In order to explain the advantages of MPGA more clearly, the same experimental conditions are used to simulate the convergence curve of the optimization process of MPGA and SGA by MATLAB simulation as shown in Figure 5.
Figure 4. Three-phase current unbalance diagram before commutation

Figure 5. MPGA and SGA optimization algorithm comparison curve

Figure 6. Three-phase current waveform diagram after commutation

From the comparison of MPGA and SGA convergence iteration times in Figure 5, it can be concluded that the MPGA algorithm has fewer iterations and the optimal value is about 0.778% after 5 iterations. It has a faster convergence speed and avoids the premature phenomenon of SGA. So as to prove the superiority and rationality of MPGA algorithm. After being optimized by the MPGA algorithm, the optimal commutation switch state matrix of its output is:

\[
L^* = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\] (17)

Therefore, the commutation execution switch that needs to perform the commutation adjustment action is shown in Table 2.

| Number | Before commutation | After commutation |
|--------|--------------------|-------------------|
| 3      | A                  | B                 |
| 5      | A                  | C                 |
The optimal commutation of the output after the optimization of the MPGA algorithm, the three-phase current waveform after the execution of each commutation switch is shown in Figure 6. It can be seen that after commutation, A, B, C three-phase current is basically equal, reaching the purpose of commutation. The three-phase unevenness of the distribution area of the district decreased from 37.7% to 0.78%.

6. Conclusion
Aiming at the problem of three-phase imbalance in low-voltage radio station, this paper designs a scheme based on intelligent fusion terminal governance, establishes three-phase unbalanced commutation model and its definite constraints, then obtains the optimal commutation decision by multi-group genetic algorithm. The results show that the system composed of intelligent fusion terminal and commutation executive switch can effectively control the three-phase imbalance in the station area and ensure the power quality. Multi-group genetic algorithm can avoid local convergence problem effectively. Compared with standard genetic algorithm, the convergence speed is fast and the efficiency is high.

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