A New Active Power Filter Partition Allocation for Distribution Networks

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Abstract—At present, the power quality compensation device configuration algorithm in distribution network is often very complex. Therefore, the dominant gene rules in nature are simulated and introduced to the algorithm. An optimal configuration model for harmonic compensation devices is established, which takes into account the weak coupling between different loads and compensation devices. Finally, the implicit genetic rule of adaptive discrete genetic algorithm (IGADGA) gets rapid convergence and high precision, and the algorithm is validated by computer simulation.

1. INTRODUCTION

In recent years, with the development of science and technology, there are more and more nonlinear loads and distributed power sources in the distribution network. But the requirement of power electronic power system for power quality has increased greatly, and the harmonic sensitivity is enhanced. Harmonic management of distribution networks has become a research hotspot [1-3].

Reference [4] introduced the idea of partition control into the FACTS control method firstly. It was proved by simulation that the partition idea is feasible in harmonic governance, but the weak coupling between intervals is not taken into account. And it is difficult to apply because this discrete optimization algorithm is complex extremely. In this paper, an adaptive discrete genetic algorithm based on explicit and implicit gene rules is proposed which contained the effect of weak harmonic coupling between regions. Finally, through the simulation verification to prove the correctness of the theory and algorithm and realize the optimization of the location and capacity configuration of the partition compensation equipment for the entire network harmonics.

2. MATERIALS AND METHODS

The harmonic coupling matrix model was derived from reference [5], which laid the theoretical foundation for the calculation of harmonic coupling admittance. Then the modal analysis method is introduced into the power flow system calculation, and the physical quantities such as the voltage distortion rate in the physical coordinate system are converted into the mathematical matrix for description, which is convenient for algorithm design. For an n-node power system topology, the power flow constraint equation is:

$$I_B = Y_B U_B$$

(1)

Among them, IB is the node injection current column vector, YB is the \(n \times n\) order node admittance matrix, and UB is the node voltage column vector.
Yh is known as the system node admittance matrix under the h-th harmonic, which can be decomposed into a diagonal matrix D under the h-th harmonic, a unit upper triangular matrix U, and a unit lower triangular matrix L, that is:

\[ Y_h = L_h D_h U_h \]  

(2)

Expand it:

\[
\begin{bmatrix}
Y_{h1} & Y_{h2} & \cdots & Y_{hn}
\end{bmatrix}
= \begin{bmatrix}
1 & Y_{h1} & Y_{h2} & \cdots & Y_{hn}
\end{bmatrix}
= \begin{bmatrix}
1 & 1 & 1 & \cdots & 1
\end{bmatrix}
\]

(3)

Then, according to the idea of "line by line normalization and elimination by column", the improved Gaussian elimination method can be used to decompose and eliminate the Z matrix. Then formula (3) can be expanded to:

\[
U_k^h = \begin{bmatrix}
Z_{h1} & Z_{h2} & \cdots & Z_{hn}
\end{bmatrix}
= \begin{bmatrix}
1 & d_{h1} & d_{h2} & \cdots & d_{hn}
\end{bmatrix}
\]

(4)

The diagonal element \(Z_{ii}\) (i=1, 2, ...,n) of the node impedance matrix Z is the node self-impedance, and its physical meaning is that when no current is injected from other nodes, the voltage of the i node when the i node injects a unit current. The non-diagonal element \(Z_{ij}\) (i=1, 2, ...,n; j=1, 2, ...,n; i ≠ j) is when no current is injected into other nodes, the voltage value of the i-node when node j injects unit current.

Harmonic node admittance matrix Yh and harmonic node impedance matrix Zh can be obtained from the system network parameters, and the injected harmonic current matrix Ih can be obtained by node measurement, PMU transfer or building a harmonic source model, and substitute into formula (4), then obtain each harmonic voltage of each node and node THD. The principle of APF compensation is to inject the harmonic currents of specific amplitude and phase into the nodes through the inverter to cancel the harmonic currents injected by the nonlinear load and the harmonic currents in the grid after the detection of the installation node, so as to improve the power quality. Equivalent to injecting a reverse harmonic current IAPF, at this time formula (4) can be modified as:

\[
U_k^h = \begin{bmatrix}
Z_{h1} & Z_{h2} & \cdots & Z_{hn}
\end{bmatrix}
= \begin{bmatrix}
1 & I_{i1} - I_{APF} & I_{i2} - I_{APF} & \cdots & I_{In} - I_{APF}
\end{bmatrix}
\]

(5)

Among them:

\[
I_{APFm} = \begin{cases}
I_{APFm} & \text{Harmonic current of APF injected at } m\text{-node} \\
0 & \text{No harmonic current of APF injected at } m\text{-node}
\end{cases}
\]

(6)

According to the modal analysis method, there is no coupling between the modal currents, and each harmonic current does not affect the independent compensation. Therefore, after determining the
compensation current value, the THD value of each node after compensation can be obtained according to formula (5).

3. HARMONIC PARTITION

3.1. Harmonic Compensation Partition Algorithm Design

In this paper, a genetic algorithm is used to solve the multi-objective model of distribution network harmonic compensation. The topology network is IEEE33 node topology as shown in Fig. 1, which contains 1 grid-connected node and 0 node, so the actual partition only calculates non-grid-connected nodes.

Because the traditional genetic algorithm coding method is extremely complex for multi-node topologies. So, for the node topology used in this paper, only 32-bit binary code segments can represent all possible partition results, and each bit with a value of 1 has a new interval, through the code segment can quickly count the number of partitions and the interval contains nodes number. For example, the initial binary code segment is:

$$x = 10000100000100000001000001000000_2$$

Then the data in TABLE I can be read out quickly:

| INTERVAL LABEL | NUMBER OF INTERVAL NODES |
|----------------|--------------------------|
| 1              | 5                        |
| 2              | 6                        |
| 3              | 9                        |
| 4              | 6                        |
| 5              | 6                        |

4. DESIGN OF ADAPTIVE GENETIC ALGORITHM FOR HARMONIC COMPENSATION OPTIMIZATION

For this type of discrete multi-constrained nonlinear integer programming problems, the traditional heuristic search algorithm has a complicated iteration process and a large amount of calculation, and it is difficult to iterate to the optimal solution.

In this paper, in the distribution network topology, aiming at the engineering application scenarios of multi-harmonic source and multi-node compensation, the algorithm is designed to optimize the configuration of harmonic compensation. On the premise of satisfying the power quality constraints, the minimum injection capacity of harmonic compensation current is taken as the compensation condition. For the n-node topology in this paper, it is necessary to compensate for the 5th, 7th, 11th, and 13th harmonics. In order to achieve the synchronization optimization of the compensation position and the compensation capacity, the individual is set to a 5-dimensional vector. The first dimension represents the installation and installation of APF. The 2nd-5th dimensions are expressed as the 5th, 7th, 11th, and 13th harmonic compensation currents, which are all set as complex numbers, including the amplitude and phase of the harmonic compensation current. That is:
Among them:
\[ \mathbf{x} = \begin{bmatrix}
I_1^0 & I_1^5 & I_1^7 & I_1^{11} & I_1^{13} \\
I_2^0 & I_2^5 & I_2^7 & I_2^{11} & I_2^{13} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
I_n^0 & I_n^5 & I_n^7 & I_n^{11} & I_n^{13}
\end{bmatrix} \]  

(8)

\[ I_m^h = \begin{cases} 
1 & \text{m node has APF} \\
0 & \text{m node has no APF}
\end{cases} \quad m = 1,2,3,\ldots,n \]  

(9)

\[ I_m^h = \begin{cases} 
I_m^h & \text{Harmonic current of APF injected at m-node} \\
0 & \text{No harmonic current of APF injected at m-node}
\end{cases} \quad h = 5,7,11,13 \quad m = 1,2,3,\ldots,n \]  

(10)

Based on the established APF mathematical model, the harmonic compensation partition model is established based on the partition idea. Through the improvement of traditional genetic operations and the introduction of natural explicit and recessive gene rules, adaptive genetic operations are used to optimize the APF configuration. The flow diagram is as shown in Fig.2.

5. Results & Discussion
The above algorithm is used to simulate the multi-harmonic source and multi-point compensation of IEEE33 node topology and verify the algorithm results.
The loads of nodes 16, 18, 29 and 30 are set as nonlinear loads, and all have 5, 7, 11, 13 harmonic current injection. First, the calculation results of the partition algorithm are shown in TABLE 2:

| INTERVAL LABEL | NUMBER OF INTERVAL NODES |
|----------------|--------------------------|
| 1              | 1, 2, 18, 19, 20, 21, 22, 23, 24 |
| 2              | 3, 4, 5, 25, 26, 27, 28, 29, 30, 31, 32 |
| 3              | 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 |

TABLE 2 RESULTS OF HARMONIC COMPENSATION

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First, compare it with the traditional genetic algorithm. Both algorithms use the same waste solution which does not meet and is far away from the power quality standard as the initial solution. The two algorithms are used to solve the topology respectively. The convergence process of the two algorithms is shown in the figure 3.

As can be seen from the above figure, compared with the traditional genetic algorithm GA, the new adaptive genetic algorithm IGADGA can not only converge to the optimal solution value faster, but also obtain a more accurate optimal solution value. TABLE III is the calculation results of the two algorithms, including the position of the compensation node, the total compensation capacity and the compensation amount of each harmonic current.

It can be seen from TABLE 3 and Fig.4 that the IGADGA algorithm configuration scheme is similar to the GA algorithm in compensation position and compensation capacity. Although the compensation capacity of IGADGA algorithm is only reduces by 1.17% compared with GA algorithm, the time required to calculate the 100 generation is only 1/3 of the GA algorithm, and the algebra near ±10% of the optimal solution is 30% earlier than GA. In general, the IGADGA algorithm only needs 23% of the calculation time of the GA algorithm to obtain the global optimal solution. The efficiency has increased by nearly five times.

| TABLE 3 COMPARE THE RESULTS OF GA AND IGADGA |
|---------------------------------------------|
| Total compensation harmonic current capacity (A) | Compensation node | 5th harmonic current compensation value (A) | 7th harmonic current compensation value (A) | 11th harmonic current compensation value (A) | 13th harmonic current compensation value (A) |
|---------------------------------------------|
| GA Algorithm                                | 33.3734           | 6.7742+0.0001i | 2.3226+1.2581i | 0.5484+0.0645i | 0.0645+0.2000i |
|                                              | 19                | 6.7742+0.0001i | 2.3226+1.2581i | 0.5484+0.0645i | 0.0645+0.2000i |
|                                              | 32                | 2.8065+0.3226i | 0.2903+0.3548i | 0.0012+0.1226i | 0.0012+0.1226i |
|                                              | 17                | 3.0837+0.7097i | 0.8387+0.7097i | 0.0068+0.0903i | 0.0068+0.0903i |
| IGADGA Algorithm                            | 33.0002           | 7.4194+1.2903i | 2.4194+1.4516i | 0.5161+0.9677i | 0.0065+0.1290i |
|                                              | 1                 | 7.4194+1.2903i | 2.4194+1.4516i | 0.5161+0.9677i | 0.0065+0.1290i |
|                                              | 32                | 2.9032+0.2903i | 0.9677+1i | 0.1161+0.0452i | 0.1161+0.0452i |
|                                              | 17                | 2.9032+0.2903i | 0.9677+1i | 0.1161+0.0452i | 0.1161+0.0452i |
In order to prove the accuracy of the proposed algorithm, the optimal APF configuration solution solved by the IGADGA algorithm was simulated and verified in MATLAB/SIMULINK, and the IEEE33 distribution network topology simulation was established. The harmonic source parameters and APF compensation parameters were consistent with the algorithm.

Compare each harmonic ratio of voltage and THD value of each node before and after compensation, as shown below:

Fig. 4. HRU of 5\textsuperscript{th} and 7\textsuperscript{th} harmonic before and after compensation

Fig. 5. HRU of 11\textsuperscript{th} and 13\textsuperscript{th} harmonic before and after compensation

Fig. 6. THD of node voltages before and after compensation

It can be seen from Fig.4 that the harmonics in the distribution network are mainly the 5th and 7th harmonics. For most nodes, the harmonic ratio of voltage of 5th and 7th harmonics after compensation is better than that before compensation, but the harmonic ratio of voltage after compensation is higher for a few nodes than before compensation. This is because the compensation method of APF injecting harmonic current may compensate for some nodes, there may be negative interaction effects, which will increase the harmonic ratio of voltage of other nodes, which conforms to the physical principle. At the same time, as can be seen from Fig.5, the 11th and 13th harmonic ratio of voltage before compensation are smaller. In order to obtain the minimum compensation capacity under the premise of ensuring that the THD value meets national standards, the harmonic ratio of voltage of 11th and 13th harmonics is increased due to the negative interaction effect, the harmonic content rate increases. In the global optimization, the compensation effect of 11th and 13th harmonics is sacrificed to seek the minimum compensation capacity under the THD value. It can be seen from Fig.6 that before the harmonic compensation, due to the influence of the nonlinear load injection harmonics, THD of most nodes exceeds the limit. After applying the harmonic compensation scheme solved by the IGADGA algorithm, all nodes meet the national power quality standard.

In practical engineering applications, targeted optimization configuration schemes can be formulated based on user needs and actual harmonic operating conditions of the distribution network. Modifying
each harmonic limit in the algorithm can achieve the requirements of harmonic targeted compensation configuration, so the algorithm has a good expansion ability.

6. CONCLUSION
In this paper, a new adaptive discrete genetic algorithm based on explicit and recessive gene rules is proposed for optimal configuration of harmonic compensation equipment in the distribution network. For the first time, the idea of partition compensation is applied to the field of harmonic compensation and adaptive improvement is made to effectively reduce the calculation complexity; and considering the effect of harmonic compensation under the influence of weak coupling between intervals, the calculation result is more accurate.

A new adaptive discrete genetic algorithm based on explicit and recessive gene rules is proposed. The example simulation of IEEE33 node and the algorithm results are compared. It proves that the algorithm proposed in this paper can quickly and accurately obtain the optimal configuration scheme for the discrete optimization configuration of harmonic compensation equipment in the distribution network.

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