Application of Distributed Power in Reactive Power Optimization of Distribution Network

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ABSTRACT

With the rapid development of new energy technologies, distributed power generation technology has attracted widely attention. The advantages of them are small investment, clean and environmental protection, reliable and flexible power supply. They can output (or absorb) continuously adjustable reactive power and participate in the reactive power optimization, which can keep the balance of reactive power and optimize the distribution of reactive power flow. In this paper, firstly, the power flow model of typical distributed power supplies: wind power, photovoltaic power and gas turbine power generation are researched. Then, the distributed power supply as a continuously adjustable reactive power device, combined with the traditional equipment, participate in reactive power optimization. An objective function considering system loss is proposed to find optimal solution. Finally, the IEEE33 node system is used to verification. Results show that the distributed power supply can effectively reduce the system loss and improve the voltage stability. Meanwhile, the effectiveness and feasibility of the improved algorithm are verified. The optimization of this paper is the improvement of genetic algorithm. It can make up for the lack of local optimization ability of genetic algorithm. Compared with the traditional genetic algorithm, the global optimization ability is greatly enhanced.

Keywords: distributed power generation, genetic algorithm, high-frequency mutation, equal-fold cloning.

INTRODUCTION

Distributed power supply has the advantages of modularity, energy conservation and environment protection [1-2]. Besides, they can balance the load on-spot, reduce the system loss and maintain system voltage. In addition, by adjusting the output of the reactive power to participate in the reactive power optimization of distribution network,

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distributed power supply can help reduce operating costs and improve operating efficiency [3]. At present, there are many objective functions for parallel network optimization of the distributed power supply, such as multi-objective function normalization weighting method and annual investment running cost fuzzy expected minimum method [4-5]. The optimization algorithms include internal point method, genetic algorithm, immune algorithm, particle swarm algorithm and so on [6]. In document [7], the non-linear mathematical model of the power system is introduced, which is based on the minimum weighted sum of the system loss, the out of limit value of node voltage and the amount of reactive power generation. The if-then rules to accelerate the convergence of genetic operation effect based on natural selection and genetic mechanism of genetic algorithm is introduced, however, the local search ability of the genetic algorithm is weak, thus it will lead to problems such as early maturity when iteration times are huge. Early maturity makes the algorithm difficult to meet the needs of the actual operation optimization. In this paper, the power flow model of wind power, photovoltaic power and micro gas turbine is established [8-10], then, this paper proposes an objective function basing on loss reduction. Meanwhile, the optimization problem is solved by using improved genetic algorithm. Aiming at the weak local search ability of algorithm, an improved genetic algorithm that introduces high-frequency mutation and equal-fold cloning is proposed. Finally, the IEEE33 node system is used to verification.

THE ESTABLISHMENT OF POWER FLOW MODEL

Gas Turbine Power Generator

There are two main structures of micro gas turbine generator system, one is the split shaft structure and the other is uniaxial structure. Split shaft micro gas turbine is directly connected to the power grid through a synchronous generator. In general, a synchronous generator with excitation regulation capacity is used as the interface, the excitation control adopted is controlled by voltage and power factor. Distributed power supply with voltage control can be used as a node in power flow calculation, and the distributed power supply with power factor control can be used as node. Therefore, the split shaft micro gas turbine can still be processed in the traditional way in the power flow calculation. In the powerlow iteration process, if the reactive power of node is out of limit, it should be converted to the corresponding node. If the node voltage is out of the limit in subsequent iterations, it should be re-transformed into a node. The single shaft micro gas turbine system speed is higher than the grid, so it is necessary to use a converter to convert the generator frequency to the power frequency before connected to the power grid. Network circuit diagram is shown in Figure 1 below:

![Micro Gas Turbine System’s Network Circuit Diagram](image)

Figure 1. Micro Gas Turbine System’s Network Circuit Diagram.
If the rectifier side uses diode uncontrolled rectifier, $K_s$, $K_{dc}$ are the equivalent coefficient of the AC part and the DC part; $\lambda_s$ is the current calculation coefficient; $I_s$ is the current amplitude of the rectifier; $I_{dc}$ is the current amplitude of the DC equivalent.

$$|I_s| = \left( \frac{K_s}{K_{dc}} \right) I_{dc}$$  \hspace{1cm} (1)

The power supply can be equivalent to the active power output and the power grid input current constant PI node. The corresponding reactive power can be calculated by the voltage, constant current amplitude and active power calculated by the previous iteration.

$$Q_{k+1} = \sqrt{P^2 \left( e_k^2 + f_k^2 \right) - P^2}$$  \hspace{1cm} (2)

Where: $\phi_{k+1}$ is the reactive power value of the $k+1$ time, $e_k$ and $f_k$ represent real and imaginary parts of distributed power supply for the kth iteration; $I$ is the amplitude of constant phase current injected into the power grid; $P$ is the constant active power value. Therefore, the value of reactive power injected into the $PI$ node can be calculated before each iteration, and the $PI$ node can be processed into $PQ$ nodes in the $k+1$ iteration.

**Wind Power Generator**

The doubly-fed power generation system is commonly seen in the wind power system. The equivalent node types are different in the power flow calculation due to different operation modes and control strategies. The steady-state equivalent circuit is shown in Figure 2. The parameters are explained as follows: $X_e$ represents for the excitation reactance, $X_s$ represents for the stator leakage reactance, $X_r$ is the rotor leakage reactance, $r_r$ is the rotor resistance, $r_s$ is the stator resistance, $r_{es}$ is the excitation resistance.

![Figure 2. The Steady-State Equivalent Circuit of Doubly-Fed Wind Generator.](image)

The total active power injected to the power system by the generator consists of two parts, one part is the active power generated by the stator winding, which can be obtained by the wind speed power characteristic. The other part is the active power generated or absorbed by the rotor winding, which is injected to the system when the rotating speed is higher than
the synchronous speed. When the speed is lower than the synchronous speed, the rotor winding absorbs the active power from the system. Reactive power also consists of two parts, one part emits or absorbs reactive power generator by the stator side, and the other part emits or absorbs reactive power from the rotor side. According to the different control modes, the doubly-fed power generation can be equivalent to different power nodes. The control modes are: controlled by constant power factor and controlled by constant voltage.

According to the equivalent circuit model of the double-fed wind motor, in the case of ignoring the stator winding resistance, the active power generated on the rotor winding is represented as equation (3):

\[
P_r = \frac{r_x x_s^2 (P_s^2 + Q_s^2)}{x_m^2 U_s^2} + \frac{2 r_x x_s}{x_m^2} Q_s - \frac{s P_r}{x_m^2} + \frac{r U_r^2}{x_m^2}
\]  
(3)

The total active power injected to the system:

\[
P_s = P_r + P_i = \frac{r_x x_s^2 (P_s^2 + Q_s^2)}{x_m^2 U_s^2} + \frac{2 r_x x_s}{x_m^2} Q_s + (1-s) P_i + \frac{r U_i^2}{x_m^2}
\]  
(4)

In the above formula, \(x = x_i + x_s\), \(P_i\) can be obtained by the wind speed power characteristic, and the slip ratio can be obtained by the speed control law of the double-fed wind turbine \(s = (\omega - \omega_0)/\omega_0\). In which \(\omega_0\) represents the synchronous speed of the generator, and it is generally a fixed value, \(\omega\) represents the rotor speed. When controlled by constant power factor, the reactive power of the stator windings is \(Q_s = P_r \tan \varphi\). Due to the small amount of active power transmitted by the converter, the reactive power emitted or absorbed by the converter is also small, and the reactive power of the wind turbine \(Q_e\) is approximately equal to \(Q_s\):

\[
Q_e = Q_s = P_r \tan \varphi
\]  
(5)

\[
P_r = P_i + P_s = \frac{r_x x_s^2 P_r^2}{x_m^2 U_r^2} (1 + \tan^2 \varphi) + \left(1 + \frac{2 r_x x_s \tan \varphi}{x_m^2} - s\right) P_i + \frac{r U_i^2}{x_m^2}
\]  
(6)

At this time, in the power flow calculation, the double-fed wind turbine controlled by constant power factor is equivalent to the \(PQ\) node.

When controlled by constant voltage, wind field node can be used as a node in power flow calculation, but due to the reactive power on stator side is affected by stator winding, rotor winding and the limitation of the maximum current of the converter, so various constraints should be considered.
Photovoltaic Power Generator

The photovoltaic power generation system is shown in Figure 3: $U_{pv}$ is DC voltage of the battery output; $m$ is the adjusting parameter of the inverter; $\varphi$ is the leading angle of inverter; $U_{ac}$ is the AC voltage output from the converter; $X_r$ represents for the transformer equivalent reactance; $U_s$ is the system bus voltage; $\delta$ and $\theta$ are the phase angles of voltage, and meets $\varphi = \delta - \theta$.

![Figure 3. Photovoltaic Power Generation System.](image)

The amplitude of $U_{ac}$ and $U_{pv}$ have the following relationship:

$$U_{ac} = mU_{pv}$$  \hspace{1cm} (7)

$$P = \frac{U_{ac}U_s}{X_r} \sin(\delta - \theta) = \frac{mU_{pv}U_s}{X_r} \sin \varphi$$  \hspace{1cm} (8)

$$Q = \frac{U_{ac}U_s \cos \varphi}{X_r} - \frac{U_s^2}{X_r} = \frac{mU_{pv}U_s \cos \varphi}{X_r} - \frac{U_s^2}{X_r}$$  \hspace{1cm} (9)

According to the above equations, the control of active power and reactive power of the photovoltaic power generation system are realized by controlling parameters $\varphi$ and $m$. Therefore, in power flow calculation, photovoltaic power generation system can be regarded as $PV$ node. Photovoltaic power station does not need to absorb reactive power from the system during normal operation. The lower limit value can be zero. If the reactive power of the grid node is out of limit, the node can be treated as $PQ$ a node, and the reactive power injected into the system is ether the upper limit or the lower limit of reactive power output.

**DISTRIBUTED POWER GRID OPTIMIZATION DESIGN**

**Mathematical Model**

Considering the losses, the scheme of reactive power optimization which includes DG is proposed and optimal solution is obtained through genetic algorithm and immune algorithm.
The specific mathematical models conclude objective function, constraint conditions, and evaluation index and so on.

The specific formula is shown below:

\[ f_A = P_{\text{loss}} + P_V + P_{TR} + P_{CP} + P_{DG} \]  

(10)

Constraint conditions are shown below:

\[
\begin{align*}
TR_{\text{min}} & \leq TR_i \leq TR_{\text{max}} \\
CP_{\text{min}} & \leq CP_i \leq CP_{\text{max}} \\
Q_{\text{min}} & \leq Q_i \leq Q_{\text{max}} \\
V_{\text{min}} & \leq V_i \leq V_{\text{max}}
\end{align*}
\]  

(11)

Where \( TR_i \) is the tap position of the transformer \( i \), \( CP_i \) is the group number of parallel capacitor \( i \), \( Q \) is the reactive power of the \( i \) th DG. Where \( P_{\text{loss}} \) represents the network loss value, and the remaining items are the penalty functions related to the constraint conditions. The subscripts correspond to each other without elaboration. The specific method of penalty function can be determined according to the actual project. This paper chooses to represent the product of the more limited times and the penalty factor. The value of the penalty factor can be determined according to the proportion of equipment invested in the actual project.

**Reactive Power Optimization Scheme**

Using the mutation of the gene in biology and the cross mutation of the chromosome, genetic algorithm can make devices participate in the reactive power optimization directly. It avoids the high requirement of derivability, continuity and so on of traditional optimization algorithm functions, and it is not necessary to iterate through all feasible solutions which means plenty time and space can be saved. By simulating the survival of the fittest in the evolutionary process, it retains a better solution after comparison, without setting explicit parameters, so that it can consciously search for better space. The probability of producing the optimal solution is increased multiply after the propagation of the optimal solution is multiplied, and the cost of time is greatly reduced. The disadvantage is that local search capability is weak. In this paper, on the basis of genetic algorithm combined with antibody affinity index of immune algorithm, the manipulation introduced which are based on immune algorithm mainly consider double cloning and high frequency mutation. In order to maintain the diversity of the population, the best individuals in each generation will be copied, then choose a few of them for high-frequency mutation. Avoid falling into the local optimum. Based on the specific process of genetic immune algorithm described above, the practical scheme of this paper is designed.
The reactive power devices researched in this paper have different types of variables, some are continuous and others are discrete. In order to unify the different variables, and make them easy to calculate, this paper used the binary method to encode variables. That is to say the output of continuous reactive power is divided into several parts. For example:

\[ Q_{DG} = \frac{n}{256} \times (Q_{min} - Q_{max}) + Q_{max} \]  

(12)

The method proposed in this paper can be realized by several steps: Firstly, establish an initial population collection with two times of the total number of the actual individual. Secondly, cross breed the first generation, the total number of the second generation is consistent with the actual number. The second generation is a group of upgraded individuals, compared with the direct application of the actual individuals, the amount remains the same but the search scopes, which makes it easier to find the optimal solution. Thirdly, cut half of the original population. Useless works will be done if the full size of the population is still being used in the following calculation procession, since the difference in evaluation between individuals is negligible.

Genetic operations in this paper put forward the concrete method of adjusting cross-exchange according to the total number of individuals. When the population is large, for example, which shows that there would still be a long period before optimal solution can be gained. This is the time that cross-exchange should be made in the unit of equipment to search the optimal solution in a wide range. When the population is small, which illustrates the difference between individual fitness values is small. The single point crossover and mutation method should be made to jump out of local optimum. The probability of cross mutation is set according to the actual situation of the calculation example. Meanwhile, considering double cloning and high frequency mutation, whose aims are maintain the diversity of the population and support the best individual will occurred in each generation. Avoid falling into the local optimum.

**CASE ANALYSIS**

This paper uses the node system IEEE33 to verify the feasibility of the proposed algorithm. The base power of the system is 10MW and the reference voltage is 12.66kV.

Combine the optimization algorithm proposed in this paper, on the basis of the other parameters remain the same, add one on-load voltage regulating transformer whose adjusting range is set to 0.9-1.1 (p.u.) in the node distribution system IEEE33. The tap adjusting range is +8, that is to say, the unit adjustment amount is 1.25%. In addition, add two with the ability of reactive power compensation, and both active outputs are 1MW, and the range of reactive output is within the range of -100-500kvar. Add two sets of parallel capacitors with respectively 4 and 7 groups, which means that the maximum reactive output can reach 600kvar and 1050kvar respectively. Put the on-load voltage regulating transformer between the source and node 1, then two distributed power supplies are added to node 2 and node 13 respectively. The parallel capacitor groups are added to access to node 6 and node 31 respectively. The node system after adding devices is shown as Figure 4:
To verify the feasibility of the reactive power optimization algorithm based on improved genetic algorithm, the example presented above is programmed and power flow is calculated. The calculated results are compared with those based on traditional genetic algorithm. To ensure the veracity of the comparison results, multiple calculations should be made. The comparison results are shown in Table 1.

Table 1. The Comparison Results of Optimization Algorithms.

<table>
<thead>
<tr>
<th></th>
<th>traditional</th>
<th>improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>genetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ratio</td>
<td>1.025</td>
<td>1.025</td>
</tr>
<tr>
<td>DG1 (kvar)</td>
<td>477.3</td>
<td>491</td>
</tr>
<tr>
<td>DG2 (kvar)</td>
<td>298.7</td>
<td>287</td>
</tr>
<tr>
<td>C1 (kvar)</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>C2 (kvar)</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>Loss (kw)</td>
<td>79.851</td>
<td>75.412</td>
</tr>
</tbody>
</table>

As is shown in Table 1, the veracity of genetic immune algorithm is verified by comparing the results from five experiments with those recorded from the traditional genetic algorithm since little differences can be seen in between.

In order to verify the algorithm can speed up the optimization. The calculated results are compared with the traditional genetic algorithm though run time and network loss. The results are shown in Table 2 and Table 3:
Table 2. The Results of Original Genetic Algorithm.

<table>
<thead>
<tr>
<th>Calculation order</th>
<th>traditional genetic algorithm</th>
<th>time(s)</th>
<th>loss (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>28</td>
<td>102.915</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>42</td>
<td>93.434</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>57</td>
<td>79.851</td>
</tr>
</tbody>
</table>

Table 3. The Results of Geneticimmune Algorithm.

<table>
<thead>
<tr>
<th>Calculation order</th>
<th>Improved genetic algorithm</th>
<th>time(s)</th>
<th>loss (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>18</td>
<td>102.305</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>32</td>
<td>89.279</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>41</td>
<td>76.285</td>
</tr>
</tbody>
</table>

By comparing the results of Table 2 and Table 3, it can be found that proposed algorithm consumes less time and reduces the system loss more effectively than the traditional one, if optimization proceeds to the same algebra.

CONCLUSION

A typical trend of distributed power supply model is built in this paper, regarded as a continuous adjustable reactive power device. The distributed power can optimize reactive power of the power grid combined with the traditional reactive power compensation equipment. Based on the objective function of network loss, the improved genetic algorithm enhances the global optimization ability. Finally using the IEEE33 node system for verification, the comparison results show that the participation of distributed power supply can effectively reduce the system network loss and improve the voltage stability, meanwhile, the feasibility and effectiveness of the improved algorithm is also verified.
REFERENCES