Optimization and control strategy of MCR reactive power allocation in urban power grid

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Abstract: Aiming at the defects of the traditional reactive power compensation method in the original system of urban power grid, such as large difference in compensation capacity and single form, a configuration optimization strategy based on MCR reactive power compensation device is proposed. The optimal compensation point is evaluated by using the comprehensive degree index of voltage stability, and the reactive power optimization mathematical model of power system is established. The optimal reactive power configuration is obtained by optimizing the parameters of the mathematical model combined with particle swarm optimization algorithm. Finally, the dynamic reactive power compensation for 220KV level regional node system is added, according to the proposed reactive power configuration optimization scheme, to conduct simulation experiments, and the results show that the proposed method is reasonable and effective.

1. Introduction

At present, switching shunt capacitor banks and reactor banks, which are widely used in urban power grid substations, have the defects that the capacity of solid resistance cannot be adjusted and the level difference is large, so they cannot adapt to the operation status and load changes of complex systems. Magnetic Control Reactor (MCR) can avoid the problem of limited compensation accuracy caused by stepwise switching and stepless smooth adjustment of reactive power capacity[1] compared with the traditional switching reactor compensation device. The reasonable allocation of compensation points and capacity of multiple MCR reactive power equipment has become an urgent problem to be solved. It uses voltage-reactive sensitivity to set compensation points in [2], but the loss reduction effect is not significant. Reference [3] uses local stability index to allocate reactive power, which cannot adapt to the dynamic changes of system load.

This paper proposes an optimization strategy of reactive power allocation of urban power grid system based on MCR reactive power compensation device. Using the comprehensive degree of voltage stability as the basis for MCR reactive power allocation candidate nodes, particle swarm optimization algorithm is used to optimize the reactive power of the calculation system with additional dynamic reactive power compensation. Combined with the simulation analysis of a 220KV regional nodes system in a city, it is proved that this reactive power allocation optimization scheme is reasonable and effective.

2. Reactive power configuration and optimization

2.1 Reactive power control mode

The fixed capacitor bank and MCR are combined in parallel to form MCR type SVC[4], and the total
reactive power output is the algebraic sum of capacitive reactive \( Q_C \) and MCR perceptual reactive \( Q_L \) of the fixed capacitor. Adjusting MCR thyristor trigger angle to control reactive power compensator output capacitive or inductive reactive power. The parallel MCR is continuously adjustable within the range of 0.5%~110% of rated capacity, and allows long-term stable operation in any capacity\(^5\). During the closed-loop operation of MCR, it can adjust the reactive capacity stepless according to the control target, with fast response speed and strong coordination and control ability. Another advantage is that the MCR has direct access to high voltage systems.

2.2 Compensation point configuration

In this paper, a voltage stability synthesis degree is proposed, which combines the voltage-reactive sensitivity index and local stability index \( L \) as the basis for candidate MCR compensation nodes.

2.2.1 Voltage-reactive sensitivity index

The singular value decomposition of the jacobian matrix of power flow is carried out to obtain the relation (1) of node voltage under the influence of reactive power changes. The condition of voltage stability is the left and right singular vector corresponding to the minimum singular value\(^3\).

\[
\begin{bmatrix}
\Delta \delta \\
\Delta U
\end{bmatrix} = \sum_{i=1}^{m} \lambda_i^{-1} r_i f_i^T \begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
\]  

Under normal working conditions, \( J \) is non-singular, \( \lambda_i = \lambda_{\text{min}} > 0 \). When the system reaches the limit of voltage stability, the corresponding state variable changes greatly, and the voltage fluctuates greatly with the slight change of reactive power. Take the left singular vector corresponding to the minimum singular value as equal to the power change of the system. That is \((\Delta P, \Delta Q)^T = r_m\), and it can be obtained

\[
\begin{bmatrix}
\Delta \delta \\
\Delta U
\end{bmatrix} = \lambda_{\text{min}}^{-1} r_m
\]  

The minimum singular value corresponds to the right singular vector as the node voltage - reactive sensitivity index. This index is a global stability index. According to the global voltage stability characteristics of the system, selecting the nodes with the most sensitive voltage change caused by reactive power change. Such weak nodes are greatly affected by reactive power changes and easily affect the global voltage stability.

2.2.2 Voltage stability index \( L \)

The relationship between voltage and current of a simple \( N \) nodes power system is

\[
\begin{bmatrix}
I_G \\
I_L
\end{bmatrix} = \begin{bmatrix}
Y_{GG} & Y_{GL} \\
Y_{LG} & Y_{LL}
\end{bmatrix} \begin{bmatrix}
U_G \\
U_L
\end{bmatrix}
\]  

Where, \( I_G \) and \( I_L \) are the current between the generator and the load nodes; \( U_G \) and \( U_L \) are the voltage between generator and load nodes. \( Y_{GG}, Y_{LG}, Y_{GL}, Y_{LL} \) are the admittance matrix elements of the system. The voltage of \( j (j \in T_l) \) of any load node is expressed as

\[
\hat{U}_j = \sum_{i \in G} z_{ji} \cdot i_i + \sum_{i \in L} f_{ji} \cdot \hat{U}_i
\]  

According to the ratio of no-load voltage \( U_{0j} \) to node voltage, the definition of local voltage stability index\(^4\) can be obtained as follows

\[
L_j = \left| 1 + \frac{U_{0j}}{U_j} \right|
\]  

Index \( L \) (0\( \leq L_j < 1 \)) can clearly reflect the distance between voltage stability and voltage instability. The greater the value is, the higher the probability of node voltage collapse will be. The index \( L \) reflects the influence degree of load nodes on system stability, and takes the local stability index of voltage stability into consideration.
2.2.3 Voltage stability synthesis
The choice of optimal compensation point should consider both economy and stability of the system. In the operation of the system, it is necessary to maintain the voltage stability of local nodes in a given range and the overall strong voltage stability level of the system. The following optimal compensation point \( F_i \) is described by combining the voltage stability index characteristics obtained by the index \( L \) and singular value decomposition method

\[
F_i = \alpha R_i + \beta L_i
\]

Where, \( \alpha \) and \( \beta \) are the corresponding proportions of global and local stability indexes respectively, and \( R_i \) represents the voltage stability index value obtained by singular value decomposition. The optimal reactive power compensation point constraint conditions are as follows

\[
\begin{align*}
\max_{x \in A} & \quad F_i \quad \text{Compensations}(x) \leq N \\
\alpha + \beta &= 1
\end{align*}
\]

Where, \( A \) is the set of candidate nodes; \( x \) is the best compensation point; \( N \) is the given number of reactive power compensation points. The \( \alpha \) and \( \beta \) are the corresponding weights when considering different global stability characteristics and local stability characteristics. In this paper, the voltage stability synthesis degree identifies the most susceptible nodes and the most susceptible nodes in the system, and the MCR configuration point is selected through constraint conditions, which can effectively reduce voltage deviation and improve the effect of reactive power compensation.

2.3 Mathematical model of reactive power optimization
In this paper, active power network loss is taken as the main objective of power system optimization. The calculation formula of active grid loss \( P_{\text{loss}} \) is as follows

\[
\min P_{\text{loss}} = \min \sum_{i=1}^{N_G} G_{k}(i,j)\left[v_i^2 + v_j^2 - 2v_i v_j \cos(\theta_i - \theta_j)\right]
\]

Where, \( N_G \) is the number of system branches, \( N_D \) is the number of system nodes, \( G_{k}(i,j) \) is the conductance between node \( i \) and \( j \), \( \theta_i \) and \( \theta_j \) are the phase angle of node \( i \) and \( j \), \( v_i \) and \( v_j \) are the voltage amplitude of node \( i \) and \( j \). Equality constraints are established according to tidal current

\[
\begin{align*}
P_{G_i} - P_{D_i} &= V_i \sum_{j=1}^{N_D} V_j (G_{i,j} \cos \theta_j + B_{i,j} \sin \theta_j) \\
Q_{G_i} - Q_{D_i} &= V_i \sum_{j=1}^{N_D} V_j (G_{i,j} \cos \theta_j - B_{i,j} \sin \theta_j)
\end{align*}
\]

Where \( P_{G_i} \) and \( P_{D_i} \) are the active power of generator nodes and load nodes, \( Q_{G_i} \) and \( Q_{D_i} \) are the reactive power of generator nodes and load nodes. \( Q_{C_i} \) is node reactive compensation capacity; \( B_{i,j} \) is the susceptance between node \( i \) and \( j \). The control variables are generator voltage and compensation capacity, and the state variables are generator reactive output and node voltage, which are limited within a reasonable range.

2.4 Optimization algorithm
In order to give full play to the advantages of stepless regulation capacity of MCR reactive power compensation device, this paper combined with particle swarm optimization to optimize the system reactive power, and took the reactive power compensation capacity of MCR type SVC as the continuous control variable.

Particle Swarm Optimization Algorithm (PSO) is based on the basic idea of updating its position and speed with the current optimal particles in the Swarm, and finding the optimal solution in the search space through iteration. Particle update of standard particle swarm optimization algorithm is carried out according to the following formula
\[
\begin{align*}
    v_y(t+1) &= \omega v_y(t) + c_1 r_1(t) [p_y(t) - x_y(t)] + c_2 r_2(t) [p_y(t) - x_y(t)] , \quad v_y \in [-v_{\text{max}}, v_{\text{max}}] \\
    x_y(t+1) &= x_y(t) + v_y(t) , \quad x_y \in [-x_{\text{max}}, x_{\text{max}}]
\end{align*}
\] (10)

Where \(i\) represents the \(i\)th particle. The \(j\) is the dimension of the particle. The \(t\) is the number of iterations. The \(c_1\) and \(c_2\) are learning factors, usually ranging from 0 to 2. The \(r_1\) and \(r_2\) are independent random functions distributed between 0 and 1. The \(v_{\text{max}}\) is the maximum particle velocity. The \(x_{\text{max}}\) is the maximum particle position. The \(\omega\) is the inertia weight, indicating the change amplitude of the particle's updating speed and position following the search process.

3. Example analysis

In this paper, a partition system with a voltage level of 220KV in a city is taken as an example to study. The system has 70 nodes and 110 branches, including 14 generator nodes and 56 load nodes. The node voltage reference is 220KV, the voltage amplitude scale is 1.0 (p.u.), and the reference power is 100MVA. The upper and lower limits of node voltage are 0.94-1.06 (p.u.). The capacity of MCR type SVC added is continuously adjustable. The lower limit and upper limit of single unit capacity are set as -40Mvar and 40Mvar.

![System grid diagram considering voltage stability synthesis](image1)

**Figure 1.** System grid diagram considering voltage stability synthesis

![Voltage stability synthesis analysis](image2)

**Figure 2.** Voltage stability synthesis analysis
MCR compensation configuration points are determined by comprehensive degree of voltage stability, comprehensive degree under the different proportion of $\alpha$ and $\beta$, as shown in figure 2, compensation point candidates set $A = \{21, 24, 25, 26, 27, 38, 40, 51, 53, 56, 68, 69\}$. Analyzing available information from figure 2, the overall power system voltage stability index is relatively high, while the index $L$ of each load node of the system is relatively low, indicating that the node load level is relatively balanced. The candidate compensation nodes choose the voltage stability synthesis with $\alpha = 0.3$ and $\beta = 0.7$.

In this paper, the amount to be compensated $N=8$ is selected for analysis and study, and different configuration schemes are compared to illustrate the compensation effect. **Scheme 1**: No dynamic reactive power compensation is added; **Scheme 2**: Add MCR to the node with the maximum voltage-reactive sensitivity index; **Scheme 3**: Add MCR to the node with the largest index; **Scheme 4**: Add MCR to the node of voltage stability synthesis candidate. Table 1 shows the comparison of active power network loss and configured capacity of different compensation schemes.

| Scheme | $P_{loss}$ (MW) | The nodes of adding MCR | Configured total capacity (Mvar) |
|--------|----------------|-------------------------|---------------------------------|
| Scheme 1 | 133.2908 | -- | 0 |
| Scheme 2 | 120.4576 | 24/25/26/27/38/40/62/69 | 248.5371 |
| Scheme 3 | 123.5271 | 30/38/43/44/46/56/67/68 | 256.3427 |
| Scheme 4 | 117.1358 | 21/24/26/27/38/51/53/68 | 222.8245 |

From table 1, this paper describes scheme 4, which indicates MCR configuration optimization method reactive optimal effect, active network loss reduces about 12.1%. From the comparison of different compensation capacities and compensation nodes, it is concluded that only using local voltage stability index $L$ for reactive power allocation can not achieve the optimal reduction effect of active power network loss. Moreover, the optimal configuration effect is not achieved in scheme 2, which indicates that there are limitations in analyzing reactive power configuration from a single index. It is more effective to consider the two index characteristics comprehensively for the whole system with voltage deviation and loss reduction.

Figure 3 shows the voltage comparison of key nodes under different schemes. Compared with no dynamic compensation in scheme 1, dynamic reactive power compensation of MCR in scheme 4 can effectively reduce the voltage deviation of nodes. In Figure 3, the voltage deviation before and after the addition of MCR at the key nodes has an obvious comparative effect. Node 65 reduces about 0.0002 p.u. after the addition of MCR. Increasing dynamic compensation can effectively reduce the voltage deviation of nodes.
deviation.

Figure 4 respectively shows the influence of different configuration schemes on node voltage and the comparison of active power network loss under the load power growth mode. According to the figure analysis, under large load, the optimal compensation point selected by the method proposed in this paper can effectively increase the node voltage stability. When the node is not close to the transmission power limit, the system can optimize the reactive power output of the compensation node to achieve the optimal loss reduction effect.

![Figure 4. Comparison of different schemes under load growth](image)

### 4. Conclusion

Aiming at the defects of the existing reactive power compensation method in the urban power grid system, this paper puts forward a reactive power allocation optimization scheme based on MCR reactive power compensation device, which is based on voltage stability synthesis to configure MCR. Compared with a unitary voltage stability index, the described scheme can comprehensively evaluate the static characteristics of the system, obtain a better compensation effect, and combine the particle swarm algorithm to optimize the configuration of reactive power. The simulation results show that this method can effectively reduce the active power loss of the system, improve the voltage stability of the system nodes, and provide theoretical guidance for the practical application of MCR into the actual power grid system.

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