Reactive Power Compensation Method Considering Minimum Effective Reactive Power Reserve

Gong Yiyu, Zhang Kai, Zhang Pu, Li Xuenan, Zuo Xianghong, Jiao Zhen and Teng Sudan
Beijing Power Economic Research Institute, Beijing Electric Power Corporation, Beijing, China
gracegong2008@163.com

Abstract. According to the calculation model of minimum generator reactive power reserve of power system voltage stability under the premise of the guarantee, the reactive power management system with reactive power compensation combined generator, the formation of a multi-objective optimization problem, propose a reactive power reserve is considered the minimum generator reactive power compensation optimization method. This method through the improvement of the objective function and constraint conditions, when the system load growth, relying solely on reactive power generation system can not meet the requirement of safe operation, increase the reactive power reserve to solve the problem of minimum generator reactive power compensation in the case of load node.

1. Introduction
With the rapid development of China's society and economy, the rapid growth of power load, power supply distance increases at the peak load to the maximum active power transmission, the transmission capacity of existing network close to the limit, the rise of voltage collapse and the development of the whole network of the possibility of accidents. Therefore, in order to improve the transmission capacity and voltage stability of the system, it is very important to optimize the reactive power distribution of the system[1].

The problem of voltage stability is essentially a power problem, and the local reactive power shortage is the root cause of voltage instability. In general, after the power system fault, the voltage level is decreased, the reactive power output decreases, and the reactive power loss increases, which leads to the reactive power gap. If there is not enough reactive power reserve in the system, the voltage instability will occur[2-7].

Power system reactive power balance is a necessary condition to ensure the voltage stability of power system, reactive power optimization can make full use of reactive power supply system, reasonable selection of reactive power compensation and compensation capacity, improve voltage quality, reduce network losses and improve voltage stability. By controlling the adjustable voltage generator, the variable capacitor and the load voltage regulating transformer[8-11].

2. Combined generator reactive power reserve and reactive power compensation
The reactive power source power system mainly includes synchronous generator, condenser, SVC/STATCOM and parallel capacitor, which has 3 continuous and dynamic voltage / reactive power control, reactive power demand is available to meet the system state or load caused by the change of
the latter, the discrete control mode, adjust the speed is usually slower mainly, in order to satisfy the demand of reactive power caused by the slow change. Considering the regulation of several compensation methods ability, adjust difference in speed and cost control, reasonable operation system and reactive power compensation control strategy, helps to ensure the voltage quality of the system at the same time, improve the economy of system operation.

Generator is an important method of power network voltage / reactive power control, and the control cost is low, so it should first use the dynamic voltage / reactive power control of the generator, and give full play to the function of the generator reactive power reserve. In this paper, the authors analyze the composition of reactive power reserves in the ground state load (λ=1) of the IEEE 9 node system in [1].

When the system load increases, reactive power output of generator gradually close to the ceiling, as shown in Figure 1, when λ = 1.35, if the reactive power reaches the upper limit line 6-9 fault generator G1, if the system load reaches 1.36, the system will only depend on the reactive power generation system can not meet the N-1 security constraints, the need to to meet the requirements of the system by adding the reactive power compensation.

![Figure 1. Composition of reactive power reserve of generators](image)

In the above example also shows that the generator of reactive power, can guide us to add reactive power compensation. It is required that the reactive power of the generator is affected by the operation mode, the load level and the fault set. Therefore, the control and configuration of reactive power compensation is uncertain.

In order to maintain the power grid in a reasonable voltage level, to meet the conditions of N-1 security constraints, to determine the minimum effective reactive power reserve and the optimal installation capacity of reactive power compensation equipment. And because the electrical distance is relatively close to the generator with a certain mutual support capacity, it is necessary to determine the minimum effective reactive power reserve in the system.

3. Reactive power compensation model based on minimum generator effective reactive power reserve

This paper focuses on the problem of the compensation point and the minimum installation capacity of the reactive power compensation of the computing system, which is based on the single power generator's reactive power reserve. Therefore, considering the minimum effective reactive power reserve of generators reactive power compensation problem can be described as follows: the structure parameters, the load of the power system and in equilibrium other active power active power output under the given conditions, the minimum effective reactive power reserve of generators and the amount of reactive power compensation as the goal, in the maintenance of power grid in a voltage a reasonable level and ensure the static voltage stability conditions, determine the optimal installation capacity of reactive compensation equipment.
Because in the actual operation, it is usually not meet the requirements of the system to provide the reactive power output. Therefore, the reactive power reserve in the rational planning of generator at the same time, it should be reasonable optimization of reactive power compensation and compensation capacity, to ensure the safe and economic operation is considered the minimum effective reactive power reserve model for reactive power compensation:

\[ f(\chi) = -C_i(Q^+_{ri}, Q^-_{ri}) + \mu C_2(Q_c) \]  

(1)

In the formula, \( C_i(\bullet) \) indicates that the reactive power reserve of generator is invalid; the \( C_2(\bullet) \) indicates that the reactive power compensation is added; the \( \mu \) expresses the correction factor, and the reactive power compensation is adjusted by adjusting the \( \mu \) value.

Calculation formula of generator reactive power reserve

\[ C_i(Q^+_{ri}, Q^-_{ri}) = \sum_{j \in S_i} w_j (Q^+_{ri} + Q^-_{ri}) \]  

(2)

Among them, SR said the reactive power set; \( Q^+_{ri} \) and \( Q^-_{ri} \) are respectively the forward and reverse generator reactive power reserve is invalid; \( wi \) generator reactive power reserve weight \( i \) is invalid, the lack of relevant information, the generator weight simply set to 1, to characterize the generator reactive power reserve has the same importance in the master system; features, can be set smaller important generator \( wi \) to reduce the amount of invalid reactive power reserve generator, thereby increasing the utilization rate of the reactive power reserve.

By maximizing the total generator reactive power reserve, the system can minimize the total effective reactive power reserve of the system in various operating conditions. If the system does not meet the requirements of the reactive power reserve, the security of the system operation will not be guaranteed, and the reactive power compensation.

Calculation formula of system reactive power compensation

\[ C_z(Q_c) = \sum_{i \in S_z} Q_{ci} \]  

(3)

In the formula, \( Q_{ci} \) indicates the reactive power compensation of node \( i \). When the reactive power reserve of the system can not meet the requirements, we can add reactive power compensation at any node to meet the need of the system voltage stability[8].

Meet the constraints of power flow equation under different operating conditions:

\[ p^i_{gi} - \hat{ \chi }^i p^i_{gi} - V^i \sum_j v^i_j (G^i_{ij} \cos \delta^i_{ij} + B^i_{ij} \sin \delta^i_{ij}) = 0 \quad j \in S_B \]  

(4)

\[ q^i_{gi} + \hat{ \chi }^i q^i_{gi} - V^i \sum_j v^i_j (G^i_{ij} \sin \delta^i_{ij} - B^i_{ij} \cos \delta^i_{ij}) = 0 \quad j \in S_B \]  

(5)

SB is a set of nodes; PGi is the active power output of generator reactive power output i; QRi generator; PLi is the active load node of I, QLi is a reactive load node i; \( Vi \) and \( \delta i \) are respectively the I node voltage amplitude and phase angle; Gi+jBij admittance i-j. \( Q_{ci} \) indicates reactive power compensation of node \( i \).

Inequality constraints are the upper and lower bounds of the node voltage, the limit of generator reactive power output and the limit of compensation capacity. Among them, the reactive power output of the generator is in the range of effective reactive power reserve.

\[ V^i_k \leq V^i_k \leq \bar{V}^i_k \quad i \in S_B \]  

(6)

\[ Q_{ni}^{-} + Q_{ni}^{+} \leq Q_{ni}^{-} \leq \bar{Q}_{ni} + Q_{ni}^{+} \quad i \in S_R \]  

(7)

\[ Q_{ni}^{-} > 0, \quad Q_{ni}^{+} > 0 \quad i \in S_R \]  

(8)

\[ 0 < Q_{ci} < M \]  

(9)
In the variable name, superscript k is used to represent the running state k, whose value is traversed by the normal running state and all the expected fault running state. M indicates the limit of reactive power compensation capacity. When the system is unable to meet the requirements of its reactive power reserve, we can add reactive power compensation at any node to meet the need of system voltage stability. But the model does not consider the regulation of the transformer tap.

3.1. Reactive power compensation based on minimal generator effective reactive power reserve

Because in the actual operation, it is usually not meet the requirements of the system to provide the reactive power output. Therefore, the reactive power reserve in the rational planning of generator at the same time, it should be reasonable optimization of reactive power compensation and compensation capacity, to ensure the safe and economic operation is considered the minimum effective reactive power reserve model for reactive power compensation:

$$\max \left( \sum_{i \in S} w_i \left( Q_{+}^{i} - Q_{-}^{i} \right) - \mu \sum_{i \in C} Q_{Ci} \right)$$

s.t.:

$$P_{G}^{k} - X^k P_{Li}^{k} - V_{i}^{k} \sum_{j} V_{j}^{k} \left( G_{ij}^{k} \cos \delta_{ij}^{k} + B_{ij}^{k} \sin \delta_{ij}^{k} \right) = 0 \quad i \in S_{k}$$

$$Q_{Gi}^{k} - X^k Q_{Li}^{k} - V_{i}^{k} \sum_{j} V_{j}^{k} \left( \delta_{ij}^{k} \sin \delta_{ij}^{k} - R_{ij}^{k} \cos \delta_{ij}^{k} \right) = 0 \quad i \in S_{k}$$

$$V_{i}^{k} \leq V_{i}^{\max} \quad i \in S_{k}$$

$$Q_{ri}^{k} \leq Q_{ri}^{\max} \leq Q_{ri}^{k} - Q_{ri}^{\max} \quad i \in S_{k}$$

$$Q_{ri}^{k} > 0 \quad Q_{ri}^{\max} > 0 \quad i \in S_{k}$$

$$0 < Q_{Ci} < M$$

In the model, we add the limit of reactive power compensation capacity. When the system is unable to meet the requirement, we can add reactive power compensation to meet the need of voltage stability of the system. But the model does not consider the regulation of the transformer tap.

4. Example analysis

This section takes the IEEE 39 node system as an example, the system has 10 generators, 12 transformers and 34 transmission lines, example analysis doesn’t take the line or transformer fault which could splitting the system into consideration.

4.1. Minimum effective reactive power reserve of generator under ground state

The node voltage limits were 0.92 and 1.08, the generator reactive power reserve of equal weight is invalid, the system load remains the ground state (lambda from 1), from the optimization model can obtain minimum generator system for effective reactive power reserve.

| Table 1. The reactive power output of each generator under the effective reactive power reserve |

|    | V0 | Q0 | Q0max | Line | Q0min | Line |
|----|----|----|-------|------|-------|------|
| Q10| 1.0048 | -0.5766 | -0.1214 | 26-27 | -0.6000 | 2-3 |
| Q11| 1.0800 | 4.1042 | 4.4850 | 15-16 | 3.7600 | 4-5 |
| Q12| 1.0509 | 2.9310 | 3.4867 | 15-16 | 2.5852 | 10-13 |
| Q13| 1.0123 | 9.9444 | 2.1400 | 26-27 | 1.8462 | 15-16 |
| Q14| 1.0295 | 1.3607 | 1.4494 | 26-27 | 1.3161 | 15-16 |
| Q15| 1.0394 | 1.2708 | 1.8609 | 23-24 | 1.1552 | 16-24 |
| Q16| 1.0612 | 0.7907 | 1.1765 | 16-21 | 0.5694 | 16-24 |
| Q17| 1.0358 | 0.4711 | 0.9414 | 2-3 | 0.2277 | 26-27 |
| Q18| 1.0122 | -0.0617 | 0.9930 | 28-29 | -0.3308 | 26-27 |
| Q19| 1.0251 | -0.0021 | 0.4295 | 6-7 | -0.1176 | 4-5 |
Table 1 shows the maximum and minimum values of the voltage and reactive power output, fault state reactive power output, and the corresponding fault line at the normal state machine end voltage and reactive power output of each generator. From the table can be seen, the generator G31 of the terminal voltage to reach the limit of 1.08, and the line 26-27 is still affecting the generator reactive power output of one of the key failure, when it is disconnected, the output of multiple generators to reach the maximum / minimum value.

**Figure 2.** The composition of reactive power reserve under the effective reactive power reserve of the ground state minimum generator

Figure 2 shows that the system has a minimum generator effective reactive power reserve, the reactive power reserve of each generator. The change of reactive power of generator is significantly reduced. At this time, the total effective reactive power reserve is 4.608, which is 41.08% less than the original 7.821. The total reverse effective reactive power reserve is 1.82, which is 40.1% lower than the original 3.04. This shows that by adjusting the generator terminal voltage, the system can ensure the safety of the same fault set only by about 60% of the original effective reactive power reserve.

Terminal voltage is the reactive power compensation of reactive power compensation and no corresponding generator terminal voltage of the generator can be seen, most of the least effective reactive power reserve of generators under the state had increased, the terminal voltage of the generator G32 the biggest change, from the original 0.983 increased to 1.0509, accordingly, its normal state the power output is greatly increased. Machine terminal voltage of the generator has 3, that is, G35, G36 and G38, the common feature is that there is a key line, the line after the fault, the electrical distance between the generator and the main body of the system is greatly increased. The terminal voltage of generator G38 decreased most significantly is precisely in line 26-27 fault, to end the generator long chain transmission system. Electrical distance significantly more drastic changes caused by the mutation of reactive power output of generator reactive power output, so the algorithm tends to decrease its normal state, which reduces the voltage of the machine, in order to reduce the fault related reactive power output of the impact. The sum of G38 forward and reverse effective reactive power reserve is reduced after optimization.

### 4.2. Considering the additional compensation device, the minimum effective reactive power reserve

When $\lambda = 1.35$, the IEEE39 node system can not meet the N-1 security constraints without adding reactive power compensation, so the reactive power compensation is added in the model. After the particle swarm optimization, the node 12 is selected as the compensation point, the compensation capacity is 0.0666, and the state of the generator after compensation is shown in table 2.

**Table 2.** The reactive power output of each generator under the effective reactive power reserve ($\lambda = 1.35$)

| Line | $V_0$ | $Q_0$ | $Q^\text{max}$ | $Q^\text{min}$ |
|------|------|------|----------------|---------------|
| 26-27 | 1.0434 | 1.1102 | 1.8276 | 0.3307 |
| 15-16 | 1.0800 | 5.7467 | 6.5724 | 5.3735 |

4.2. Considering the additional compensation device, the minimum effective reactive power reserve

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Table 2 shows that under this condition, the maximum and minimum values of reactive power output, fault state reactive power output, and the corresponding fault line. The table shows, has a great influence on line 15-16 and 26-27 fault, the reason is that: the line 15-16 and 26-27 as the contact line of two regions, when it is opened, will reduce the relevant regions, which leads to the reactive power fluctuated substantially related to the generator.

Figure 3. Minimum effective reactive power reserve of the generator under the addition of reactive power compensation after reactive power reserve (λ=1.35)

Figure 3 is the composition of the generator reactive power reserve when the load is 1.35. The G32 and G34 generator generator positive effective reactive power reserve has zero voltage generator can play a supporting role has tended to limit the distance from the generator G33 and generator G34 is close, there is still an invalid reactive power reserve. And the system chooses to carry out reactive power compensation in node 12, in order to prevent the system crash caused by the shortage of generator G32 reactive power output.

4.3. Effect of load level on reactive power compensation capacity

Table 3 is the compensation point of different load factor and the compensation capacity, because node 12 reactive power generator is mainly composed of G32 supply, and the existing state of generator reactive power reserve of G32, so the choice of reactive power compensation in node 12, to reduce the reactive power demand of generator G32 in node 15; the two region of the contact line, the distance of each generator electrical distance is far, select the compensation in node 15, can shorten the generator to node 15 and near node load reactive power transmission distance to local compensation effectively.

| Load factor | Compensating node | Compensation capacity |
|-------------|-------------------|----------------------|
| λ=1.35      | 12                | 0.0666               |
|             | 4                 | 0.0527               |
|             | 15                | 0.4538               |
|             | 11                | 0.4641               |
|             | 15                | 0.4541               |
|             | 8                 | 0.3367               |
|             | 12                | 0.9351               |
|             | 14                | 0.9716               |
5. Conclusion
In this paper, a multi-objective optimization model is established by combining the optimization of reactive power compensation and the optimization of reactive power reserve. In the priority of the generator reactive power reserve, if still can not meet the system requirements, to take additional reactive power compensation method to meet the system safety requirements.

6. References
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