Analysis of Reactive Power Demand Based on Voltage-Reactive Power Correlation

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Abstract. The inaccuracy of reactive power demand analysis in practical power system often leads to the problem of low voltage stability margin. In this paper, the analysis method of voltage-reactive power correlation is proposed, which is used to solve the inaccuracy of reactive power demand analysis. The proposed method can quickly analyze the reactive power demand of each region only according to the voltage stability margin index. The local reactive power compensation and the input reactive power on the system side are considered in the derivation of the voltage stability margin. Therefore, the proposed method accords with the practice of power system. The effectiveness of the proposed method is proved by a simple system.

1. Introduction

The normal operation of the power system will be affected by various kinds of uncertain disturbances. These effects include the changes of system operation parameters, load level and network topology. The use of new energy sources and new technologies has also had a great impact on the stability characteristics of power systems [1-2].

The research object of voltage stability characteristic is the system which can recover to normal operation state through its own regulation ability after being subjected to small disturbance [3]. The primary purpose of voltage stability research is to analyze the cause, mode, dominant factors of voltage instability and the relationship between voltage instability and other types of instability (angle instability, frequency instability, etc.) [4-5]. Take the shunt capacitor as an example, in the actual operation of power grid, dispatchers generally believe that the shunt capacitor will increase the local reactive power support, and then improve the node voltage, which is ultimately conducive to the improvement of voltage stability level [6-7]. However, the effect of reactive power compensation on the stability is not only considering the local factors, but also considering the impact on the global stability. For those dynamic process changes of voltage stability, the idea of linearization equivalence is often used [8].

In the actual power system operation, the reactive power situation in each region is the key factor to affect the voltage stability level [9]. The mechanism of voltage instability associated with reactive power exceeding the limit is often related to the system transmission power reaching the limit power [10]. Therefore, when analyzing the stability characteristics of the actual power system, it is necessary to establish a characteristic analysis model which is in line with the actual operation of the system, and obtain the index to judge the voltage stability level of each region [11-13]. In order to improve the voltage stability of the whole power grid, the voltage stability margin can be improved by...
the practical strategy [14]. Therefore, it is necessary to study the relationship between voltage and reactive power [15-16].

This paper uses local information to quickly evaluate the reactive power compensation demand of each node. The proposed method only needs to obtain the nodal voltage variation ratio at the load side, the reactive power change ratio consumed by the load side and the reactive power change ratio transmitted to the load side by the system side, and then the reactive power demand of each node can be obtained. The method of obtaining the reactive power compensation demand of the voltage-reactive power correlation change is to study the relationship between the local reactive power compensation and the system input reactive power compensation, so as to obtain the reactive power demand in the region. The application of this method to guide the switching of reactive power equipment in the actual power system operation and to guide the power network planning and operation, can be more in-depth understanding of the characteristics of the power system.

2. Voltage-reactive Power correlation

2.1 The necessity of studying the relationship between Voltage and reactive Power

The correlation between voltage and reactive power shows that the voltage stability margin is determined by the equivalent impedance of the system side and the equivalent impedance of the load side. Assuming that the equivalent impedance of the system side is constant, the magnitude of the equivalent impedance of the load side determines the voltage stability margin value of the node. When the load power changes slightly, the relationship between load power and voltage stability level is shown. The model of the knowable transmission line is shown in figure 1.

\[
\begin{align*}
\frac{P_i+jQ_i}{V_i} & \quad \frac{G_j-jB_j}{2} \quad \frac{P_j+jQ_j}{V_j} \\
& \quad \frac{B_j}{2} \quad \frac{B_j}{2} \quad \frac{L_j}{2} \quad \frac{B_j}{2}
\end{align*}
\]

**Figure.1** The model of the knowable transmission line

In order to give the analysis results intuitively and succinctly, it is assumed that the influence of the changes of parallel reactive power on the load side on other parameters can be ignored. Other things being equal, the equivalent impedance of the load side in the figure is expressed as follows.

\[
Z_{d,j} = V_j^2 / (P_D + j \left( \frac{B_j}{2} \cdot V_j^2 - Q_D \right)) \quad (1)
\]

When the system side equivalent impedance is constant, it is easy to see from the above formula that when the load consumes reactive power, the increase of reactive power compensation will make the load side equivalent impedance mode increase. The voltage stability margin of the node will be improved. The voltage stability margin can be improved by adding reactive power compensation to the node. On the other hand, for the reverse reactive power load, the increase of reactive power compensation will reduce the equivalent impedance modulus of the load side, and then reduce the voltage stability margin of the node. It can be seen that the reactive power compensation demand in each region is closely related to the operating state, and changes with the operating state changes. The system side equivalent impedance is not constant. In order to quickly and accurately assess the reactive power compensation demand in various regions, it is necessary to further analyze the correlation between voltage and reactive power.

2.2 Derivation of the correlation between Voltage and reactive Power

In this section, based on the improved dynamic equivalence analysis, a new method of reactive power compensation demand assessment based on the correlation between voltage and reactive power is proposed.

The parameter relationship in figure 1 satisfies the following formula.
Where $B_{cc}$ is the shunt capacitance, $B_c$ is the line charging capacitance, $B_{ij}$ is the line admittance.

Formula 2 can be written in the form of Formula 3.

$$B_{ij}^2 \cdot V_j^2 - 2B_{ij} \cdot V_j \cdot V_i + \left( \frac{B_c + B_{cc}}{2} + B_{ij} \right) V_j^2 - Q_D + Q_{ij} = 0 \quad (3)$$

The following is the condition that formula 3 is solvable.

$$B_{ij}^2 \cdot V_j^2 - \left( \frac{B_c + B_{cc}}{2} + B_{ij} \right) \cdot V_j^2 \geq Q_{ij} \quad (4)$$

And

$$\frac{B_{ij}^2}{2} \cdot V_j^2 + Q_D - \left( \frac{B_c + B_{cc}}{2} + B_{ij} \right) \cdot V_j^2 \geq Q_{ij} \quad (5)$$

Then the following formula can be derived.

$$- \frac{B_c^2 + 4B_c B_{ij}}{2B_c + 4B_{ij}} V_j^2 - B_{cc} V_j^2 + Q_D \geq Q_{ij} \quad (6)$$

Where:

$$K_1 = \frac{B_c^2 + 4B_c B_{ij}}{2B_c + 4B_{ij}} \quad (7)$$

$$K_2 = B_{cc}$$

Assuming that the margin is a substitution of $K_3$ into the upper equation, the following form can be obtained.

$$-(K_1 + K_2) V_j^2 + Q_D = Q_{ij} + K_3 \quad (8)$$

Consider that the critical stability margin is zero, so $K_3$ is equal to zero.

$$-(K_1 + K_2) V_j^2 + Q_D = Q_{ij} \quad (9)$$

If the disturbance causes the node voltage to drop, the $V_j$ becomes the original A times ($0 < A < 1$). The reactive power consumed by the load is changed to the original B times, and the reactive power transmitted by the system is changed to the original C times, then the formula 10 can be deduced.

$$Q_{Dj} \geq Q_{ij} + (K_1 + K_2) V_{ij}^2 \quad (10)$$

In this case, the state variables are $V_{ij}=AV_j$, $Q_{Dj}=BQ_D$ and $Q_{Dj}=CQ_{ij}$ substituting the above formula and combining the condition that no disturbance occurs.

$$-(K_1 + K_2)(AV_j)^2 + BQ_D \geq C(-K_1 + K_2)V_j^2 + Q_{ij} \quad (11)$$

So formula 12 is satisfied.

$$(C - A^2)(K_1 + K_2) V_j^2 + (B - C)Q_D \geq 0 \quad (12)$$

3. Reactive Power compensation demand

It is easy to see that in formula 12, there is a $(K_1+K_2)$ greater than 0. It is only necessary to analyze the polarity relationship between the voltage variation ratio $A$ of the load node. The reactive power $Q_D$ and its variation ratio $B$ consumed by the load and the reactive power variation ratio $C$ transmitted by the system. The relationship between reactive power injection and stability limit can be judged.

There are three scenarios.

1) Condition $C=A^2$ satisfies.

The critical condition for stability at this point is to satisfy the following formula.
Take the load absorbing reactive power as an example. In formula 13, the ratio of reactive power variation of load consumption is larger than that of reactive power input, and the nodal voltage has a solution, and the faster the reactive power of load consumption increases, the better the stability of the system is. On the contrary, the case that the load reversely sends the reactive power can also be obtained. The stability critical is that the reactive power variation of load consumption is the same as that of system input reactive power.

2) Condition $C > A^2$ satisfies.

Formula 14 can be satisfied at this time.

$$K_2 \geq \frac{(C - B)Q_D}{(C - A^2)V_j^2} - K_1$$ (14)

Under this condition, the more reactive power provided by the shunt capacitor on the load side, the more favorable to the stability of the system, and the critical value of stability is equal.

3) Condition $C < A^2$ satisfies.

The following formula is true

$$K_2 \leq \frac{(C - B)Q_D}{(C - A^2)V_j^2} - K_1$$ (15)

From the above analysis, it can be seen that the critical condition of stable state is as follows.

$$(C - B)\frac{Q_D}{V_j^2} = (B_{cc} + \frac{B_c^2 + 4B_cB_j}{2B_c + 4B_j})(C - A^2)$$ (16)

It is easy to see that in either case, the ratio of reactive power change C is equal to the ratio of reactive power change B consumed by the load, and there is a square relationship between the ratio of reactive power change C and the ratio of nodal voltage change A, which is the critical point of voltage stability. This accords with the general inference of the principle of dynamic equivalence, so when the system is running normally, we only need to compare the relationship between the reactive power change ratio C and the nodal voltage change ratio A square, and the more reactive power provided by the shunt capacitor is not the better.

4. Simulation analysis

Taking IEEE14 system as an example, the simulation results show the correctness and effectiveness of the proposed method. According to the proposed method, the reactive power demand can be rapidly assessed by calculating the stability margin of each load node in the IEEE14 node (the less the stability margin, the more the reactive power demand). The stability margin of each node is shown in Table 1 when the load increases to make the system approach the stability limit.

| Node | $\mu$/pu |
|------|----------|
| 4    | 0.1113   |
| 5    | 0.1303   |
| 9    | 0.0522   |
| 10   | 0.0503   |
| 11   | 0.0527   |
| 12   | 0.0501   |
| 13   | 0.0490   |
| 14   | 0.0419   |

Theoretically, the voltage stability level can be improved by satisfying the reactive power demand at nodes 12, 13 and 14 with the least margin. The comparison before and after the reactive power demand is satisfied is shown in Table 2.
Tab.2 The comparison before and after the reactive power demand

| Node | No compensation | Compensation at 12 | Compensation at 13 | Compensation at 14 |
|------|-----------------|--------------------|--------------------|--------------------|
| 4    | 0.7689          | 0.9015             | 0.906              | 0.9058             |
| 5    | 0.7935          | 0.9036             | 0.9114             | 0.919              |
| 9    | 0.6936          | 0.9502             | 0.9286             | 0.946              |
| 10   | 0.6811          | 0.9551             | 0.9277             | 0.938              |
| 11   | 0.7             | 0.951              | 0.9501             | 0.9537             |
| 12   | 0.6961          | 0.9857             | 1.05               | 0.9682             |
| 13   | 0.6816          | 0.9747             | 0.9866             | 0.9699             |
| 14   | 0.6344          | 0.9363             | 0.9175             | 1.029              |

The overall effect of compensation on voltage at 12, 13, and 14 is 1.9089, 1.9287, and 1.9804, respectively. This shows that the smaller the margin of the node to meet the reactive power demand, the more can improve the voltage level.

5. Conclusion
In the normal operation system, when the rate of change of input no power is equal to the square of the rate of change of load voltage near the critical point of stability, the stability mainly depends on the relationship between the ratio of no power and the ratio of reactive power input. When the input reactive power change rate, the relationship between input reactive power change rate and input reactive power change rate. When the input reactive power rate of change and the input reactive power rate of change, the input reactive power rate of change and the relationship between the input reactive power rate of change.
The power is not equal to the square of the rate of change of the voltage at the load side. The critical value of load side reactive power demand is related to line data, load no power, load side voltage, input reactive power change rate, voltage change rate and load consumption reactive power change rate. When the system is close to the critical point of voltage stability, the voltage stability margin of nodes is close to zero, thus avoiding the tedious ratio determination. Through this part of the proposed method, we can quickly assess the reactive power compensation demand of each node according to the local information, improve the stability margin, and specifically improve the maximum transmission power limit.

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