Research on Three-phase Unbalanced Overvoltage Suppression Method Based on Active Inverter

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Abstract. A three-phase unbalanced overvoltage suppression method based on active inverter is proposed for the three-phase unbalanced voltage caused by the imbalance of three relative parameters in the power grid. According to the zero-sequence current generated by the neutral point in the three-phase unbalanced state in the system, the tracking inverter circuit is correspondingly injected with a certain magnitude and phase current to compensate the three-phase unbalanced current without changing the grid-to-ground insulation. Under the condition of parameters, the three-phase unbalanced overvoltage is quickly and accurately suppressed, and the three-phase voltage balance of the grid is forced. Due to the complex and variable structure of the distribution network, the three-phase unbalance phenomenon is particularly prominent. Therefore, the distribution network is very representative. The reliability of the proposed method is verified by simulation analysis.

1. Introduction
In China's power distribution network, due to the wiring mode, asymmetrical arrangement of voltage transformers in the line, and disconnection faults, etc., it is easy to cause asymmetry of three-phase to ground parameters, resulting in three-phase unbalanced voltage. Especially in the operation mode of the neutral point through the arc suppression coil, the input of the inductive element may also resonate with the ground capacitance, which further amplifies the three-phase unbalanced voltage and generate a three-phase unbalanced overvoltage [1]. Unbalanced over-voltage will increase the loss line of the transmission line, and even cause the power supply equipment to not work properly when the resonance state [2]. Therefore, in order to eliminate the adverse effects caused by unbalanced overvoltage, effective measures must be taken to suppress three-phase unbalanced overvoltage.

The traditional methods of suppressing three-phase unbalanced overvoltage at home and abroad are mainly manual switching capacitors or reactors that are simple and economical to operate [3–4]. The main principle is that the three phase-to-ground parameters are balanced by the input of capacitors or reactors, and then the three-phase voltages are also balanced. However, the use of this method is based on the premise that the three relative ground parameters of the power grid are known to achieve the desired compensation effect. However, in the actual operation of the power grid, the three-phase-to-ground parameters are complex and changeable, and the measurement is difficult. Therefore, this method is difficult to accurately and quickly suppress three-phase unbalanced overvoltages [5].
In the system of neutral point grounded by arc suppression coil, adjusting the size of the arc suppression coil can suppress the neutral point displacement voltage to a certain extent. However, in order to prevent resonance in the three-phase-to-earth circuit, a combination of a damping resistor and an arc suppression coil is generally used, that is, a following-setting arc suppression coil is used to solve the neutral point displacement voltage issue. However, this method also cannot accurately measure the parameters to ground, and then dynamically adjusts the resistance value to suppress the unbalanced voltage, which still has certain limitations.

In reference [4-5], the method of injecting zero sequence current into the neutral point to suppress the displacement voltage of the neutral point is proposed. When seeking the phase and amplitude of the injected current, the parameters of the system to the ground must be known. The parameters are complex and changeable, so the implementation of this method is greatly limited. In reference [6], a closed-loop control method of proportional resonance (PR) for injection current is proposed. Through the mathematical analysis of the relationship between the amplitude of neutral point voltage and the amplitude and phase of injection current, the optimal injection current is obtained. However, in the process of this method, the selection of reference current is highly required, and in the PR closed-loop control system, the transfer function still needs to involve the parameters to the ground, so it can't achieve the desired effect.

In order to solve the problem of three-phase unbalanced over-voltage, this paper proposes a new method of fast and accurate suppression of three-phase unbalanced over-voltage based on active inverter. A single-phase active inverter is installed between the neutral point and the earth, and it is equivalent to a controllable current source. By measuring the zero sequence current of the neutral point as a feedback control signal, the reverse current is generated and injected into the neutral point, so as to realize the real-time and accurate suppression of the displacement voltage of the neutral point and the three-phase unbalanced over-voltage of the power grid. Because the distribution network structure is complex, the three-phase imbalance problem is more prominent, and has a strong representativeness. Therefore, this paper takes the distribution network as the research object to demonstrate the method.

2. The principle of three-phase unbalanced overvoltage suppression

The primary side of load transformers in China's distribution network mostly adopts ungrounded connection, so it will not affect the zero-sequence current of the distribution network. Therefore, in the study of zero sequence voltage control in distribution network, this paper only analyzes the three-phase unbalanced voltage caused by the asymmetry of ground parameters, without considering the influence of load. The neutral point via arc suppression coil grounding method is widely used in distribution networks due to its superiority, and its performance research has far-reaching practical significance. So take this as an example for analysis, and its wiring diagram is shown in Fig.1.

![Fig.1 Neutral point grounding system through arc suppression coil](image)

![Fig.2 Equivalent circuit diagram of neutral point grounded by arc suppression coil](image)
In Fig.1, $E_A$, $E_B$, and $E_C$ are the three relative neutral point voltages; $C_A, C_B, C_C$ and $g_A, g_B$ and $g_C$ are the three-phase wire-to-ground capacitance and leakage conductance; $L$ is the inductance of the arc suppression coil, and $L_g$ is the arc suppression coil conductance.

When the system is operating normally, the arc suppression coil and the three-phase to ground capacitance of the power grid form a series circuit. When the three-phase parameters are asymmetric, the vector sum of the three-phase power supply is not zero, then there will be asymmetric voltage $U_{\infty}$, resulting in zero sequence current flowing in the loop. Due to the existence of zero sequence current, the potential difference between the two ends of arc suppression coil is called neutral displacement voltage $U_0$.

When the three phases of the power grid are unbalanced, it is generally considered that the leakage conductance of the three phases to the ground is equal to $g_0$, and the asymmetric voltage can be expressed as follows:

$$U_{\infty}=\frac{C_L+\alpha^2 C_B+\alpha C_C}{C_A+C_B+C_C}\left[1-\frac{j}{\omega (C_A+C_B+C_C)}\right]U_\alpha$$  \hspace{1cm} (1)

Where: $\alpha = \angle 120^\circ$, $U_\alpha$ is the grid phase voltage.

In Fig.2, $g_L$ is the equivalent loss conductance of arc suppression coil, $g$ is the three phase ground conductance, and $C$ is the three phase ground capacitance.

According to Fig.2, the relationship can be expressed as follows:

$$U_{\infty}\left(\frac{g+j\omega C}{g_L+\frac{1}{j\omega L}}\right)\left(\frac{1}{g_L+\frac{1}{j\omega L}}\right)=U_0$$  \hspace{1cm} (2)

When the three phase to earth parameters are balanced, $C_A = C_B = C_C$, $g_A = g_B = g_C$, the neutral point voltage is zero, and the neutral point has no zero sequence current.

When the three phase to ground parameters are unbalanced, there is displacement voltage at the neutral point. According to Kirchhoff’s law, the zero sequence current generated by the neutral point is:

$$I = E_AY_A + E_BY_B + E_CY_C + U_0(Y_A + Y_B + Y_C + Y_0)$$  \hspace{1cm} (3)

In the formula, $Y_A, Y_B, Y_C$ are the parallel admittance of three phase to ground parameters respectively, $Y_A = \frac{1}{r_A} + j\omega C_A, Y_B = \frac{1}{r_B} + j\omega C_B, Y_C = \frac{1}{r_C} + j\omega C_C, Y_0$ are the neutral grounding admittance, $Y_0 = \frac{1}{r_0} + \frac{1}{j\omega L_0}$.

According to formula (3), when the zero sequence current of the neutral point is known, because the parameters of the power supply and the ground are constant, the displacement voltage of the neutral point has a linear relationship with the zero sequence current. If the zero sequence current can be controlled, the displacement voltage of the neutral point can be adjusted. According to this control principle, it is proposed to inject a certain amount and direction of current into the neutral point to limit the zero sequence current. Through mathematical analysis, the vector sum of the two quantities is the minimum value when the two quantities are the same in size and opposite in direction. The derivation process is as follows: if the mathematical expression of zero sequence current is $I_0 = I_m \sin(\omega t + \phi)$, if the mathematical expression of compensation current is $I_i = I_m \sin(\omega t + \phi \pm \pi)$, then the neutral point current is:
\[ I = I_0 + I_I \]
\[ = I_m \sin(\alpha + \varphi) + I_m \sin(\alpha + \varphi + \pi) \]
\[ = 2I_m \sin(\alpha + \varphi + \alpha + \varphi + \pi) \cos(\alpha + \varphi + \alpha + \varphi + \pi) \]
\[ = 2I_m \sin(\alpha + \varphi + \pi) \cos(\frac{\pi}{2}) \]
\[ = 0 \]

It can be seen from the formula derivation that this method takes the zero sequence current of neutral point as the control variable, and still achieves good three-phase unbalanced voltage suppression effect when the system parameters are unknown or the measurement is inaccurate. It can effectively solve the problems of slow compensation speed and poor compensation effect of traditional methods, greatly improve the operation reliability of power grid and improve the operation environment of the system.

3. Basic principle of hysteresis comparison control

The tracking control method takes the desired output current or voltage waveform as the command signal, compares the instantaneous value of the actual current or voltage waveform, and determines the on-off of the inverter circuit switch device according to the comparison results, so as to obtain the ideal actual output signal. Among them, hysteresis comparison method and triangular wave comparison method are commonly used.

The main purpose of the active inverter used in this paper is to inject compensation current into the neutral point, so the current tracking control method is adopted. In the current tracking PWM inverter circuit, the triangle wave comparison control mode needs to compare the command current with the actual output current to form the deviation current, and then compare the amplifier with the triangle wave to form the PWM waveform. However, the amplifier usually has a proportional characteristic, and its coefficient directly affects the effect of current tracking in the inverter circuit. The control process involves many links and the control mode is complex. The hysteresis comparison current tracking PWM inverter has the advantages of fast current response, simple circuit structure, real-time control of output current and meeting the requirements of the active inverter used in this paper. Therefore, the hysteresis comparison current tracking control method is selected, and its specific working circuit is shown in Fig.3 below.

In the circuit, IGBT and diode are used as the components to control the on-off current. Here, taking the single-phase half bridge model as an example, the deviation \( i^* - i \) between the command current \( i^* \) and the actual output current \( i \) controls the output of the comparator. The output current is adjusted by the on-off of devices V1 and V2, so that the output current can track the command signal. When the ring width is 2h, the output current \( i \) follows the command current \( i^* \) zigzagly.

![Fig.3 Hysteresis comparison mode current tracking control](image1)

![Fig.4 Command current and output current of hysteresis comparison mode](image2)

It can be seen from Fig.4 that when the ring width is selected appropriately, it has a good tracking effect. When the hardware meets the requirements, the hysteresis loop width can be reduced as much
as possible, so as to reduce the generation of a large number of harmonics and avoid interference to the normal operation of the grid.

4. Example analysis

As an important link between substation and users, 10kV distribution network plays an important role in the whole power supply network, and the grid structure is complex, which is more likely to produce three-phase imbalance phenomenon, so it is more representative to take it as the research object. This paper uses Matlab / Simulink simulation software to build a 10kV distribution network simulation model. In order to facilitate measurement and calculation, in the process of simulation analysis, the capacitance and conductance of the line to the ground are all represented by centralized parameters. In practical application, because the 10kV distribution network is mostly connected to the grid by triangle grounding, in order to analyze the current situation at the neutral point, the grounding transformer is used in the simulation model. At the same time, in order to facilitate the theoretical analysis, the compensation current is injected directly from the neutral point.

The system parameters are set to:

| Parameter | Value           |
|-----------|-----------------|
| $L$       | 0.2H            |
| $g_L$     | 0.4S            |
| $g_A$, $g_B$, $g_C$ | $8.33 \times 10^{-6}$ S |
| $C_A$, $C_B$, $C_C$ | $3 \mu F$, $3.5 \mu F$, $4 \mu F$ |

According to the simulation result from Fig 5, when the distribution network is in three-phase unbalanced state, zero sequence current is generated at the neutral point, and the active inverter is put into operation in 0.2s. The generated compensation current will compensate the zero sequence current.
at the neutral point, so that the displacement voltage of the neutral point is suppressed to zero, effectively preventing the generation of three-phase unbalanced over-voltage. The measurement results are shown in Fig 6-7. In order to verify the active suppression effect of the distribution network in the three-phase extreme imbalance state, the system model is set at 0.1s when the single-phase short circuit occurs, and the change of zero sequence current and displacement voltage at the neutral point is shown in Fig.8-9.

The results show that the zero sequence current and displacement voltage of the neutral point increase sharply when the single-phase ground short circuit occurs within 0.1s, but the three-phase unbalanced over-voltage can still be effectively limited when the active inverter can generate enough compensation current.

![Figure 8](image8.png)
**Fig.8** Zero sequence current of neutral point when A-phase short-circuit is grounded in 0.1s and compensated in 0.2s

![Figure 9](image9.png)
**Fig.9** Neutral point displacement voltage when A-phase short-circuit is grounded in 0.1s and compensated in 0.2s

From the above simulation analysis, we can see that the method of injecting zero sequence current into the distribution network through PWM active inverter can effectively suppress the three-phase unbalanced over-voltage, and the neutral point displacement over-voltage can be completely suppressed to zero after compensation, and the effect of over-voltage Suppression is very significant.

5. Conclusions
Through the analysis of the measurement results, the following conclusions can be drawn:

(1) The hysteresis current tracking method can realize the real-time tracking of the zero sequence current of the neutral point. The tracking control method is simple and effective, and has great flexibility.

(2) In the three phase unbalanced state, the inverse current is generated by the active inverter, and the neutral displacement voltage is effectively suppressed by compensating the zero sequence current of the neutral point.

(3) Compared with the practical measurement method, this method can be realized when the parameters of the three phase to ground are unknown, and can avoid the influence of the changes of the parameters of the three phase to ground.

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