Analysis of Influence of Inverter New Energy Transient Short-Circuit Current Harmonic Component on Transformer Differential Protection

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Abstract. The second harmonic braking protection is the key to the differential excitation inrush current of the transformer and the quick action of the differential protection. In this paper, it is verified that the large-scale inverter type power supply may affect the second harmonic braking protection of the transformer. The mechanism of generating the second harmonic component of the current during the short-circuit fault of the inverter-type power supply is analyzed. Further analysis of the secondary harmonic current generated by the inverter-type power supply during the fault in the transformer zone may cause the second harmonic braking component of the transformer. Finally, the correctness of the analysis is verified based on the PSCAD/EMTDC transient electromagnetic simulation software.

1. Introduction
At present, the penetration rate of new energy sources continues to increase, and the development of wind power and photovoltaic power generation is particularly rapid. The large-scale access of new energy sources makes the power system safe and stable and faces new challenges. New energy sources include partial power conversion (dual-fed wind turbines) and full-power conversion power supplies. Typical full-power conversion power supplies (also known as inverter-type power supplies) include direct-drive wind turbine grid-connected systems and photovoltaic grid-connected power generation. The system is different from the traditional power supply. The application of a large number of power electronic devices in the inverter power supply makes the transient short-circuit process extremely complicated. At present, domestic and foreign scholars' research on the impact of new energy access to the power grid mainly focuses on the protection of new energy stations. As well as the research on relay protection of distribution network with new energy access [1], the research on the impact of large-scale new energy access on power equipment is relatively scarce. Accurately grasping the transient short-circuit characteristics of the inverter type power supply is the key to solving the problem of relay protection after the large-scale inverter type power supply is connected. Literature 2 points out that the inverter-type power supply has a transition period of 10~40ms in the short-circuit transient process, and the short-circuit current provided by it contains more harmonic components. The composition of harmonic components and its influence on relay protection are not further analyzed. In the literature 3, it is pointed out that the output current of the inverter-type power supply contains more DC component and second harmonic component in the short-circuit transient. The DC component of the short-circuit...
current provided by the inverter-type power supply reaches 38.97% and the second harmonic component. It is about 34.3%, and it is pointed out that with the increase of the grid-connected capacity of the inverter power supply, the influence of the harmonic components contained in the output current on the power grid is more obvious.

This paper focuses on the large-scale access of inverter power supply. Based on the typical control strategy of inverter power supply, the mechanism and characteristics of the second harmonic component in the transient current short-circuit output current of inverter power supply are analyzed. The second harmonic component of the output of the inverter type power supply may exceed the second harmonic braking setting range of the transformer, causing the second harmonic braking protection component to malfunction. To improve the above-mentioned phenomenon from the inverter control level, ensure the safe and stable operation of the transformer and system.

2. Transformer protection second harmonic braking principle

Differential protection is the most important protection for power system protection. Current differential protection is the main protection of transformer due to its fast speed and good selectivity. The principle wiring diagram of the single-phase double-winding transformer longitudinal differential protection is as follows:

\[ I_k = |I_1 + I_2| \]

Figure 1. Schematic diagram of longitudinal differential protection of single-phase double-winding transformer

In the picture, \( I_1 \), \( I_2 \) are the current on the primary side and the secondary side of the transformer, respectively. \( I_1 \), \( I_2 \) is the secondary current measurement current of the corresponding current transformer, the current flowing into the differential relay. \( I_k = |I_1 + I_2| \) Usually, the influence of excitation current on transformer differential protection is considered in the action equation. Under normal operation or external short circuit, the transformer will not saturate. Excitation current \( I_\mu \) generally does not exceed 2%~5% of rated current. Which is \( I_1 + I_2 = I_\mu = 0 \). The current component KD does not operate; when a phase-to-phase short circuit occurs between the current transformers on both sides, and the grounding is short-circuited (ie, the internal fault of the transformer), the current flowing into the differential relay component reflects the current at the short-circuit point, and when the short-circuit point current is greater than the set value The differential protection quickly removes the fault, and the differential protection action criterion is:

\[ I_k = |I_1 + I_2| \geq I_{\text{set}} \]  \hspace{1cm} (1)

In the formula, \( I_{\text{set}} \) is the operating current of the differential protection.

In the project, the short-time blocking differential protection is used to identify the magnetizing inrush current to ensure the correct action of the transformer longitudinal differential protection. The magnetizing inrush current contains a large number of high-order harmonics, of which the second harmonic is dominant. In order to identify the inrush current, the second harmonic blocking component is generally configured in the differential protection. The blocking expression is:
\[ I_{h2} \geq k_2 I_1 \]  \hspace{1cm} (2)

In the formula, \( I_{h2} \) is the value of the second harmonic component in the differential current, \( I_1 \) is the value of the fundamental frequency component in the differential current, \( k_2 \) is the setting value of the second harmonic braking coefficient in the differential protection. When the transformer is put into operation or external fault is removed, the protection component detects that the second harmonic content in the differential current is greater than the setting value, and the differential relay is blocked, according to the minimum second harmonic content under various excitation inrush currents. To carry out the setting, that is, generally take 0.15-0.2 in formula [4]

3. Grid-connected inverter power control strategy and electromagnetic transient model

In this paper, the inverter-type power supply is connected to the L-type three-phase grid-connected inverter control system. The typical grid-connected inverter power supply adopts double-loop control. The main circuit model and the control circuit under the synchronous rotating coordinate system are shown in Figure 1:

![Figure 2. Inverter power supply topology](image)

The controller portion of Figure 2 typically employs a dual-loop control strategy for the voltage outer loop current inner loop. Under normal operating conditions, the voltage outer loop obtains the d-axis current inner loop reference value by maximum power tracking \( i_{d-ref} \), Q-axis current reference \( i_{q-ref} \). Given according to the reactive power reference value; In the fault state, the system is in grid connection control at the initial stage of the fault. When the grid voltage falls and the drop is deep, the system disconnects the outer loop control, and the current inner loop reference value \( i_{d-ref} \) is adaptively given according to the voltage drop degree. The voltage outer loop control structure is as follows: According to the inverter control principle, the control block diagram from the DC side voltage \( U_{dc} \) to the inverter current d-axis component is shown in Figure 2:

![Figure 3. Control block diagram of DC bus voltage to the d-axis component of the inner ring of the converter](image)
In Figure 3, $K_{vp} + K_{vi} / s$ is the transfer function of the outer loop voltage PI regulator. $K_{PWM} / 1.5T_s + 1$ is the inverter transfer function, where $K_{PWM}$ is the current inner loop sampling period, $K_{v} + K_{i} / s$ is the inverter equivalent gain, $(1 / R) / (R + (L / R) s)$ is the transfer function of the inner loop current PI regulator, and 6 is the transfer function of the AC side filter [5].

In Figure 3, the transfer function of the DC voltage component of the inverter to the d-axis component of the inner loop current:

$$W_{\phi} = \frac{\zeta_1(s)}{U_{dc} - U_{dc}'} = \frac{a_{h}K_{PWM}}{L} \left(\frac{K_{vp} + K_{vi}}{s + \zeta_1(s + \zeta_1)}\right)$$

Among them:

$$\zeta_1 = \frac{(R+K_{vp}K_{v})\alpha_t^2}{\sqrt{[(R+K_{PWM}K_{v})\alpha_t^2 - \omega K_{PWM}K_{v}]}} \frac{1}{2L}$$

4. Second harmonic expression of transient short-circuit current of inverter type power supply

Considering the DC component in the grid-connected voltage, assuming that a short-circuit fault occurs in the grid voltage, the vector expression of the voltage and current of the grid-connected point of the inverter-type power supply is:

$$u_g = U_1 e^{j\theta} e^{j\omega t} + U_0 e^{-j\omega t}$$

$$i_g = I_1 e^{j\theta} e^{j\omega t} + I_0 e^{-j\omega t}$$

In the formula, $I_1$ is the amplitude of the transient short-circuit current of the inverter type power supply, $\phi_1$ is the initial phase angle of the fundamental frequency component, and $U_0$ and $I_0$ are the magnitude of the short-circuit voltage and the DC component of the current. Convert the above expression into a synchronous rotation coordinate system vector expression as:

$$u_{gd} = U_1 e^{j\theta} + U_0 e^{-j\omega t} e^{j\omega t}$$

$$i_{gd} = I_1 e^{j\theta} + I_0 e^{-j\omega t} e^{j\omega t}$$

From the instantaneous power theory [6], the instantaneous power expression of the inverter-type power supply based on the grid voltage orientation is:

$$P_{gw} = 1.5I_1^*U_0 + U_1 I_1 e^{j\omega t} + I_0 U_1 e^{-j\omega t}$$

Due to the harmonic component of the output short-circuit current and the power grid [7], the fundamental frequency fluctuation occurs in the output active power, according to the power transmission balance:

$$C \frac{dU_{dc}}{dt} = i_m - I_g = \frac{P_{g} - P_{gw}}{U_{dc}}$$

At the moment of short circuit, the active power $P_{gw}$ provided by the inverter system remains unchanged. The fundamental frequency fluctuation of the active power $P_{g-loc}$ on the output side of the
inverter will cause the fundamental frequency fluctuation component in the DC side voltage, assuming the fundamental frequency fluctuation component of the DC side voltage. For:

$$\Delta U_{dc} = U_{dcb} \cos(\alpha t + \varphi_{dc}) e^{-\frac{j}{\tau_a}}$$  \hspace{1cm} (11)

According to the outer loop transfer function of the inverter voltage in section 1.1, the time domain expression of the fundamental wave component in the d-axis current obtained by the voltage external loop transfer function of equation (3) (4) can be obtained as follows:

$$\Delta i_{dl}(t) = -\frac{\omega_1 K_{PWM}}{2L} \left( E_x U_{dcb} e^{j\omega t} e^{-\frac{j}{\tau_a}} + E_x^* U_{dcb}^* e^{-j\omega t} e^{-\frac{j}{\tau_a}} \right)$$  \hspace{1cm} (12)

Among them:

$$E_x = \begin{bmatrix} K_p (\omega_1 - j \tau_a) + K_v \\ j \omega_1 (\omega_1 - j \tau_a + \zeta_j) \end{bmatrix} \left[ K_p(j \omega_1 - 1/\tau_a + K_v) \right]$$  \hspace{1cm} (13)

The dq axis component is transformed into the abc three-phase coordinate system component orthogonal rotation transformation matrix by Parker inverse transformation [8]:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\omega t + \theta_0) & -\sin(\omega t + \theta_0) & 1 \\ \cos(\omega t + \theta_0 + \frac{2\pi}{3}) & -\sin(\omega t + \theta_0 + \frac{2\pi}{3}) & 1 \\ \cos(\omega t + \theta_0 + \frac{2\pi}{3}) & -\sin(\omega t + \theta_0 + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_c \end{bmatrix}$$  \hspace{1cm} (14)

Where $\theta_0$ is the initial phase angle between the d-axis of the rotating coordinate system and the a-axis of the stationary coordinate system.

Combined with (12) (14), the fundamental frequency fluctuation is generated by the Parker inverse transform in the abc coordinate system to generate the second harmonic component. The expression of the second harmonic component in the three-phase current is:

$$i_{gh} = \frac{\omega_1 K_{PWM}}{2L} E_x U_{dcb} e^{j(2\omega t + \theta_0)} e^{-\frac{j}{\tau_a}}$$  \hspace{1cm} (15)

In summary, since the inverter output current contains a DC component, when the DC component of the grid-connected voltage is taken into account, a fundamental frequency fluctuation component is generated in the inverter output power, and the fundamental frequency fluctuation component causes a DC-side voltage to generate a fundamental frequency. Fluctuation, the introduction of the outer loop of the inverter controls the fundamental frequency fluctuation component in the d-axis current, and the second harmonic component is generated in the three-phase short-circuit current by the Parker inverse transform.

5. Experiment and simulation

5.1. Short circuit test with inverter type power supply system

Based on the PSCAD/EMTDC electromagnetic transient simulation platform, this paper constructs the grid electromagnetic transient simulation model with inverter type power generation unit as shown in Fig. 6.
The photovoltaic power generation system is connected to busbar B with a voltage rating of 10kV. Line L1 unit length is: \( r_1 = 0.173 \, \Omega/km \), \( r_2 = 0.313 \, \Omega/km \), \( r_3 = 0.29 \, \Omega/km \), \( x_1 = 0.48 \, \Omega/km \), \( x_2 = 0.5 \, \Omega/km \). The length is 2km. The capacity of the two-winding transformer is 20MVA and the ratio is 10kV/110kV. Power G system equivalent impedance \( X_G = 1.6 + j \times 10 \, \Omega \). The photovoltaic grid-connected system has a capacity of 10 MW and a rated voltage of 10 kV.

The fault location f sets the high voltage side outlet of the step-up transformer (as shown in Figure 6). When \( t=3s \), a three-phase short-circuit fault occurs at f, the grid voltage drops to 20%, and the voltage at the grid point PCC is as shown in Fig. 7. The short-circuit current and transformer differential current on the inverter type power supply side are shown in Figure 8:
According to the analysis in Section 2, the transient of the three-phase short-circuit fault, due to the DC attenuation component in the short-circuit current and the drop of the grid voltage, causes a disturbance component in the d-axis current of the inner loop, which is controlled by the inverter in the three-phase short-circuit current. A second harmonic component is generated. In addition, due to the attenuation of the DC component and the detection of the voltage drop below 90% for the control strategy switching, the system tends to stabilize under the new inner loop current reference value after 1-2 power frequency cycles, showing Figure 8a. Under the condition that the external power grid is weak, when the fault occurs in the step-up transformer, the short-circuit current provided by the inverter-type power supply accounts for a large part of the differential current. At this time, the differential current of the step-up transformer is shown in Figure 8c. The second harmonic is extracted using the FFT algorithm for the differential current shown in Fig. 8c), and the second harmonic component of each phase differential current is represented by the fundamental component as shown in Fig. 9.
It can be seen from Fig. 9 that the second harmonic content of the transformer differential current exceeds the setting value $k_2$ (15%) of the second harmonic blocking, which may cause the transformer differential protection to refuse.

The above simulations verify that under the condition of weak grid, when the fault occurs in the transformer area, the second harmonic content of the fault current provided by the photovoltaic power supply side may exceed the second harmonic braking range of the transformer, which makes the transformer differential protection exist. Risk of action.

6. Conclusion

Large-scale access to inverter-type power supplies makes analysis of short-circuit current characteristics, especially harmonic characteristics, more important. In this paper, the mechanism of the second harmonic component generation of transient short-circuit current of inverter power supply is analyzed in detail. On this basis, the influence of the second harmonic component on transformer differential protection is analyzed. The conclusions drawn in this paper provide a reference for the transformer protection configuration after the photovoltaic power generation system is connected to the grid.

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