An improved new transformer type arc suppression reactor

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Abstract—In this paper, to accurately compensate the arc suppression coil, the structure of the transformer is improved. Here, a fixed inductive element is connected in series with the short-circuit winding, which combines with the leakage inductance of the original transformer to form a new short circuit impedance. The improved transformer reduces the manufacturing cost and difficulty of the controllable inductor, reduces the requirements for the winding of the reactor, and makes the manufacturing easier.

1. Introduction
In the power system, the neutral point is usually ungrounded. When the neutral point of the distribution network is ungrounded, when a single-phase to ground short-circuit occurs, the three-phase line voltage is still balanced, which can be used in the event of a fault[1-3].

At the same time, a large number of cable circuits are used in the transmission lines of the distribution network, which makes the capacitance value of the distribution network to the ground gradually increase[4]. Therefore, when a single-phase grounding short circuit occurs in the distribution network, the capacitive current to the ground generated at the grounding point increases and can reach 60A-70A. When the arc current of the grounding point increases, the grounding arc cannot be extinguished quickly and automatically, which is likely to cause serious insulation damage, leading to more serious faults such as phase-to-phase short-circuit, leading to large-scale power outages. In the power system, single-phase ground faults account for more than 70% of all problems, seriously affecting the reliability and safety of the power system.

2. The principle of the magnetic flux compensation controllable reactor of the control winding
In the control winding of the arc suppression reactor, a magnetic flux compensation controllable reactor is used. When current is injected into the control winding through a full-bridge inverter, the main magnetic flux in the iron core will change to realize the function of the controllable reactance. The primary working winding and the secondary control winding of the transformer-type reactor can be equivalent to a special linear impedance network[5-7]. The current or voltage of one of the ports (secondary winding) can be controlled, and it can be used on the primary side of the reactor. The output equivalent impedance of the winding produces a controllable amount of change.

The principle of magnetic flux compensation transformer T-type equivalent circuit is shown in Figure 1.
The main body of the transformer-type arc suppression reactor is a transformer, and the primary winding (AB) is connected in series between the neutral point and the ground. U1 represents the neutral point voltage, and the secondary winding ab is connected to a controllable current source (full-bridge inverter).

The magnetic potentials generated by the primary current and the secondary current are:

\[ F_1 = W_1 I_1 \]  
\[ F_2 = W_2 I_2 \]

The two magnetic potentials generated by the primary and secondary windings will respectively establish four main magnetic fluxes in the transformer core: the leakage flux \( \phi_{1\sigma} \) on the primary side, the leakage flux \( \phi_{2\sigma} \) on the secondary side and the excitation flux \( \phi_{1m}, \phi_{2m} \). Among them, the leakage magnetic flux type does not form a loop through the iron core, and the excitation magnetic flux forms a loop through the iron core part, which has energy exchange, and the excitation magnetic flux is much larger than the leakage magnetic flux. According to the magnetic circuit theorem, the magnetic circuit equation of the primary winding can be obtained as, \( \lambda_{1\sigma} \) and \( \lambda_{2\sigma} \) are the permeance of the primary leakage magnetic flux and the excitation magnetic flux.

\[ \phi_{1\sigma} = \lambda_{1\sigma} F_1 = \lambda_{1\sigma} W_1 I_1 \]
\[ \phi_{2\sigma} = \lambda_{2\sigma} F_2 = \lambda_{2\sigma} W_2 I_2 \]
\[ \phi_{1m} = \lambda_{1m} F_1 = \lambda_{1m} W_1 I_1 \]
\[ \phi_{2m} = \lambda_{2m} F_2 = \lambda_{2m} W_2 I_2 \]

Through Equation (3), it can be concluded that the induced electromotive force of the windings on both sides is \( e_1 \) and \( e_2 \), which are the excitation potential of the primary winding and the excitation potential of the secondary winding, respectively.

\[ e_1 = -W_1 \frac{d}{dt} \left( \phi_{1m} + \phi_{2m} \right) = -W_1 \frac{d}{dt} \phi_m \]
\[ e_2 = -W_2 \frac{d}{dt} \left( \phi_{1m} + \phi_{2m} \right) = -W_2 \frac{d}{dt} \phi_m \]  

\( e_{1\sigma} \) and \( e_{2\sigma} \) are the leakage potentials of the primary and secondary sides, respectively.

\[ e_{1\sigma} = -W_1 \frac{d}{dt} \phi_{1\sigma} \]
\[ e_{2\sigma} = -W_2 \frac{d}{dt} \phi_{2\sigma} \]

The main magnetic flux in the iron core forms a loop through the iron core, and is co-excited by the primary and secondary winding currents, which can be expressed as \( \phi_m = \phi_{1m} + \phi_{2m} \). Finally, equation 4 is calculated.
\[ e_1 = -\left(W_1^2 \lambda_m\right) \frac{dI_1}{dt} - \left(W_1 W_2 \lambda_m\right) \frac{dI_2}{dt} \]
\[ e_2 = -\left(W_2^2 \lambda_m\right) \frac{dI_2}{dt} - \left(W_1 W_2 \lambda_m\right) \frac{dI_1}{dt} \]
\[ e_{1\sigma} = -\left(W_1^2 \lambda_{1\sigma}\right) \frac{dI_1}{dt} \]
\[ e_{2\sigma} = -\left(W_2^2 \lambda_{2\sigma}\right) \frac{dI_2}{dt} \]

According to KVL, the terminal voltage of the transformer is

\[ U_1 = I_1 Z_{1\sigma} - (e_1 + e_{1\sigma}) = Z_{1\sigma} I_1 + L_{11} \frac{dI_1}{dt} + M_{12} \frac{dI_2}{dt} \]
\[ U_2 = I_2 Z_{2\sigma} - (e_2 + e_{2\sigma}) = Z_{2\sigma} I_1 + L_{22} \frac{dI_2}{dt} + M_{12} \frac{dI_1}{dt} \]

where \( L_{11} = W_1^2 \lambda_{1\sigma} + W_1 \lambda_m \), \( L_{22} = W_2^2 \lambda_{2\sigma} + W_2 \lambda_m \), \( L_{22} = W_2^2 \lambda_{2\sigma} + W_2 \lambda_m \), \( M_{12} = W_1 W_2 \lambda_m \), \( Z_{1\sigma} \)
and \( Z_{2\sigma} \) are the equivalent impedances of the primary and secondary sides, respectively.

The terminal voltage equation of the primary winding is

\[ U_1 = I_1 Z_{1\sigma} - E_1 \]

The vector relationship between the current injected into the secondary winding and the primary current is:

\[ I_2 = -\alpha \cdot k \cdot I_1, \quad (0 \leq \alpha \leq 1) \]

The main flux of the transformer is

\[ F_r = W_1 I_1 + W_2 I_2 = (1 - \alpha) W_1 I_1 \]

The induced electromotive force generated by the main magnetic flux on the primary side of the transformer is:

\[ E_1 = -j 4.44 f W_1 (1 - \alpha) \phi_m = -(1 - \alpha) Z_m \]

The equivalent impedance of the primary side port of the series transformer is:

\[ Z_{AB} = \frac{U_1}{I_1} = Z_{1\sigma} + (1 - \alpha) Z_m \]
\[ X_{AB} = \frac{U_1}{I_1} = X_{1\sigma} + (1 - \alpha) X_m = (X_{11} - \alpha X_m) \]
inverter is used to control the injection current of the secondary side of the reactor, the response speed is fast, the accuracy is high, and the continuous linear change of the equivalent reactance value can be achieved.

When \( \alpha = 0 \), the secondary winding injection current \( I_2 = 0 \), which is equivalent to an open circuit of the control winding. At this time, the output equivalent reactance of the primary side is the sum of the excitation impedance and the leakage reactance of the primary side. The excitation reactance is much larger than the leakage reactance. The leakage reactance is negligible, and it is equivalent to the reactor without magnetic flux compensation:

\[
Z_{AB} = \frac{U_1}{I_1} = Z_{1e} + Z_m = (R_{1e} + R_m) + j\omega(L_{1e} + L_m)
\]

(14)

When \( \alpha = 1 \), the secondary winding injection current \( I_1 = -I_2 \), the output equivalent impedance of the primary winding is the leakage reactance value:

\[
Z_{AB} = \frac{U_1}{I_1} = Z_{1e} = R_{1e} + j\omega L_{1e}
\]

(15)

When \( \alpha = \frac{L_{11}}{M_{12}} \), the secondary winding injection current \( I_2 = -(\frac{L_{11}}{M_{12}})I_1 \), the equivalent impedance of the port is:

\[
Z_{AB} = \frac{U_1}{I_1} = Z_{1e} + \left(1 - \frac{L_{11}}{M_{12}}\right)Z_m = R_{1e} + \left(1 - \frac{L_{11}}{M_{12}}\right)R_m
\]

(16)

At this time, the equivalent impedance output by the primary winding of the controllable reactor reaches the minimum, which is approximately the coil resistance (the coil reactance is zero). It can be seen from the above formula that the principle of magnetic flux compensation is to control the main magnetic flux of the iron core by controlling the relationship between the primary and secondary winding currents, and to realize the controllable reactor by changing the magnetic flux. The output equivalent reactance of the primary winding is inversely proportional to the flux compensation coefficient \( \alpha \). When the magnetic flux compensation coefficient is selected reasonably, the equivalent reactance of the controllable reactor can be adjusted in a larger range, from the coil impedance adjustment to the excitation impedance.

3. Results and Discussions

The magnetic flux compensation controllable reactor of the control winding, its main structure includes a transformer with an iron core air gap, a single-phase full-bridge inverter, a sampling circuit and a closed-loop control circuit. The primary winding (working winding) is connected in series between the neutral point and the ground, and the secondary winding (control winding) is connected to the inverter output after LC filtering. Measuring the current of the primary winding and the current of the secondary winding in the system in real time, so that the current relational expression satisfies \( I_2 = -\alpha \cdot k \cdot I_1 \).

Real-time current tracking control is a core link in the system. To ensure the rapid accuracy of the control system, the input current should be controlled by adjusting the inverter. The switch tube should be fully utilized to make the inverter work stable, safer and reliable. At the same time, it is ensured that the error is reduced as much as possible when the inverter is adjusted, and the current control is accurate. This article chooses PI current tracking control strategy, which has good real-time and robustness, and the experimental program design is simple and easy to operate.

In MATLAB, the DC bus voltage is 240V, the transformation ratio of the primary and secondary windings of the transformer is 4, the system voltage is 150V, 50Hz, and the load uses a linear resistance load \( R = 5\Omega \). The primary side of the controllable reactor needs to be connected in series between the neutral point of the distribution network and the ground. When a single-phase grounding short circuit occurs, the neutral point voltage is the phase voltage. Replace with a stable AC current...
source in the simulation. Real-time current detection is performed on the primary side of the reactor, and a current $I_2$ is injected from the secondary side of the reactor, and the equivalent reactance of the primary side of the reactor is changed by controlling the ratio coefficient of $I_1$ and $I_2$, thereby achieving the arc suppression effect.

By controlling the value of the compensation coefficient $\alpha$, the simulation result is obtained.

Fig. 2 The primary and secondary current waveform when $\alpha=0$

When the magnetic flux compensation degree $\alpha$ is adjusted to 0 when the arc suppression reactor controls the winding operation, the secondary current is close to 0 at this time. At this time, the inverter does not enter the working state.

Fig. 3 The primary and secondary current waveform when $\alpha=0.2$

Fig. 4 The primary and secondary current waveform when $\alpha=0.8$
It can be seen from Figure 2 and Figure 3 that using the PI current tracking control strategy, the primary current can be measured in real time, and the inverter output current can be controlled to perfectly track the primary current, with high accuracy and fast response speed. The impedance value of the primary port AB can be changed by changing the coefficient $\alpha$. As the coefficient $\alpha$ becomes larger, the equivalent impedance of the primary side port of the series transformer becomes larger, which is consistent with the theoretical analysis.

4. Conclusion
This paper analyzes the principle and structure of controllable reactors, and the known topology is analyzed. The improvement is to connect a fixed inductance value in series with the short-circuit winding to determine the short-circuit equivalent reactance value, which reduces the difficulty of making the reactor and better realizes the large-capacity controllable reactor.

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