Arc Suppression Method for Distribution Network with New Energy Based on Active Inverter Split-phase Injection

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Abstract. With the continuous development and promotion of new energy technology, the traditional distribution network structure has been changed. After the new energy power is connected, the distribution network has changed from a traditional single-ended power supply radiation network to a dual-end or multi-end power supply network. Some active arc suppression methods often ignore the impact of new energy power supply when calculating the injected current. Aiming at the above problems, and drawing on the existing flexible grounding technology, this paper proposes an arc suppression method for new energy distribution networks based on active inverter split-phase injection, which comprehensively considers the impact of system-side power and new energy-side power on the injection current calculation. It is shown that this method can effectively compensate the fault current and can effectively suppress the re-combustion of AC arc.

1. Introduction

The distribution network has a complex structure and a changeable operating environment, which is prone to random failures. About 70% of distribution network failures are transient ground faults[1]. With the continuous development and promotion of new energy technologies, the topology of traditional distribution networks has been changed. The distribution network has changed from a traditional single-ended power supply to a dual-end or multi-end power supply network. Makes the distribution network ground fault handling more troublesome.

Arc suppression methods include voltage and current suppression. References [2-5] use the current arc suppression method. Among them, the grounding method adopted in [2] is a neutral point connected in parallel with the arc-suppression coil. In the initial stage of the fault, the fault current is reduced through the compensation of the arc-suppression coil. Then, the resistance is put in to avoid series connection between the inductor and the capacitor to ground. Unreal grounding caused by resonance. Reference [3] realized arc suppression by a method of combining arc suppression coil and failover device. This method first compensates the residual fault to a small value by using the arc suppression coil, and then invests in the failover device to make the fault point voltage clamped to 0V. A resistor is connected in parallel on the ground loop to reduce the harm caused by the failure of phase selection. Reference [4] uses a dynamically tuned arc suppression coil to perform arc suppression. This method monitors the capacitance current of each phase line to ground in real time. The capacitance of the arc suppression coil is calculated by monitoring the capacitance current data.
obtained after the ground fault. Value to fully compensate the capacitor current. The above method mainly compensates the fault current through the arc suppression coil, and the inductance value of the arc suppression coil is completed under the power frequency data, so that only the reactive component of the fault current can be compensated, and the active and harmonic components cannot be compensated. Reference [5] injects zero-sequence current to the system at a neutral point through a single-phase cascaded H-bridge, and calculates the data that needs compensation by monitoring the data of the phase-to-ground power electromotive force and line-to-ground parameters to achieve compensation of fault current. References [6-8] use the voltage arc suppression method. Among them, reference [6-7] uses arc switching to perform arc extinguishing. The arc extinguishing method is: when it is judged that a fault occurs in the line, the fault phase is directly short-circuited, and the fault current is “transferred” to a dedicated effluent channel or other. The safety ground path can reduce the fault line fault current while clamping the fault phase voltage to 0V. However, this method needs to directly short-circuit the faulted phase, which has a large impact on the system. Because of the existence of soil resistance, the voltage at the fault point cannot be completely guaranteed to be 0V. Literature 8 realizes arc suppression by installing a single-phase active inverter device in the distribution network. The zero-sequence voltage is adjusted by the zero-sequence current output by the active inverter, and then the fault phase voltage is adjusted.

At present, the existing passive arc suppression methods have certain inherent defects in principle. For example, the distribution network is grounded through the arc suppression coil, it can compensate the reactive power component of the fault current, but it cannot compensate the active component. When the fault phase is shorted, it will bring a huge impact to the system. The active arc suppression method can be used to achieve full fault current compensation in principle, and the fault phase voltage is clamped to 0V. However, the current active injection arc suppression method does not consider the three-phase asymmetry of the system when calculating the injection current. The impact of injection method arc suppression when the distribution network is connected to a new energy source has not been considered. In view of the above problems, an arc suppression method for a new energy distribution network based on active inverter split phase injection is proposed with reference to the existing flexible grounding technology.

2. Arc suppression principle

The topology diagram of a new energy distribution network with active inverter split-phase injection arc suppression is shown in Figure 1. To simplify the analysis, this article only uses two-terminal power supply as an example. In Figure 1, N is the neutral point of the system-side power supply; \( Z_n \) is the impedance from the neutral point on the system side to ground; \( \bar{E}_{a1}, \bar{E}_{b1}, \bar{E}_{c1} \) are the three-phase power emf of the system side power A, B, and C, respectively; \( \bar{E}_{a2}, \bar{E}_{b2}, \bar{E}_{c2} \) are the three-phase power electromotive force of new energy power sources A, B, and C, respectively; \( \bar{E}_{a3}, \bar{E}_{b3}, \bar{E}_{c3} \) are the system-side power supply internal resistances; \( Z_{a2}, Z_{b2}, Z_{c2} \) are new energy power source internal resistance and line impedance; \( g_a, g_b, g_c \) are A, B, and C three-phase line leakage conductances to ground; \( c_a, c_b, \) and \( c_c \) are A, B, and C three-phase line distributed capacitances to ground; \( \bar{I}_a, \bar{I}_b, \bar{I}_c \) are the currents output by the active inverters connected to the heads of the three-phase lines A, B, and C; DC voltage source can be obtained from the secondary side of the distribution transformer through the rectifier circuit; \( R_f \) is the transition resistance.

For the circuit voltage equation of the circuit shown in Figure 1, let the opposite point be the reference node, phase A is the fault phase, the neutral point of the system-side power supply is \( \bar{U}_{a1} \), phase A voltage is \( \bar{U}_{a2} \), phase B voltage is \( \bar{U}_{b3} \), phase C voltage is \( \bar{U}_{a4} \), the neutral point of the new energy source is \( \bar{U}_{a5} \), and The node voltage equation is shown in Equation 1.
Figure 1. Circuit diagram of new energy distribution network with active inverter split-phase injection

\[
\begin{align*}
\frac{U_{a1}}{Z_0} + & \frac{U_{a1} - U_{a2} + E_{A1}}{Z_{A1}} + \frac{U_{a1} - U_{a3} + E_{B1}}{Z_{B1}} + \frac{U_{a1} - U_{a4} + E_{C1}}{Z_{C1}} = 0 \\
\frac{U_{a2} - U_{a1} - E_{A1}}{Z_{A1}} + & \frac{U_{a2} - U_{a5} - E_{A2}}{Z_{A2}} + \frac{U_{a2} - g_A + j\omega C_A}{1} = I_{i1} \\
\frac{U_{a3} - U_{a1} - E_{B1}}{Z_{B1}} + & \frac{U_{a3} - U_{a5} - E_{B2}}{Z_{B2}} + \frac{U_{a3} - g_B + j\omega C_B}{1} = I_{i2} \\
\frac{U_{a4} - U_{a1} - E_{C1}}{Z_{C1}} + & \frac{U_{a4} - U_{a5} - E_{C2}}{Z_{C2}} + \frac{U_{a4} - g_C + j\omega C_C}{1} = I_{i3} \\
\frac{U_{a5} - U_{a2} + E_{A2}}{Z_{A2}} + & \frac{U_{a5} - U_{a3} + E_{B2}}{Z_{B2}} + \frac{U_{a5} - U_{a4} + E_{C2}}{Z_{C2}} = 0
\end{align*}
\]

The system of equations contains 5 unknowns, and the order is high, which is not conducive to direct calculations. Changing it into a matrix is expressed as:

\[
\begin{bmatrix}
    a_1 & a_3 & a_4 & 0 & U_{a1} \\
    a_2 & a_5 & 0 & 0 & a_6 & U_{a2} \\
    a_5 & 0 & a_7 & 0 & a_8 & U_{a3} \\
    a_4 & 0 & a_9 & a_6 & a_10 & a_{11} & U_{a4} \\
    0 & a_6 & a_9 & a_{10} & a_{11} & U_{a5} \\
\end{bmatrix} =
\begin{bmatrix}
    b_1 \\
    b_2 \\
    b_3 \\
    b_4 \\
    b_5
\end{bmatrix}
\]

In equation (2), \( a_1 = 1/Z_0 + 1/Z_{A1} + 1/Z_{B1} + 1/Z_{C1} \), \( a_2 = -1/Z_{A1} \), \( a_3 = -Z_{B1} \), \( a_4 = -Z_{C1} \), \( a_5 = -1/Z_{A2} \), \( a_6 = 1/Z_{A1} + 1/Z_{A2} + g_A + j\omega C_A \), \( a_7 = 1/Z_{B1} + 1/Z_{B2} + g_B + j\omega C_B \), \( a_8 = -1/Z_{B1} \), \( a_9 = -1/Z_{B2} \), \( a_{10} = -1/Z_{C2} \), \( a_{11} = 1/Z_{C1} + 1/Z_{C2} + g_C + j\omega C_C \), \( a_{12} = -1/Z_{A2} - 1/Z_{B2} + g_{C2} \), \( b_1 = -E_{A1}/Z_{A1} - E_{B1}/Z_{B1} - E_{C1}/Z_{C1} \), \( b_2 = E_{A1}/Z_{A1} + E_{A2}/Z_{A2} + I_{i1} \), \( b_3 = E_{B1}/Z_{B1} + E_{B2}/Z_{B2} + I_{i2} \), \( b_4 = E_{C1}/Z_{C1} + E_{C2}/Z_{C2} + I_{i3} \), \( b_5 = E_{A2}/Z_{A2} + E_{B2}/Z_{B2} + E_{C2}/Z_{C2} + I_{i1} \).

By linearly transforming the matrix shown in equation (2), the voltage of the fault phase A phase can be obtained as:

\[
U_f = U_{a5} = E_A Y_{A1}(D+E) + E_B Y_{B1}(D+B) + E_C Y_{C1}(D+C) + E_A Y_{A2}(A+E) + E_B Y_{B2}(A+B) + E_C Y_{C2}(A+C) + I_{i1} + I_{i2} + I_{i3}
\]

In formula (3):

\[
A = \begin{pmatrix}
    g_A & -1 & 0 & 0 & 0 \\
    0 & 0 & g_A & -1 & 0 \\
    0 & 0 & 0 & 0 & g_A \\
\end{pmatrix} / g_1
\]

\[
B = \begin{pmatrix}
    g_A E_A^3 - E_A^3 & g_A E_A^2 - E_A^2 & g_A E_A - E_A \\
    E_A^3 & E_A^2 & E_A \\
\end{pmatrix} / g_1
\]
\[
C = \frac{1}{g_1} \left( \frac{c e c_2}{e_1} - c_i \right) - A \frac{g_2}{g_1} 
\]
(6)

\[
D = \frac{a_2}{a_1} \left[ (1 - \frac{c_2}{c_1} - \frac{c}{c_1} - \frac{c}{c_1} - A) + \frac{a_2 B}{a_1} + \frac{A c}{a_1} \right] 
\]
(7)

\[
E = 1 - \frac{c_2}{c_1} - \frac{c}{c_1} - \frac{c}{c_1} - A 
\]
(8)

In equations (4) to (8), \( c_1 = a_1 \frac{a_2 c_2}{a_1}, c_2 = a_1 \frac{a_2 c_2}{a_1}, c_3 = a_6, e_1 = c_3, e_2 = c_6 \frac{c_2 c_5}{c_1}, e_3 = c_7 - \frac{c_2 c_4}{c_1}, g_1 = e_1 - \frac{e_2^2}{e_1}, g_2 = e_3 - \frac{e_4 e_3}{e_4}, g_3 = e_4 \frac{e_3}{e_4} \). 

From equation (3), it can be known that when the active inverter injection current satisfies the equation shown in equation (9), the fault phase voltage will become 0V.

\[
- \left( E I_{a1} + B I_{a2} + C I_{a3} \right) = \hat{E}_{a1} Y_{a1} (D + E) + \hat{E}_{a2} Y_{a2} (D + B) + \hat{E}_{a3} Y_{a3} (D + C) + \hat{E}_{a1} Y_{a1} (A + E) + \hat{E}_{a2} Y_{a2} (A + B) + \hat{E}_{a3} Y_{a3} (A + C) 
\]
(9)

### 3. Active inverter injection

According to the number of active inverters put into operation, the injection method can be divided into single-phase injection, two-phase injection, and three-phase common injection. When the injection method is single-phase injection, each divided phase active inverter must meet the requirements:

\[
\begin{align*}
\hat{I}_{a} &= K[\hat{E}_{a1} Y_{a1} (D + E) + \hat{E}_{a2} Y_{a2} (D + B) + \hat{E}_{a3} Y_{a3} (D + C) + \hat{E}_{a1} Y_{a1} (A + E) + \hat{E}_{a2} Y_{a2} (A + B) + \hat{E}_{a3} Y_{a3} (A + C)] \\
K &= -1/E, \text{ if } k = 1 \\
K &= -1/B, \text{ if } k = 2 \\
K &= -1/C, \text{ if } k = 3
\end{align*}
\]
(10)

When single-phase injection is used, all compensation currents are provided by one-phase active inverter, and the output current of the other two-phase active inverter is 0. This injection method can be applied to lower voltage levels or active inverter devices. In the case of large capacity, when one phase of the active inverter fails and is in operation or one of the phases of the active inverter is overhauled, the remaining two phases of the active inverter can be used as backup to ensure the validity during the maintenance Arcing ability.

When the injection method is two-phase injection, each split-phase active inverter must satisfy the formula shown in equation (11). When two-phase injection is used, theoretically only the sum of the injected currents needs to satisfy Equation (9), and the injected currents of the active inverters of each split phase can satisfy Equation (11). The control strategy of the active inverter, the current ratio shared by the two active inverters that provide current should be the same, that is, \( l = 0.5 \). This injection method is suitable for the case where the capacity of the active inverter device is medium. When one of the active inverters injected with current is withdrawn from operation due to a fault or requires maintenance, the remaining active inverter can be used as a backup to ensure that effective arc extinction during maintenance.

When using three-phase common injection, each split-phase active inverter needs to meet satisfy Equation (10). When using three-phase common injection, theoretically only the sum of the injected currents needs to satisfy Equation (9), and the active inverter output currents of the divided phases can satisfy Equation (12), which also improves the service life of the arc suppression device and simplifies the control. Strategy, the current ratio shared by the three active inverters that provide current should be the same, that is, \( l = 1/3, p = 1/3 \).
4. Simulation analysis

Build a simulation model as shown in Figure 1 on MATLAB / SIMULINK. The system voltage is 10kV, the simulation time is set to 0.5s, a single-phase ground fault occurs at 0.1s, phase A is the fault phase, and active inverter at 0.3s. Injected current, where the type of distribution line wire is LJ-70, and the line parameters are determined by consulting the literature and looking up the table as shown in Table 1.

Table 1. Simulation line parameters

| parameter name | Value | parameter name | Value |
|----------------|-------|----------------|-------|
| $g_A / S$      | 1/1500| $Z_{A1} / \Omega$ | 0.7166+0.9 |
| $g_B / S$      | 1/1500| $Z_{B1} / \Omega$ | 0.7166+0.9 |
| $g_C / S$      | 1500  | $Z_{C1} / \Omega$ | 0.7166+0.9 |
| $c_A / \mu F$  | 15.9  | $Z_{A2} / \Omega$ | 3.58+4.5 |
| $c_B / \mu F$  | 15.9  | $Z_{B2} / \Omega$ | 3.58+4.5 |
| $c_C / \mu F$  | 15.9  | $Z_{C2} / \Omega$ | 3.58+4.5 |
| $Z_0 / \Omega$ | j75   | $R_f / \Omega$ | 200   |

The simulation is divided into two scenarios. The first scenario is the arc suppression based on active inverter split-phase injection when the fault resistance is constant, and the transition resistance is $R_f$; the second scenario is based on the Suppression of source-inverted split-phase injection. The fault current waveform in the first simulation scenario is shown in Figure 2 (a), and the fault current waveform in the second simulation scenario is shown in Figure 2 (b). From the fault current waveform in Figure 2, it can be known that the system will generate a larger fault current after a ground fault occurs. After the active inverter device injects current for 0.2s, the fault current will be reduced to 0 in
a short time. The voltage across the track gap will also be suppressed to 0V, and the AC arc will lose the conditions for reburning.

![Fault current waveform](image)

(a) Grounded via 200Ω  
(b) Arc ground

**Figure 2.** Fault current waveform

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5. Conclusion

Aiming at the inadequacy of the current active arc extinguishing method in deriving the injection current formula, the shortage of new energy power supply is not considered. This paper proposes an arc extinguishing method for new energy distribution networks based on active inverter split phase injection. This method obtains the injection current formula of the double-ended power distribution network by connecting the active inverter device at the head end of the line and pushing it through the node voltage method. The simulation results show that this method can effectively suppress the re-combustion of AC arc.

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