Application of Parallel Resonance System in Insulation Detection of Low Voltage Power Grid

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Abstract. This paper made analysis on the topic of Low-voltage network that contacts parallel resonance system with cable. A new method in detecting insulation parameters was presented through added testing resistance in single phase. The corresponding circuit model is established and the theory is proved that there is linearity among resonance capacitance, inductance and insulated resistance. Simulation study was carried out in this paper. The research shows: the testing error of this insulation detection method is within±0.5% which has high accuracy.

1. Preface
The insulation parameters of low-voltage power grid to the ground are important parameters related to the safe operation of power grid, which must be measured frequently. At present, there are mainly methods for measuring the earth insulation resistance, such as DC detection method[1], On line monitoring method of cable insulation with additional DC power supply[2], Multi-channel insulation resistance automatic detection method[3], Neutral point applied voltage method[4], and Injection signal measurement[5]. The above methods can not distinguish the insulation resistance and the distributed capacitance of the grid, which is easy to cause the measurement error. Moreover, the errors caused by additional components involved in calculation will affect the accuracy of calculation. For the above reasons, based on the analysis of the working principle of low voltage cable series resonance system, this paper presents an on-line measurement method of insulation resistance to ground by using additional grounding resistance. This method is safe and simple to operate and suitable for engineering applications.

2. Working principle of low voltage resonance system
The power supply circuit of series resonance system of low voltage network is shown in Figure 1. \( L_1, L_2, L_3 \) are three sets of inductors which are wound around the same high conductive core. The design ensures that the working flux is not saturated, which is approximately linear inductance, without magnetic leakage and full coupling \( L_1 = L_2 = L_3 = L \). Self-inductance equals mutual inductance \( M_1 = M_2 = M_3 = M = L \); \( R_0 \) is inductance internal resistance; \( r \) is the insulation resistance and \( C_0 \) is the ground distribution capacitance of the grid; \( R \) is for testing resistance; The three phase parallel capacitance equal \( C_1 = C_2 = C_3 = C \); \( L_1, L_2, L_3, C_1, C_2, C_3 \) is the three resonant circuit [6].
2.1. Operation of power grid with low voltage resonance system.

![Fig. 1 circuit diagram of insulation resistance test](image)

In the normal operation of the power grid, disconnecting switch $S$, from KCL, we can get formula (1),

$$I_{C1} + I_{C2} + I_{C3} + I_{L1} + I_{L2} + I_{L3} = I_A + I_B + I_C$$

(1)

because the relationship between voltage and current of inductance and capacitance satisfies the formula (2) to (3),

$$\begin{cases}
I_{C1} = j\omega C_1 (j\omega L_1 I_{L1} + j\omega M_{12} I_{L2} + j\omega M_{13} I_{L3}) \\
I_{C2} = j\omega C_2 (j\omega M_{12} I_{L1} + j\omega L_2 I_{L2} + j\omega M_{23} I_{L3}) \\
I_{C3} = j\omega C_3 (j\omega M_{13} I_{L1} + j\omega M_{23} I_{L2} + j\omega L_3 I_{L3}) 
\end{cases}$$

(2)

$$\begin{cases}
I_L = I_{L1} + I_{L2} + I_{L3} \\
I_C = I_{C1} + I_{C2} + I_{C3} \\
I_A + I_B + I_C = 0 \\
U_A + U_B + U_C = 0
\end{cases}$$

(3)

solute formula (1) to (3), we can get formula (4):

$$(1 - 3\omega^2 LC) I_L = 0$$

(4)

Because of no resonance ($3\omega^2 LC \neq 1$), therefore, $I_L = 0$. Then, the voltage drops at the two ends of the resonant system is shown in formula (5):

$$j\omega L I_L = j\omega L(I_{L1} + I_{L2} + I_{L3}) = U_{L1} + U_{L2} + U_{L3} = 0$$

(5)

From equate (5) it can be seen the voltage drop at the two ends of the resonant system is $0V$, and the three phase voltage is all added to the load. The low voltage resonance system has no effect on the normal operation of the power grid.

2.2 The magnitude of test current after additional grounding resistance.

Assuming additional grounding resistance $R$ in the A phase in Fig. 1[7,8], closing switch $S$, from KCL we can get formula (6):

$$I_{C1} + I_{C2} + I_{C3} + I_{L1} + I_{L2} + I_{L3} = I_A + I_B + I_C + I_R$$

(6)

solute (1) to (7), we can get formula(7), Because of the resonance ($3\omega^2 LC = 1$), the testing current is $I_R = 0$ which ensuring the safety of the test.
\[(1 - 3\omega^2 LC) I_L = I_R \]  

(7)

2.3 Load operation in case of failure

Through the analysis of Eq. (7), it is known that the phase voltage is measured after adding the grounding resistance, \( U_R = R I_R = 0 \), so the network equation of the power supply system after adding the grounding resistance is as formula (8):

\[
\begin{align*}
-U_A + j\omega L_1 I_{1L} + j\omega M_{12} I_{1L2} + j\omega M_{13} I_{1L3} + U_{1B} - (j\omega M_{12} I_{2L} + j\omega L_2 I_{2L2} + j\omega M_{13} I_{2L3}) + U_B &= 0 \\
-U_B + j\omega M_{12} I_{1L} + j\omega L_2 I_{1L2} + j\omega M_{23} I_{1L3} + U_{BC} - (j\omega M_{12} I_{3L} + j\omega L_3 I_{3L2} + j\omega M_{23} I_{3L3}) + U_C &= 0 \\
-U_C + j\omega M_{13} I_{1L} + j\omega M_{23} I_{2L} + j\omega L_3 I_{3L3} + U_{CA} - (j\omega M_{13} I_{3L} + j\omega M_{23} I_{3L2} + j\omega L_3 I_{3L1}) + U_A &= 0
\end{align*}
\]

(8)

Solute formula (8), we can get formula (9):

\[
U_{AB} + U_{BC} + U_{CA} = 0
\]

(9)

That is, the line voltage of the three-phase load is balanced, and the normal operation of the load is not affected by the additional grounding resistance, thus ensuring the reliability of the system power supply during the test process and realizing the on-line test.

3. Measurement of insulation resistance to earth

Additional grounding resistance \( R_f \). The switch S is closed in Figure 1, and the network equation is listed as formula (10):

\[
\begin{align*}
U_A &= j\omega L_1 I_{1L} + j\omega M_{12} I_{1L2} + j\omega M_{13} I_{1L3} + R_0 I_{1L} + r(I_1 - I_A - I_R) \\
U_B &= j\omega M_{12} I_{1L} + j\omega L_2 I_{1L2} + j\omega M_{23} I_{1L3} + R_0 I_{1L2} + r(I_2 - I_B) \\
U_C &= j\omega M_{13} I_{1L} + j\omega M_{23} I_{1L2} + j\omega L_3 I_{1L3} + R_0 I_{1L3} + r(I_3 - I_C)
\end{align*}
\]

(10)

Also, \( I_1 + I_2 + I_3 = I_{CL1} + I_{CL1} + I_{CL2} + I_{CL2} + I_{CL3} + I_{CL3} \)

(11)

The equation (3) (11) is substituted by equation (12).

\[
0 = 3 j\omega L_1 I_{1L} + R_0 I_{1L} + r(I_{L} + I_{C} - I_R)
\]

(12)

Also because of,

\[
\begin{align*}
j\omega L_1 I_{1L} + j\omega M_{12} I_{1L2} + j\omega M_{13} I_{1L3} + R_0 I_{1L} &= \frac{1}{j\omega C_1} I_{C1} \\
j\omega M_{12} I_{1L} + j\omega L_2 I_{1L2} + j\omega M_{23} I_{1L3} + R_0 I_{1L2} &= \frac{1}{j\omega C_2} I_{C2} \\
j\omega M_{13} I_{1L} + j\omega M_{23} I_{1L2} + j\omega L_3 I_{1L3} + R_0 I_{1L3} &= \frac{1}{j\omega C_3} I_{C3}
\end{align*}
\]

(13)

Solute(3) (13), we can get formula (14):

\[
I_C = -3\omega^2 LC I_{1L} + R_0 j\omega C I_{1L}
\]

(14)

Substituting (14) in (12), we can get formula (15):

\[
0 = \frac{3 j\omega L_1 I_{1L}}{r} + \frac{R_0}{r} I_{1L} + (I_{1L} + R_0 j\omega C I_{1L} - 3\omega^2 LC I_{1L} - I_R)
\]

(15)
In consideration of \( R_0 \ll r \), so \( I_0 \) is:

\[
I_0 = j(3\frac{\omega L}{r} + R_0\omega C) + (1 - 3\omega^2 LC)I_L
\] (16)

Under the resonance condition \( 3\omega^2 LC = 1 \), only when it is satisfied \( 3\frac{\omega L}{r} + R_0\omega C = 0 \) that the test current can be established \( I_0 = 0 \). The calculation of resonant inductance \( L \) and resonant capacitance \( C \) of the equation \( 3\frac{\omega L}{r} + R_0\omega C = 0 \) with minimum value under resonance condition \( 3\omega^2 LC = 1 \) is as the following:

Order, \( F(L, C, \lambda) = \frac{3\omega L}{r} + R_0\omega C + \lambda(1 - 3\omega^2 LC) \), then, we can get formula (17):

\[
\begin{align*}
\frac{\partial F}{\partial L} &= \frac{3\omega}{r} - \lambda 3\omega^2 C = 0 \\
\frac{\partial F}{\partial C} &= R_0\omega - \lambda 3\omega^2 L = 0 \\
1 &= 3\omega^2 LC
\end{align*}
\] (17)

By solving the equation (17), it is found that there is a certain functional relationship between resonant capacitance \( C \), inductance \( L \), internal resistance of inductance coil \( R_0 \), and angle frequency \( \omega \) and ground insulation resistance \( r \) and ground distributed capacitance \( C_0 \). That relational expression is in formula (18), (19):

\[
r = \frac{9\omega^2 L^2}{R_0}
\] (18)

\[
C_0 = \frac{1}{3\omega^2 L} - C
\] (19)

The parameters of resonant capacitance and inductance are known at design time, and the internal resistance of the inductance coil can be measured, so that the insulation resistance to the ground can be calculated.

**4. Simulation research**

The simulation circuit is in Fig.1, three-phase power supply is obtained, the inductance parameter of the inductance is 4.67H, the direct-current resistance parameter of the inductance is 0.2\( \Omega \), the adjustable capacity parameter is varied among 0.01\( \mu F \) to 0.33\( \mu F \), the load is 100H, the test resistance is 1\( k\Omega \). The simulation test is carried out by using simulation software PSpice.
The error between simulation results and calculation results is -0.092%. The simulation results are shown in Table 1:

| supply voltage ($V$) | inductance ($H$) | additional resistance ($\Omega$) | test current ($mA$) | insulation resistance ($\Omega$) | error ($\Delta r\%$) |
|----------------------|-----------------|-------------------------------|-------------------|-------------------------------|------------------|
| 220                  | 4.67            | $10^3$                        | 5                 | 98.01                         | -0.092           |

5. Conclusion
According to the above research and analysis, there is a certain proportion relationship among resonant capacitance, inductance and ground insulation resistance in the low voltage power supply system of series resonant system. The single-phase-to-ground fault is composed of additional resistance, and the value of ground insulation resistance can be safely measured on-line by choosing reasonable inductance parameters of resonant capacitance. This method is safe and simple to operate, and is suitable for engineering applications.

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