Online measurement of distributed capacitance in distribution network

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Abstract. The distributed capacitance current of distribution network is the main factor of single-phase grounding current. In the current engineering, the distributed capacitance current is mostly measured by testing the distributed capacitance. Using the volt and amper relationship of capacitor element can be indirectly realizing the test of distributed capacitance current. Most of the existing distributed capacitance measurement methods use the total impedance of the system to replace the distributed capacitance, which is easily to cause measurement error. Based on the analysis of the distribution network operation, this paper proposes an online measurement technology of distribution network which can precisely test the distributed capacitance. The physical engineering model is established, and the simulation research and design is carried out. The research shows that the online test technology of distributed capacitance can control the test accuracy below 1%, which can effectively make up for the deficiency of the existing distributed capacitance testing technology. It can realize the online detection of the distributed capacitance current of the distribution network, and ensure the operation safety.

1. Introduction

The distributed capacitance current of distribution network is the main factor that constitutes the single-phase grounding current of power grid. In the current engineering, the distributed capacitance current is mostly measured by testing the distributed capacitance. Using the volt and amper relationship of capacitor element can be indirectly realizing the test of distributed capacitance current. Most of the existing distributed capacitance testing methods replace the distributed capacitance with the total impedance of the power system, which is easily to cause measurement error and affect the test accuracy[1,2]. Moreover, the errors cause by additional components involve in calculation will also affect the accuracy of capacitance calculation. Based on the analysis of distribution network operation of series resonance system, this paper proposes an online measurement technology of distribution network to test the distributed capacitance. The online test technology of distributed capacitance has characteristics of high test accuracy, safety, and reliability, which can effectively make up for the shortcomings of the existing technology and ensure the safety of distribution network operation. It provides a good idea and method for insulation detection of distribution network.
2. Analysis of test circuit operation

2.1. Testing Principle

The circuit structure of the low-voltage distribution network of the series resonance system is shown in figure 1. The resonant system is composed of coils and capacitors in parallel. Each phase of the coil has the same self-inductance and mutual inductance, and the self-inductance is equal to mutual inductance; the three-phase parallel capacitance is equal. In order to discuss the problem conveniently, the influence of coil internal resistance is temporarily ignored. In the normal operation of distribution network, the three-phase coil current flowing through the resonance system is symmetrical, the three-phase magnetic potential in the iron core is balanced, and the voltage at both ends of the resonance system drops to zero. Therefore, the operation of the three-phase symmetrical system is not affected by the series resonance system [3]. In the test conditions, the single-phase grounding test point is built, which can be seen from the sequence component analysis that the voltage at both ends of inductance coil of each phase is the zero sequence voltage generated by zero sequence current. Using KCL theorem, the power supply circuit diagram with resonance system in figure 1 can be equivalent to the resonant grounding system of neutral point [4], as shown in figure 2. In this way, the high impedance provided by the resonant system suppresses the residual current at the test point and effectively ensures the safety of the tester and equipment.

![Figure 1. Power supply circuit with resonance system](image1)

![Figure 2. Equivalent circuit diagram](image2)

2.2. Test Security Analysis

In practical engineering, considering insulation parameters of power grid and the internal resistance of resonance coil, the equivalent circuit of the test system is shown in figure 3, and the physical quantities are expressed in vector form. Among them, the three-phase power supply are respectively with \( U_A \), \( U_B \), and \( U_C \); The resonant system has the same self-inductance as \( L_1 = L_2 = L_3 = L \); The mutual inductance is the same as \( M_{12} = M_{13} = M_{23} \), and they are completely coupled; The parallel capacitance is equal as \( C_1 = C_2 = C_3 = C \); The internal resistance of the coil is equal as \( R_{01} = R_{02} = R_{03} = R_0 \); \( C_0 \) is the distributed capacitance; \( r \) is the line resistance; \( Z \) is the three-phase symmetrical load; \( R_t \) is the test resistance. Assuming that phase A builds the grounding test point, the switch S is closed in figure 3 [5, 6].
Figure 3. Test system circuit

The network equations of a phase fault are obtained as equation (1) and (2).

Among equation (1) and (2), $I_R$ is test current; $I_{L1}$, $I_{L2}$, and $I_{L3}$ are inductance current of each phase; $I_{C1}$, $I_{C2}$, and $I_{C3}$ are capacitance current of each phase; $I_1$, $I_2$, and $I_3$ are current of each phase; $I_A$, $I_B$, and $I_C$ are load current. $I_0$ is zero sequence current of power grid; $I_{CO}$ is zero sequence current that flowing through the capacitance of each phase; and $I_{LO}$ is zero sequence current flowing through the inductance of each phase. According to the relationship between voltage and current of inductance and capacitance element, equation (3) is obtained.

By introducing equation (2) and (3) into equation (1), the expression of test current $I_R$ is as equation(4).

Using the method of conditional extremum to solve equation (4), the distribution capacitance $C_0$ and resonance parameters of the power grid $L$, $(C_0 + C)$ are obtained, which satisfy the equation (5).

From equation (5) we can see that selecting the appropriate resonance parameters can make the test current value to be $0.4$ and ensure the safety of the test process. The product of resonance parameters of distribution network is a mathematical relationship as $1/(3\omega^2)$.
3. Simulation study

3.1. Selection of Simulation Parameters

According to the operation of distribution network, the voltage amplitude of three-phase power line is taken as $380V$ in figure 3; the three-phase load is $Z_A = Z_B = Z_C = 200\Omega$; considering the factors of person and equipment in safety, the test resistance value is $R_f = 1\Omega$ which approximate to resistance of human body; the value of resonance parameters that inductance $L$, capacitance $(C_0 + C)$ are based on the following principles.

Through the transient analysis in the test situation, it can be seen from the analytical equation of the test current $i_p$ that the transient ends when the exponential term in the amplitude decays to $0A$. After the $3\tau-5\tau$ general time constant, the test current can be approximated as reaching the steady state, where $\tau = 6(C_0 + C)R_f$. According to the relationship between the safety current and the time specified in IEC-TC64 [7], the transition time is less than $10ms$, the test resistance $R_f$ and capacitance $(C_0 + C)$ are satisfied with equation (6).

$$30R_f(C_0 + C) \leq 10ms$$

In actual engineering test environment, in order to make the circuit parallel resonance and resonance frequency in real, the selection of inductance $L$, capacitance $(C_0 + C)$ and inductance internal resistance of resonant circuit $R_0$ should be satisfied with equation (7).

$$3L \geq (C_0 + C)R_0^2$$

Through the above analysis with equation (6) and (7), and according to the actual operation of the distribution network, the values of resonance parameters are limited in a limited range. We can order the values of resonance parameters as the following: the value of inductance is $L = 2.5H$, and its value of internal resistance is $R_0 = 0.5\Omega$; the capacitance value is $(C_0 + C) = 0.95\mu F$; the distribution network frequency is $50Hz$; according to figure 3, the system simulation program is compiled in normal and test condition, and the simulation results are shown in figure 4.

3.2. Simulation Result

3.2.1. Simulation results in normal operation.

Turn off the switch in figure 3, and the simulation results in normal operation are shown in figure 4.

3.2.2. Simulation results in test condition.

Closing the switch in figure 3, in test condition the simulation results are shown in figure 5.
It can be seen from figure 4 and figure 5, that the voltage drop at both ends of the resonance system is very small in the normal operation of the distribution network, which has no impact on the normal operation of the circuit, however, in the test condition, the voltage drop at shunt capacitor is almost equal to the supply voltage that shows the resonant circuit provides a high impedance. The detection voltage can drive the control system to act and switch the adjustable capacitance value reasonably in test environment. The test current drops below safety current in $10\text{ms}$ which keeps the test equipment and person in safety. The test results of distributed capacitance are shown in table 1. The test current is $5\text{mA}$ that is below safety current. The test error of grid distributed capacitance is less than 1% which has a high accuracy.

Table 1. Test results of distributed capacitance.

| Supply voltage $U$ (V) | Test current $I_R$ (mA) | Detection voltage $U$ (V) | Distributed capacitance $C_0$ (uF) | Error $\Delta C_0\%$ |
|------------------------|--------------------------|---------------------------|----------------------------------|---------------------|
| 202                    | 5                        | 5                         | 0.4034                           | +0.85               |
| 207                    | 5                        | 5                         | 0.4036                           | +0.87               |
| 217                    | 5                        | 5                         | 0.4034                           | +0.85               |
| 222                    | 5                        | 5                         | 0.4036                           | +0.90               |
| 224                    | 5                        | 5                         | 0.4037                           | +0.91               |

4. Test scheme design

Automation control technology is widely used in power grid monitoring system, which plays a positive role in improving the operation quality of power grid, realizing integrated regulation and optimizing the rational allocation of resources. PLC control technology has the functions of stability, compatibility, flexibility, and self-healing, it is widely used in modern smart grid monitoring system\cite{8,9}. For the series resonance system of distribution network outgoing line, PLC control technology is used to predict the line distributed capacitance. The prediction scheme is shown in figure 6. The switching control circuit of resonant capacitor is shown in figure 7.
Figure 6. Overall scheme of distributed capacitance test

As is shown in figure 6, the working principle is as follows: in the test environment, PLC sends out instructions, and the test resistance is attached to the test phase of the power grid by the resistance switching control circuit. The test current is transmitted to PLC control system through leakage current transformer TA. The PLC control system calculates, judges, and processes the detection results, then obtains the output display of the ground detection voltage, and compares it with \( V_0 \) by its control program to judge the value of the capacitance that needed to be put into the power grid, so as to realize the on-line and accurate regulation of the shunt capacitor.

5. Conclusion
In this paper, the distributed capacitance online test error is less than 1%, which has a high precision. The test current is below safety current which can keeps the test person and equipment in safety. This testing technology can indirectly realize the test of the distributed capacitance current of the distribution network, and effectively make up for the shortcomings of the existing technology in testing distributed capacitance current. It ensures the distribution network operation safety whether in normal operation or in test condition, and provides a new idea and method for the online monitoring of high voltage power grid.

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