The Partial Discharge Field Test of 1000kV Shunt Reactors

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Abstract. Aiming at the insulation performance field diagnosis of 1000kV shunt reactors, the series resonant withstand voltage test equipment is developed. The test equipment mainly consists of the frequency conversion power supply, the excitation transformer, the series resonant capacitor, the wave blocking resistor and the voltage divider. The resonant frequency is between 30 and 300 Hz, the rated voltage is 1200kV, and the capacity is 1000 kW. During the test, the discharge is monitored at the high voltage bushing terminal and the 1000kV reactor insulation is analyzed. By using the developed test equipment, the 1000kV reactor in 1000kV Xuyi Station is tested, which verifies the validity of the on-site partial discharge measurement test.

1. Introduction
The 1000kV Shunt Reactor is an important equipment to support the long-distance transmission of AC projects. In the 1000kV transmission and transformation projects that have been put into operation, there are many reactor insulation defects, such as the collision between the lead wire insulation support fixing bolt shield cap and clamp fixing bolt. From the field test technology of 1000kV shunt reactors, the test voltage in the existing test items is far lower than the reactor operating conditions, so it is difficult to effectively detect the reactor insulation defects.

At present, IEC 60076, GB 1094.3 have made detailed provisions on lightning impulse test, switching impulse test and induced voltage withstand test to assess the insulation of 1000kV shunt reactors. Q/GDW 306-2009 requires the lightning impulse test, operation impulse test and long-term induced voltage test at the high voltage side of UHV reactors in factory test, which is used to check the main insulation at high voltage side and longitudinal insulation of windings. However, there are no requirements for the impulse and induced voltage withstand test of 1000kV reactor in the field test, and there is no relevant experience to follow [1-3]. Since 2008, Ma Jixian, Liu Yun and others have successively carried out series resonance withstand voltage tests on 500kV Shunt reactors, which verified the feasibility of on-site induction withstand voltage test [4-5]. Wu Peng, Wang Shengjie and others analyzed the field partial discharge test method of 1000kV and 750kV shunt reactors [6-8]. For the partial discharge test of UHV reactors, there are many problems, such as large test capacity and complex test equipment. Due to the wide range of high voltage area, the PD shielding technology is difficult, and the design of PD detection circuit is complex. In order to solve these problems, the key parameters of the main equipment of the series resonant circuit are calculated, and then the equipment is developed including the capacitor, voltage equalizing cover and other equipment. Finally, the field test is carried out in the 1000kV Xuyi station to verify the effectiveness of the field test.
2. Calculation of key parameters of main equipment in withstand voltage test

The test voltage is generated based on the principle of series resonance. During the test, the high-voltage shunt reactor is an inductive element and resonates with the capacitor in series to generate high voltage. The power supply only provides the active power loss of the circuit. The test equipment is mainly composed of frequency conversion power supply without partial discharge, excitation transformer, resonant capacitor, wave blocking reactor, voltage divider without partial discharge, etc. During the withstand voltage test, the partial discharge signal is monitored through the end screen of the high voltage bushing of the reactor. The electrical connection diagram of test equipment is shown in Figure 1.

![Figure 1. Schematic diagram of electrical connection for equipment](image)

The technical parameters of 1000kV shunt reactors of UHV Xuyi station are shown in Table 1. Taking it as an example, the key technical parameters of main equipment in the test equipment are calculated.

| Parameters          | Values | Parameters          | Values |
|---------------------|--------|---------------------|--------|
| Rated capacity/MVA  | 240    | Rated voltage/kV    | 1100 / √3 |
| Loss/kW             | 450    | Winding resistance/Ω | 1.6    |
| Rated reactance/Ω   | 1680   | Rated inductance/H  | 5.53   |
| Rated frequency/Hz  | 50     | Rated current/A     | 378    |

2.1. Determine the test frequency

At present, the adjustable frequency range of the mature frequency conversion power supply is between 30 and 300Hz. Referring to the factory test requirements of Q/GDW 306-2009 for 1000kV shunt reactor, the test frequency is no less than 100Hz. So the frequency in the reactor withstand voltage test is between 100 and 300. The test resonance frequency is related to the loop inductance and capacitance, and the calculation formula is shown in formula (1). The higher the frequency is, the smaller the series resonant capacitance is when the inductance of the tested reactor is determined. But the increase of frequency will increase the active power loss of the resonant capacitor. Based on comprehensive consideration, the test frequency of 250Hz, which is the base to design the main equipment.

\[ f = \frac{1}{2\pi\sqrt{LC}} \]  

2.2. Determine the maximum test voltage

Referring to the requirements for factory test of 1000kV shunt reactors in Q/GDW 306-2009, the maximum test voltage \( U_m = 1.7U_m / \sqrt{3} = 1080kV \), as shown in Figure 2.
2.3. Calculation of key parameters of main equipment

In this section, the key parameters of resonant capacitor, excitation transformer, frequency conversion power supply, wave blocking reactor and voltage divider are calculated.

When the test voltage is 1080kV and the frequency is 250Hz, the current flowing through the reactor and resonant capacitor is equal, and the value is 128A.

1) The high voltage end of the resonant capacitor is connected to the high voltage end of the reactor under test, and the voltage is 1080kV. The low voltage end of the resonant capacitor is connected to the excitation transformer, and the voltage is related to the quality factor of series resonant circuit. In the circuit, the quality factor $Q = (\omega L) / R$, in which $L$ and $R$ are the inductance and resistance in the resonant circuit respectively. The way to increase the quality factor $Q$ is to reduce the loop loss resistance.

According to formula (1), the capacitance of resonant capacitor $C$ is 75.82nf. Suppose that the voltage at the low voltage end of the capacitor is close to 0, the capacitor bears 1080kV voltage and 128A current. With a certain margin, the rated voltage of the capacitor is 1200kV and the working frequency is between 30 Hz and 300Hz.

2) The excitation transformer has the function of boosting voltage. Its low-voltage side is connected with the output end of frequency conversion power supply, and its high-voltage side is connected with resonant capacitor. The working frequency is between 30 and 300Hz. Considering the difference of the tested reactor and the uncertainty of the loop resistance, the quality factor can not be determined, which is generally from 100 to 900. So the transformation ratio choices should be flexible. The low voltage side of excitation transformer is generally set with 350V, 400V and 450V. And the high voltage side is set with multiple choices between 15kV and 1.5kV.

The capacity of excitation transformer should be greater than the sum of active power loss of capacitor, reactor, excitation transformer and other equipment. And the active power loss of capacitor and reactor is the main sources. The active power loss of reactors includes iron loss and copper loss, which is about 282kW at 250Hz[7]. The active power loss of the resonant capacitor is related to the dielectric loss of the capacitor. It is conservatively estimated that the dielectric loss is less than 0.3%. According to the dielectric loss, the capacitor loss is 416kW. Therefore, the capacity of excitation transformer is required to be greater than 700kW. Considering the loss of excitation transformer itself, it needs to be further increased. The design capacity of excitation transformer is 1000kVA, and each transformer is 500KVA in parallel.

3) The frequency conversion power supply converts the power frequency into 30 - 300Hz, and the converted frequency is the resonant frequency. The low voltage side of the frequency conversion power supply is connected with a 50Hz three-phase power supply, and the high voltage side voltage is 350V, 400V and 450V. The capacity of frequency conversion power supply should be larger than the excitation transformer, because of the loss of frequency conversion power supply itself. The design capacity is 1000kVA, composed of two sets in parallel and each one is 500kVA.
4) Considering the partial discharge requirement of the test, in order to shield the external interference of the reactor, a wave blocking reactor is installed between the reactor and the resonant capacitor. The wave blocking reactor can block the partial discharge signal whose center frequency is about 100kHz, and does not affect the test under the test frequency. In this paper, the inductance of wave blocking reactor is 2mH and the current carrying capacity is 150A.

5) The voltage divider is used to measure the voltage information in the withstand voltage test of the tested reactor. According to the maximum voltage 1080kV in the test, the rated voltage of the capacitor divider is 1200kV.

| equipment               | number | key parameters                      |
|-------------------------|--------|-------------------------------------|
| frequency conversion power supply | 2 sets | 500kW; 30-300Hz.                   |
| excitation transformer  | 2 sets | 500kVA; 30-300Hz; multiple ratios. |
| capacitor               | 12 sets| 300kV; 101.34nF; 30-300Hz; three sets in parallel which form a group and four groups in series |
| wave blocking reactor   | 1 set  | 2mH; 150A.                          |
| voltage divider         | 1 set  | 1200kV.                             |

### 3. Development of field withstand voltage test equipment

In the withstand voltage test equipment of 1000kV shunt reactor, the frequency conversion power supply, excitation transformer, wave blocking reactor and voltage divider have mature product design. However, there is no mature product in the market of high voltage and large capacity resonant capacitor.

In this paper, a 300kV/101.34nf capacitor is developed, which adopts film paper composite insulation. Under the test voltage of 300kV and frequency of 250Hz, the dielectric loss is 0.03%, which is greatly reduced compared with the design value.

Because the low voltage end of the capacitor is connected with the high voltage of the excitation transformer, the voltage is relative to the quality factor. And the insulation support base is installed at the low voltage side of the capacitor to realize the insulation to the ground, as shown in Figure 3.

In addition, the capacitor equalizing cover needs to meet the requirements of no corona under the applied voltage of 1080kV, which is also a difficult problem due to the limitation of transportation. The double-layer structure is adopted in the developed equalizing cover, and the double layers are connected by four supporting rods, which is convenient for arranging the wave blocking reactor and connecting the high-voltage leads. Each ring in the layers consists of two semicircles. The equipment is assembled before the test, and disassembled and transported after the test.

(a)the capacitor support base          (b)the capacitor equalizing cover

Figure 3. Capacitor support base and equalizing cover
4. Field withstand voltage test

At Xuyi station, the equipment developed was used to carry out the partial discharge measurement test, as shown in Figure 4. According to the factory test of high voltage reactor and the requirements of on-site handover test of 1000kV transformers, the time sequence and voltage requirements of voltage applied in on-site test of 1000kV reactor are determined, which is shown in Figure 5.

$$A=5\text{min}, \ B=120\times\text{rated frequency/test frequency}, \ C=60\text{min}$$

$$U_m=1100\text{kV}, \ U_1=1.1U_m/\sqrt{3}=698\text{kV}, \ U_2=1.3U_m/\sqrt{3}=825\text{kV}, \ U_3=1.5U_m/\sqrt{3}=952\text{kV}$$

In the test, the test frequency is 239.1 Hz and quality factor $Q = 380$. In different stages of the test, the voltage and current at the high-voltage end of the reactor, the apparent discharge of the high-voltage bushing end screen detection, and the voltage at the high-voltage side of the excitation transformer are shown in Table 3.

Table 3. Measurement data during the test

| High voltage terminal voltage (kV) | Discharge quantity (pC) | High voltage side voltage of excitation transformer (kV) | Low voltage side current of excitation transformer (A) | Low voltage side voltage of excitation transformer (V) |
|-----------------------------------|-------------------------|--------------------------------------------------------|------------------------------------------------------|------------------------------------------------------|
| 696                               | 70                      | 1.8                                                   | 408                                                  | 188                                                  |
| 821                               | 92                      | 2.2                                                   | 485                                                  | 216                                                  |
| 949                               | /                       | 2.5                                                   | 560                                                  | 245                                                  |

5. Conclusion

Through series resonant circuit design, equipment development and field test, the new equipment and method are provided for field insulation detection of 1000kV reactor.
(1) Based on the principle of series resonance, the field withstand voltage test equipment for 1000kV reactor is mainly composed of frequency conversion power supply, excitation transformer, resonant capacitor, wave blocking reactor and voltage divider. The key technical parameters of the equipment are obtained through calculation.

(2) The 300kV/101.34nf capacitor and 1200kV equalizing cover for capacitor were developed, which solved the problems of transportation and installation.

(3) The 1000kV reactor test in Xuyi UHV power station verifies the effectiveness of the equipment and method, and provides experience for the insulation assessment and diagnosis of UHV reactors.

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