How to Evaluate Insulation Condition of 750kV Power Transformer Based on FDS

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Abstract: The reliability of power transformer depends to a large extent on the insulation system. The lifetime of power transformer shortens with the deterioration of insulation system. The power transformer is expected to extend its service life and operate safely. Therefore, insulation diagnosis and lifetime evaluation are necessary. In this paper, a new test method based on frequency domain spectroscopy (FDS) is presented. The 750kV power transformer in Lanzhou East substation is measured on site through the FDS method. The measured results are consistent with those of preventive test. The water content of power transformer is qualified and insulation condition is good. The FDS method, a new preventive test method, will be widely used in future.

Key words: oil-immersed transformer, dielectric response, FDS, insulation, aging

1. Introduction

The oil-immersed power transformer is one of important pieces of equipment in the electric system and plays a prominent role in safe operation of electric system. The reliability of electric system operation depends to a large extent on insulation system. According to the statistics, accidents caused by various insulation faults account for above 85% of all power transformer accidents. The insulation intensity of power transformer declines as a result of the impact of electric, thermal and mechanical stress. Generally speaking, lifespan of power transformer ranges from 20a to 40a. As the power transformer extends the service time, some has been phased out while others are still in service. Considering the economy and safety, power transformer is expected to extend its service life and operate safely. Hence, it is necessary to conduct the insulation diagnosis and lifetime evaluation for oil-immersed power transformer to determine whether an old transformer continues to work or should be inspected and maintained.

According to dielectric physics, dielectric materials are prone to have many response phenomena in the electric field, such as return voltage, polarization depolarization current and frequency domain spectroscopy (FDS). In recent years, researchers abroad have applied these test methods to insulation tests of field electric equipment. They belong to nondestructive testing (NDT) methods and it is not necessary to hang the cover. However, the study of these methods just started at home.

Compared with other methods, FDS method has more advantages. The author introduces the method and applies it to diagnose the insulation condition of power transformer. The on-site instance is also given.

2. Principle and Method of Diagnosing Insulation Condition of Power Transformer

The insulation system of oil-immersed power transformer is mainly composed of insulation oil and solid insulation (paper, insulation board, and belt). As the aging of power transformer intensifies, mechanical intensity of solid insulation will decrease, which leads to the reduction of transformer winding's capability to resist the impact of high current of short circuit and the reliability of power transformer operation. The lifetime of power transformer is directly determined by the condition of solid insulation. At present, the most commonly used methods to diagnose solid insulation include TS, DP, DGA and Furan etc. These methods have some limitations to certain degree.

A series of products such as CO, CO_2, furfural, acetone and moisture will generate in the solid insulation during the process of aging because of chemical action. The moisture is the aged product, but meanwhile, it can accelerate the process of aging. The moisture content of solid insulation, an important sign of aging degree, can be used to reflect the aging condition of solid insulation. The Karl-Fischer titration approach is utilized to measure the moisture content. According to the balanced relation of oil-paper moisture, the moisture content of solid insulation can be calculated. Above 99% of moisture exists in the solid insulation and less than 1% remains in the oil. In addition, the moisture moves from the oil to the paper under different temperatures. It needs a long time for the moisture to balance between oil and paper. Hence, this method has great limitations.

The moisture, as a strong-polarity dielectric, has a significant influence on the polarity feature of oil-paper insulation. So, the dielectric response method can be adopted to reflect the moisture content, and further the aging condition of insulation.

3. Basic Principle of FDS

Assume that dielectric material is linear, even and isotropic, measuring results of FDS depend on the dielectric response function. The dielectric response function *f*(t) shows the impulse response of medium material, satisfying the following formula:

$$f(t)=0,\ \forall t<0 \quad \lim_{t\to\infty} f(t)=0 \tag{1}$$

As for isotropic medium, there exists the following relation:

$$D(t)=\varepsilon_0 E(t)+P(t) \tag{2}$$

The relation between the polarization and dielectric response can be expressed as follows:

$$P(t)=\varepsilon_0\int_{-\infty}^{t} f(t-\tau)E(\tau)\mathrm{d}\tau=\varepsilon_0\int_{0}^{\infty} f(\tau)E(t-\tau)\mathrm{d}\tau \tag{3}$$

According to Maxwell equation, when electric field $E(t)$ is applied on dielectric material and t=0, current density represented by $j(t)$ will generate:

$$j(t)=\sigma_0 E(t)+\frac{\mathrm{d}D(t)}{\mathrm{d}t} \quad (4)$$

Where:

σ_0--DC electric conductivity of dielectric material

The current density flowing through dielectric material will be obtained:

$$j(t)=\sigma_0 E(t)+\varepsilon_0\frac{\mathrm{d}E(t)}{\mathrm{d}t}+\varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\int_0^t f(t-\tau)E(\tau)\mathrm{d}\tau \quad (5)$$

In the frequency domain, the polarizability is the Fourier transform of dielectric response function:

$$\chi(\omega)=\chi'(\omega)-i\chi''(\omega)=\int_0^\infty f(t)\exp(-i\omega t)\mathrm{d}t \quad (6)$$

The polarization action under frequency domain can be expressed as follows:

$$P(\omega)=\varepsilon_0\chi(\omega)E(\omega) \quad (7)$$

$$j(\omega)=\sigma_0 E(\omega)+i\omega D(\omega) \quad (8)$$

The formula (2) and (6) are combined into (9):

$$j(\omega)=\{\sigma_0+i\omega\varepsilon_0[1+\chi'(\omega)-i\chi''(\omega)]\}E(\omega)=\{\sigma_0+\omega\varepsilon_0\chi''(\omega)+i\omega\varepsilon_0[1+\chi'(\omega)]\}E(\omega) \quad (9)$$

Definition:

$$D(\omega)=\varepsilon_0\varepsilon_r(\omega)E(\omega)=\varepsilon_0[1+\chi'(\omega)-i\chi''(\omega)]E(\omega) \quad (10)$$

Therefore:

$$\varepsilon_r(\omega)=\varepsilon_r'(\omega)-i\varepsilon_r''(\omega)=1+\chi'(\omega)-i\chi''(\omega) \quad (11)$$

The dielectric coefficient can be expressed:

$$\tan\delta(\omega)=\frac{\varepsilon_r''(\omega)}{\varepsilon_r'(\omega)}=\frac{\chi''(\omega)}{1+\chi'(\omega)} \quad (12)$$

Complex capacitance $C(\omega)$ is introduced. The relation between current and voltage is as follows:

$$I(\omega)=i\omega C(\omega)U(\omega) \quad (13)$$

$$C(\omega)=C'(\omega)-iC''(\omega)=C_0\{\varepsilon_r'(\omega)-i\varepsilon_r''(\omega)\} \quad (14)$$

$$\tan\delta(\omega)=\frac{C''(\omega)}{C'(\omega)} \quad (15)$$

Within the frequency domain, the dielectric attribute of dielectric material can be represented by complex capacitance and relative complex dielectric constant. Through calculating impedance value of dielectric material under different frequencies, corresponding complex capacitance and relative complex dielectric constant can also be obtained. Accordingly, FDS will be gained.

The oil-paper insulation system is composed of transformer oil and insulation pasteboard and will generate interface polarization. The dielectric response of mineral oil is relatively simple and is determined by dielectric coefficient. On the contrary, power transformer pasteboard is determined by its dielectric response function. The moisture content and aging products affect the function. If the dimension and response function of one dielectric are known, dielectric response of insulation system can be calculated.

4. On-site Test for 750kV Power Transformer Based on FDS

4.1 Test instrument and measuring method

The relevant instrument can be used to obtain the FDS of power transformer insulation, for instance, IDAX-206 insulation diagnosis analyzer. The instrument can apply the variable frequency AC voltage to two terminals of insulation system. The complex capacitance tan δ is calculated by measuring the current, which flows through the insulation system. Then frequency attribute curve is obtained. The MODS software is used to conduct fitting analysis for curves. The moisture content in the power transformer pasteboard is clear so that we can determine the condition of the insulation for power transformer.

Based on whether or not the insulation to be measured is grounded, there are two wiring methods - UST (Ungrounded Specimen Test) and GST (Grounded Specimen Test). The UST method is mainly applied to these test objects with both terminals ungrounded while the other method is used for test objects with one terminal grounded.

Corresponding measuring templates are internally installed in the IDAX-206 based on the difference of equipment and insulation type. The corresponding template is chosen and wiring is done. Then, measurement of relevant parameters are realized.

4.2 On-site wiring method

The No.1 750kV main transformer in Lanzhou East substation was put into operation in September 2005. The power transformer is made up of three single-phase power transformers and one spare-phase power transformer. The power transformer belongs to three-winding structure (750/330/63kV); self-coupling winding for high and medium voltage; star connection; neutral point is grounded; triangle connection for low voltage. In June 2008, IDAX-206 tester is used to conduct the FDS test for phase A and B power transformer, and spare phase power transformer.

In the test, outlet terminals of high-voltage bushings of phase A and B power transformer are connected with power grid, and it is hard to disconnect them. Besides, the busbar is connected to arrester, capacitive voltage transformer and grounding knife switch. There are plenty of additional capacitance, which has a great impact on results. Therefore, low-voltage terminals of power transformer should be connected with high-voltage electrodes (Hi) of tester while grounded high voltage, medium voltage and neutral point are linked to low-voltage electrode (Lo) and grounding electrode (Ground) of tester. By doing so, GST wiring method without shielding is formed, which is shown in Fig.1 (a). At this time, measuring results reflect the whole insulation of low-voltage winding to high-medium voltage winding and ground, that is, $C_T//C_{HT}$. However, high-medium voltage winding to ground insulation C_H is not reflected. Based on the on-site condition, if the wiring method is adjusted flexibly and the effect of line on the test is eliminated, some insulation parameters can still be measured.

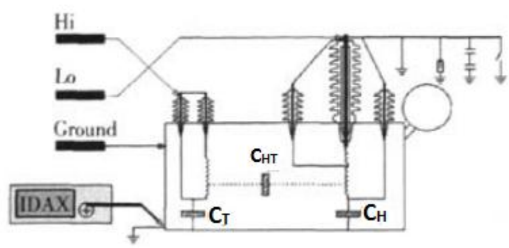

Fig.1 (a) Diagram of C_T & C_{HT} insulation wiring

The spare-phase power transformer is dissociated from the system and all its windings are not connected with power grid. The corresponding template can be adopted to measure. Wiring methods are shown in Fig.1 (b) and (c). The C_{HR} (high-medium voltage winding to low-voltage winding), C_H (high-medium voltage winding to the ground) and low-voltage winding to ground and low-voltage winding to ground C_T insulation are measured respectively. In order to compare with phase A and B power transformer, they can also be measured according to wiring method shown in Fig.1(a).

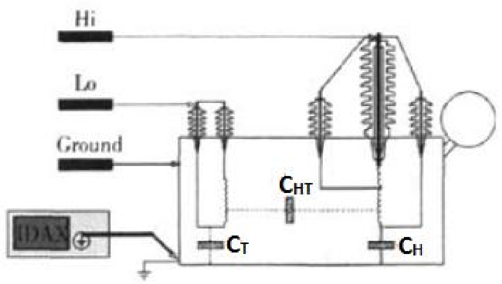

Fig.1 (b) Diagram of C_H & C_{HT} insulation wiring

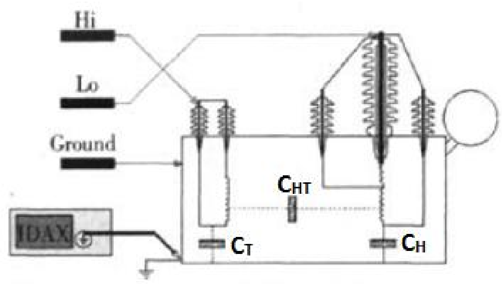

Fig.1 (c) Diagram of C_T insulation wiring

5. Measuring Results and Analysis

5.1 Curve of dielectric frequency attribute

The tan δ -f attribute curve of phase A, B and spare power transformers shown in Fig.2 (a) is obtained through the wiring method shown in Fig.1 (a). Under different temperatures, tan δ -f attribute curves of spare power transformer shown in Fig.2 (b), (c) and (d) are gained according to Fig.1(b) and (c).

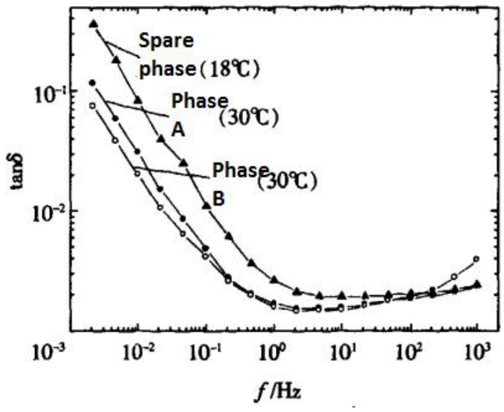

Fig.2 (a) C_T//C_{HT} insulation of each phase transformer

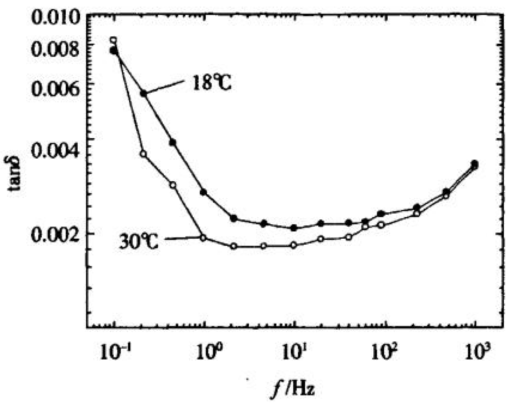

Fig.2 (b) C_H insulation of spare phase transformer

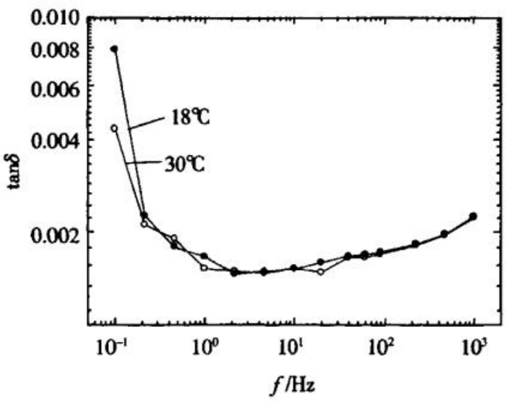

Fig.2 (c) C_{HT} insulation of spare phase transformer

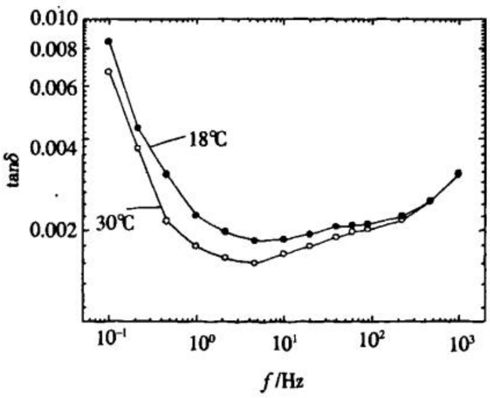

Fig.2 (d) C_T insulation of spare phase transformer

5.2 Moisture content and analysis of dielectric attribute

According to results, MODS software offered by the instrument is used to estimate the moisture content in the solid insulation. Results are shown in Tab.1 and 2.

Tab.1 Estimation of moisture content in solid insulation of $C_T//C_{HT}$

Test object	Oil temperature/℃	Moisture content/%
Phase A	30	0.4
Phase B	30	0.4
Spare phase	18	0.7

Tab.2 Estimation of moisture content in solid insulation of No.1 750kV transformer spare phase

Insulation type	Phase	Oil temperature/℃	Moisture content /%
High-medium voltage-ground	C_H	18 30	0.8 0.8
High-medium voltage-LV	C_{HT}	18 30	0.8 0.4
LV-ground	C_T	18 30	0.8 0.4

According to the *Regulations for Preventive Test*, the moisture content in the new power transformer pasteboard should be less than 0.5%, and less than 1.0% for transformer in operation. If the moisture content ranges from 1.5% to 2.5%, power transformer is damped; if moisture content is between 2.5% and 4%, power transformer is badly damped.

Based on the results, moisture content in all insulation of power transformer is no more than 1.0%. It is preliminary determined that insulation condition of phase A, B and spare phase is good.

According to Fig.2 (a), tan δ -f attribute curve of phase A power transformer is basically overlapped with that of phase B power transformer. During the operation, the load of phase A transformer and phase B transformer is almost balanced, so it is determined that aging degree and moisture content are basically the same. All can be verified through the data shown in Tab.1.

Compared with spare-phase power transformer, both phase A and phase B power transformer are bound to age once put into operation and moisture content is higher. But the difference is small because of short years of service. Given the temperature discrepancy, insulation temperature is obviously lower (18°) when spare phase power transformer is being measured. According to the principle pf oil-paper moisture balance, the moisture will move from the oil to the board. Therefore, even if spare phase transformer is not put into use, the moisture content in the solid insulation is still higher than phase A and B. The comparison of Fig.2 (a) and Tab.1 shows that the lower the temperature is, the easier the moisture moves to solid insulation. So the value of dielectric will become greater.

In the Fig.2 (b), (c) and (d), part of insulation of spare power transformer C_H and C_T have very high dielectric value when the temperature is low. While the dielectric value of C_{HT} is not affected by the temperature. Reasons are as follows. The winding insulation of power transformer is mainly made up of oil-paper compound insulation. The pasteboard and brace occupy a large proportion. The moisture content in the paper will greatly affect the FDS. The winding to ground insulation is mainly composed of transformer oil, which plays a decisive role in insulation condition. When the temperature falls, the moisture spreads to the pasteboard. It takes several months to balance. That is impossible for power transformer in actual operation. When the temperature falls, the moisture converts into floating moisture. So, the oil presents strong polarity and the dielectric value increases, which is shown in Fig.2 (b) and (d). The moisture content in the pasteboard changes slightly and the dielectric value remains the same, which is shown in Fig.2 (c).

5.3 Comparison of FDS and preventive test

The FDS method is used to obtain the test data of low-voltage winding to high-medium voltage winding and ground for phase A and B power transformer. Please refer to Tab.3.

Tab.3 Data of 750kV power transformer under power frequency

PT	Temperature/℃	Cx/pF	Tan δ /%
Phase A	30	26290	0.1792
Phase B	30	25790	0.1787

Data of preventive test for this transformer is shown in Tab.4.

PT	Date	T/℃	Cx/pF	Tan δ /%
Phase A	16-05-2007	32	26323	0.177
	27-04-2006	18	26562	0.179
Phase B	15-05-2007	27	25831	0.177
	25-04-2006	22.5	26081	0.181

Based on Tab.3 and Tab.4, it is found

that the data obtained through FDS method is consistent with preventive test data. The FDS can be used for measuring the dielectric and capacitance of oil-paper insulation.

6. Conclusions

The No.1 750kV main transformer in Lanzhou East substation is measured through the method of FDS. The moisture content in the solid insulation of this transformer is less than specified value and its insulation id good.

The FDS method is a nondestructive and easy-to-use diagnosis method. It is not necessary to hang the cover of power transformer and take a sample. Measuring results are correct and reliable. This method is suitable for on-site test. The moisture content in solid insulation can be estimated through measuring the FDS of oil-paper insulation system. Based on that, we can diagnose and evaluate the aging degree of power transformer. It is a supplement to traditional solid insulation diagnosis methods and will be widely used in the future.

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