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The Nonlinear Behavior of the Transformer Insulation System

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Abstract- Dielectric Response Analysis of power transformer is widely used in a number of field tests and research projects. Both Dielectric Frequency Response (DFR) and Polarization and Depolarization Current (PDC) combined with proper paper-oil modeling are able to give more reliable condition assessment of power transformers. Power factor/dissipation factor test at power frequency (50/60 Hz) usually exhibits a flat response as a function of test voltage if the insulation is in good condition. However, the voltage dependent behavior starts to appear if the existence of the polarization voltage is prolonged. The mineral oil and cellulose of the transformer/bushing insulation system form the interface where electric charges accumulate and thus the nonlinear property shows. The nonlinear property depends on the electric field strength as well as the geometry of the insulation system. Several transformers with different power ratings and a condenser bushing are tested by the Dielectric Response method from 20 V to 1.4 kV_{rms}. The measurements show that the nonlinear behavior may exist at low frequencies while the high frequency parameters are voltage independent. Furthermore, larger power transformers are less sensitive to the test voltages. The high voltage distortion of the PDC method could be more than the DFR method because of its longer polarization period. The test voltage and frequency need to be carefully chosen before carrying out any insulation test.

Keywords: Power transformer, bushing, Dielectric Frequency Response, Polarization and Depolarization, cellulose, mineral oil, insulation, moisture determination, nonlinear behavior, voltage dependent, distortion.

I. INTRODUCTION

Moisture is one of the factors deteriorating the insulation of the power components. The presence of moisture in power transformers decreases both electrical and mechanical strength.

Various methods are available to evaluate the moisture condition in power transformers. Some of these methods such as power factor (PF), dissipation factor (DF), loss tangent ($\tan\delta$) testing and insulation resistance (IR) testing have been used by industry for decades to evaluate the insulation system of large power transformers. Advanced diagnostic technologies [1] such as Dielectric Frequency Response (DFR) method, and Polarization-Depolarization Current (PDC) method have been recently developed as a more effective diagnostic tool because they could distinguish properties of both cellulose and oil insulation.

Power factor/dissipation factor testing of transmission transformers is usually performed at 10 kV and at line frequency, while the voltage of IR testing depends on the rating of power transformers. DFR and PDC methods are usually performed at low voltages, typically below 2 kVpp. The voltage dependence of the oil - paper insulation system is investigated and analyzed in this paper. The thorough research is done on a medium size transformer located in Sweden. For other components, the voltage dependent feature is presented and discussed briefly

II. DFR TESTING AND PDC TESTING

The insulation PF (DF or $\tan\delta$) testing of power transformers is carried out at line frequency. The DFR method is similar to the power factor test except that it measures the capacitance and loss of transformers in a wide-frequency range, typically from 1 kHz down to 1 mHz. The advantage of the DFR method is that with the mathematic model [2] and a reference database, it can easily distinguish the properties of cellulose and of oil respectively. The moisture content in the cellulose and the conductivity of the oil are obtained.

The IR testing measures resistance of the insulation in power transformers over time. It applies a DC voltage to the test object and records the test current. The PDC method is an extension of IR testing except that the test time is longer, typically 10,000 (ten thousand) seconds. Fig. 1 is an example of the DFR response and the polarization current of the interwinding insulation of a transformer.

Fig. 1. Typical (a) DFR test results and (b) polarization current test result

III. VOLTAGE DEPENDENCE OF THE INSULATION PROPERTY

A power transformer rated at 2 MVA is tested by the frequency domain method, DFR and the time domain method, PDC respectively. The test voltages are between 20 V and 1.4 kVrms.

A. Testing in the Frequency Domain

Fig. 2 shows the (a) capacitance and (b) loss factor of a power transformer located in Sweden measured at various frequencies from 1 kHz to 1 mHz. It could be seen from the figure that low frequency property of the insulation material shows the voltage dependent phenomenon.

To be able to know which voltage curve gives more reliable insulation property, the test current curves at some low frequency points are recorded and shown in Fig. 3. The y-axis is the p.u. current value which is calculated as the measured current divided by the RMS value of the test voltage.

Fig. 2. DFR results at various test voltages. (a)/ (b) represents the real/imaginary part of the complex permittivity.

Fig. 3 Test currents of the transformer at some low frequency points

The current curves indicate that as the frequency goes lower and the test voltage increases, the distortion of the test current starts to appear. The distortion of the current curve reflects that the insulation system is not linear anymore. The total harmonic distortion (THD) is defined as the ratio of the sum of the all harmonic currents to the current of the fundamental frequency. In this case it is given by:

$$THD = \frac{\sqrt{\sum_{n=2}^8 I_n^2}}{I_1} \quad (1)$$

At 20 V, the harmonics at all testing frequencies are very close to zero. Each harmonic content and THDs at 1.4 kV_{rms} are listed in the table. It shows that at high voltages, with the decrease of the test frequency, the 3rd harmonic starts to

appear and becomes more significant. This is the main reason for the current curve distortion. The harmonics of the test current are recorded in Table I.

TABLE I
THD_i at various test frequencies and voltages

Harmonic Components	Test Frequency (mHz)			
	1	2.1	4.6	10
n = 2 @ 1400V	0.0006	0.0011	0.0023	0.0020
n = 3 @ 1400V	0.0489	0.0306	0.0246	0.0178
n = 4 @ 1400V	<0.001	<0.0010	<0.0010	<0.0010
n = 5 @ 1400V	0.0165	0.0088	0.0028	0.0029
n = 6 @ 1400V	<0.001	<0.0010	<0.0010	<0.0010
n = 7 @ 1400V	0.0060	0.0033	0.0009	0.0005
n = 8 @ 1400V	<0.001	<0.0010	<0.0010	<0.0010
THD @ 1400V	0.0520	0.0320	0.0249	0.0181
THD @ 20V	0.0042	0.0034	0.0016	0.0010

B. Time domain testing

The PDC measurements with different test voltages also show different results. The x-axis of Fig. 4 is the time in second. The y-axis is the p.u. current.

The results suggest that the insulation resistance as well as the PI/DAR is voltage dependent. As discussed in the above section, the existence of high polarization voltage and long period at the same time makes the insulation system not linear any more.

Fig. 4 Current over time curves (PDC measurement) at various test voltages

The voltage dependence of the insulation system is known as the Garton effect [3]. When oil and paper are in contact and form the interface, charge (conductive ions in oil) accumulation process could occur at the interface due to the differences of their electrical properties. The accumulation

speed is proportional to the field strength that is perpendicular to the interface and the ion accelerating time. In frequency domain, applied voltage changes its polarity regularly and therefore even if the field strength is high, as long as the charging period is not long, the charge accumulation at the interface could be neglected. But if the frequency goes lower, which means that the charging period is increased, the accumulation will occur so the nonlinear phenomenon appears. In the time domain measurement, the applied voltage is usually high DC voltage. If the field strength becomes strong enough to make ions in oil move, the test object would always show non-linear behavior.

IV. CASE STUDY

Few transformers and bushings with different power ratings are also investigated with various test voltages. These transformers and bushings represent different structure of the insulation system, i.e. the size of the oil-paper interface, relative ratio of cellulose and oil.

A. HVDC Transformer

A single phase 800 kV HVDC Transformer made by ABB is tested by the DFR method. The results in Fig. 5 show that the HVDC transformer is voltage independent at voltages below 1.4 kVrms. The reason could be that in big transformers, the field strength is not strong enough to make ions in oil move.

Fig. 5 DFR results of the HVDC transformer at 140V and 1.4 kV

B. Shell Type Transformer

A three-winding shell type transformer rated at 233/44 kV, 125 MVA was tested by the DFR method using different voltages. The results show slight voltage dependence at low frequencies. Very small differences are observed on the dielectric response at different voltages; thus, the Garton

Effect is observed with very low influence on the dielectric response.

Fig. 6 DFR results of a shell type transformer. (a) – entire frequency band; (b) – zoomed in band from 1mHz to 0.1 Hz.

C. Small Distribution Transformer

Distribution transformers are not typically tested by the DFR method because of the great number existing in the power grid. However a small distribution transformer is tested by the DFR method for research purposes under 20Vrms and 1.4kVrms as well.

Fig. 7 DFR results of a distribution transformer. (a) – 20 V DFR result ; (b) – 1.4 kV DFR result. The red curve is the database curve while the green curve is the test result.

There is obvious deviation in this case and it is interesting to see the post analysis by the software which gives the moisture content information. The moisture contents given by the software are 2.1% at 20 V and 2.5% at 1.4 kV. The absolute moisture content error at 1.4 kV is about 0.4%. The auto-matched geometries of the 1.4 kV curve are quite different from the other one, from 22/25 at 20 V to 41/15 at 1.4 kV.

D. Bushing

A 126 kV condenser bushing manufactured in China is also investigated by the DFR method at different voltages. The results are shown in Fig.8. There is no obvious voltage dependent phenomenon at low frequencies although the field strength in bushing should be no less than that in power transformers.

The reason why bushing doesn't show the nonlinear property is because of its insulation structure. The insulation between the central conductor and the bushing tap is the Kraft Paper bulk. The main part of the oil-paper interface is perpendicular to the central conductor rather than parallel with the conductor or metal foils.

Fig. 8 (a) -DFR results of the bushing at 20 V and 140 V respectively. (b) - DFR results of the bushing at 140 V and 1.4 kV respectively.

A simple 2-D condenser bushing model is simulated in FEM analysis software and the result is shown in Fig. 9. The majority of the stress is distributed within the insulation between the central conductor and the first layer of the metal foil, which is also supported by [4]. This means that the effective oil-paper interface is relatively short compared with the dimension of the insulation system. In addition to that, the nonlinear behavior depends on the axial (y-direction) field strength because it has to be perpendicular to the interface. But the axial field strength is very small compared with radial (x-direction) field strength.

Fig. 9 Simulated potential and field distribution inside the condenser bushing model.

V. CONCLUSION

The insulation condition of power components could be investigated by DC method (IR, DAR, PI, and PDC) and/or AC method ($\tan \delta$ and DFR). The insulation system is a nonlinear system in case that the field strength caused by the test voltage is strong enough to make ions in oil move towards the oil-paper interface and the polarization voltage exists for a certain period.

For the oil-paper nonlinear insulation system at very low frequencies, AC method is preferred because the total polarization effect is much smaller than the one observed in the DC method. The dielectric response of cellulose at low frequency is more sensitive to water. However, for nonlinear systems, the idea of running a DFR test down to 0.1 mHz in order to obtain more accurate moisture estimation instead of only down to 1 mHz is questionable. The reason for going to very low frequencies should be related to the effect of temperature [5] on the dielectric response and not the accuracy of moisture estimation. In cases where it is necessary to use higher test voltages, such as in HV substations, once the 3rd harmonic starts to influence the dielectric response, it is recommended to limit the lowest frequency value of the sweep which is usually determined by the temperature of the insulation system.

REFERENCES

- [1] S. M. Gubanski, et al., "Dielectric Response Diagnoses for Transformer Windings," CIGRE 2010
- [2] U. Gafvert, L. Adeen, M. Tapper, P. Ghasemi, and B. Jonsson, "Dielectric Spectroscopy in Time and Frequency Domain Applied to Diagnostics of Power Transformers," *International Conference on Properties and Applications of Dielectric Materials*, Xi'an, China, 2000, pp. 825-830
- [3] C. G. Garton, "Dielectric Loss in Thin Films of Insulating Liquids," *Proceeding Institution Electrical Engineering*, Vol.88 (1941) p.103-120
- [4] D.J. Smith, S.G. McMeekin, B.G. Stewart, P.A. Wallace, "The modelling of electric field, capacitance and dissipation factor of a high voltage bushing over varying frequency," *Universities Power Engineering 47th International Conference (UPEC)*, 2012
- [5] P. Werelius, J. Cheng, D. Robalino, M. Ohlen, "Dielectric Frequency Response Measurements and Dissipation Factor Temperature Dependence," *Proceedings of the IEEE International Symposium on Electrical Insulation, ISEI, Puerto Rico, 2012*