Practical Experience on Transformer Insulation Condition Assessment

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Abstract: Dielectric measurement methods are used for acquisition of moisture content in oil-paper-insulation of power transformers. Two equivalent principles exist: Time domain and frequency domain measurement. In this paper practical experience on measurement of Polarization and Depolarization Currents (PDC) on power transformers ranging from 100 to 800 MVA under different environmental conditions is described. Depending on the transformer type there are different strategies possible for cabling and grounding. Typical setups and resulting problems, e.g. the appearance of AC noise resulting from coupling of nearby energized lines or equipment and its reduction during measurements are discussed. On-site measurements on three coupled 110 MVA 400/220 kV single phase auto transformers before and after insulation oil reclaiming are presented.

INTRODUCTION

The reliable availability of large power transformers is of essential importance for power plant and transmission network companies. Most of the German and central European power transformer population was installed in the 1960s and 1970s and has now reached an age from 30 to 40 years. At this point it is important to keep an eye on a transformer's electrical condition. A VDN (German Electricity Association) study with data collected between 1994 and 2001 shows that failure rates on large high voltage power transformers are in the range of 1% to 2% per year [5].

Today, the trend is towards longer operating time in combination with condition based maintenance. This requires careful observation of the ageing process of the equipment and reliable methods of condition assessment. From the authors' experience, the methods can be divided in basic and advanced diagnostics:

Basic diagnostics

There are several routine diagnostic methods for a basic condition assessment. If results are over limit values, there should be further investigation. Basic diagnostic includes:

Oil analysis: Breakdown voltage, moisture content (Karl-Fischer-Titration), total acid number (TAN), oil colour, tan δ of oil, dissolved gas analysis (DGA)

Basic electrical measurements: Winding resistance, insulation resistance, no-load current, capacity and tan δ measurement of insulation system

Basic assessment: review of exterior transformer condition (weathering, oil leakage etc.) and operation history

Some of these actions can be executed during on-line operation, so that there is no down-time. Especially dissolved gas analysis has been proven to be a powerful tool to detect various electrical problems [7].

Advanced diagnostics

Advanced diagnostics are carried out on a suspected issue and can give the operator a clue for further procedure to conserve value of the equipment and planning of investments.

An important off-line method for the non-destructive determination of insulation system moisture content is the measurement of polarization and depolarization currents. The fundamental theory of the method is already well known [2] . However, there are several traps when performing on-site measurements which are discussed in this paper.

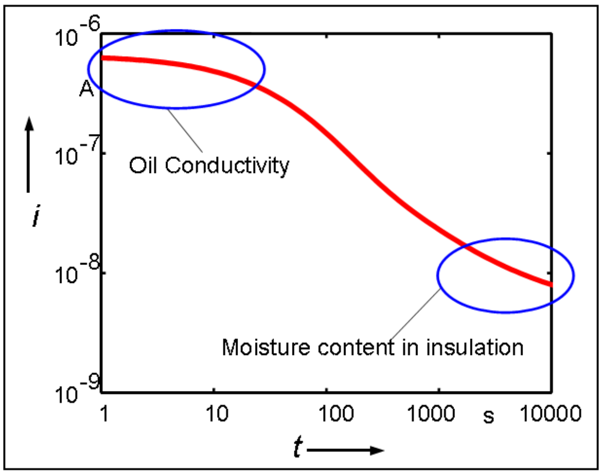

Fig. 1: Typical polarization current spectrum in time domain

PRACTICAL MEASUREMENT ISSUES

Rain

Rain makes on-site measurements not only uncomfortable but often impossible. Rain seems to generate leakage DC currents which superimpose the desired measurement currents. The magnitude of these leakage currents depends on rain intensity and sometimes exceeds 100 nA, what makes measurement difficult to impossible. As there seems to be no chance to distinguish between currents through the oil-paper-insulation system and leakage currents caused by rain, the effect has not been yet further investigated.

Nearby corona discharge

Rain usually causes intensified corona discharge on energized lines and connectors. Nearby corona discharge has not proven to be a source of AC noise or leakage currents in laboratory experiment: PDC measurements have been performed on a distribution transformer in direct proximity to a thin wire, where a high AC voltage causes corona discharge. Under all conditions (position and intensity) there was no different behaviour of measurement circuit like without corona discharge.

Polarization voltage

The maximum polarization voltage is determined by the transformer's geometry and the resulting electrical field strengths in the oil-paper-insulation. If field strength of approximately 1 kV/cm is exceeded, there can be different effects leading to non-linear behaviour: Charge injection from the electrons and field-induced dissociation leads to apparent higher oil conductivity [6]. As the electrical field distribution inside the power transformer is not known at measurement, the polarization voltage should be kept as low as possible.

A polarization voltage of 500 V has led to satisfying results on all measurements performed on various power transformers in power plants and switchyards.

On-Site Setup

An immanent problem of PDC measurements is the creation of a more or less cabling loop. Following the Maxwell Equations, this creates a plain where parasitic AC currents can be induced, e.g. from ground currents in power plants or in switchyards. For good measurement results, this plain should be reduced to a minimum, depending on the local situation.

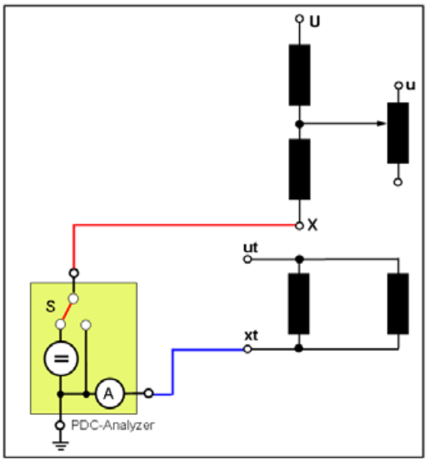

Fig. 2: Setup of measurement circuit with a single phase auto transformer with tertiary winding

It has been observed that other nearby energized equipment, especially other power transformers causes coupling of AC currents in the measurement circuits. This current superimposes the desired DC current and often exceeds the DC current by a factor of 10^3 to 10^4. Usually other equipment cannot be switched off due to operational availability. So it is essential to use filtering circuits in the electrometer for accurate measurements.

Especially on large high voltage power transformers with long upright or inclined bushings it has to be taken care on cable quality. To keep distances short or due to local conditions, measurement cables often hang down from bushing directly to the ground. Sometimes this causes cable oscillation excited even by light wind. If during measurement the cables are moved there can be a significant noise current caused by the triboelectric effect. Triboelectric currents are generated by charges created at the interface between a conductor and an insulator due to friction (see Fig. 3). Free electrons rub off the conductor and create a charge imbalance that causes a current flow. There are special low noise cables available with semi conducting layers between insulators and conductors which significantly decrease triboelectric noise. Also it is important to ensure that cables are not being moved during measurement [1].

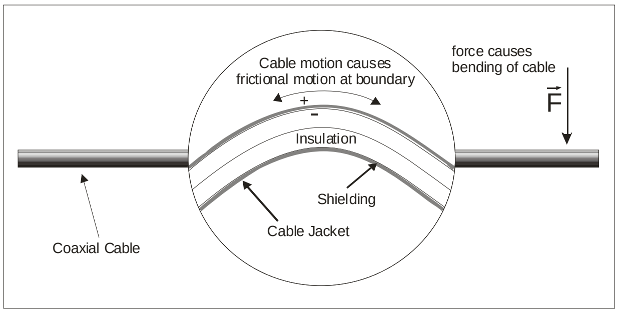

Fig. 3: Triboelectric effect

CONDUCTIVITY PHENOMENA IN OIL-PAPER-INSULATION

Theory

Carbonic acids are emerged mostly on ageing of saturated hydrocarbons. Carbonic acids contribute to conductivity only on it's dissociation. If water is present in the oil, the acids can dissociate to ions and so the overall conductivity is increased:

$$H_2O + H\text{-}COOH \quad \rightarrow \quad H\text{-}COO^- + H_3O^+ \qquad (1)$$

So water itself does not increase conductivity. But with the existence of carbonic acids dissociation will increase conductivity noticeable. Acids and their aldehyde groups are suspected to cause further degradation on oil paper insulation systems and can have therefore an influence on ageing [3].

Oil Treatment

The conductivity mechanism mentioned above has been proved with PDC measurements performed before and after insulation oil treatment on three 38 year old 110 MVA single phase auto transformers identical in construction (see circuit diagram Fig. 2).

The reclaiming process revokes impurities, acids and miscellaneous components from the insulation oil, but does not remove water from oil and therefore is not used to dry the insulation system.

Table 1 presents the measurement results before and after oil treatment. Although the PDC measurement after the oil treatment has been performed at higher insulation system temperatures, the oil conductivity has decreased.

As expected, the oil reclaiming has not led to lower moisture content in the oil paper insulation system. For future drying, a stationary oil drying system has been installed in this case.

OIL TEMPERATURE

PDC measurements require constant insulation temperatures during application for accurateness, as the polarization current is temperature dependant (Fig. 4).

During on-site measurements there are often time restrictions imposed by load scheduling which do not allow cooling down of the power transformer to a steady state temperature. So there is a gradient of oil temperature during measurement that reaches sometimes up to 10 K during a measurement period of 10.000 s. Also, it is difficult to determine the actual insulation system temperature between the transformer windings. Both effects cause inaccurate interpretation of measurement results. The DC resistance of each winding is recorded in the transformer documentation and has been measured during factory testing. The value is calculated to a temperature of 348 K (75° C). The resistance of copper is temperature dependant:

$$R_{T_1} = R(T_0)(1 + \alpha(T - T_0)) \qquad (2)$$

where $R(T_0)$ is known the specific resistance at 293 K (20°C) and α is the temperature coefficient of copper. As the winding's resistance is known at 348 K, the equation is transformed to:

$$T_2 = \frac{R_{T_2}}{R_{T_1}}\left(\frac{1}{\alpha} + T_1 - T_0\right) + T_0 - \frac{1}{\alpha} \qquad (3)$$

measurement category	Transformer A		Transformer B		Transformer C	
	Feb. 05	**Oct. 05**	**Feb. 05**	**Oct. 05**	**Feb. 05**	**Oct. 05**
Temperature [°C]	**+5**	**+23**	**0**	**+22**	**+3**	**+15**
Measured capacitance [pF]	**6343**	**6302**	**6142**	**6080**	**6126**	**6072**
oil condutivity σ_{oil} [1/Ωm]	**$4{,}5\cdot10^{-12}$**	**$1{,}7\cdot10^{-12}$**	**$5{,}9\cdot10^{-12}$**	**$1{,}9\cdot10^{-12}$**	**$5{,}2\cdot10^{-12}$**	**$1{,}5\cdot10^{-12}$**
moisture content in board insulation	**3 %**	**3 %**	**3,5 %**	**2,5 %**	**3 %**	**2,5 %**
insulation resistance R_{15} [GΩ]	**3,77**	**4,63**	**3,09**	**4,78**	**3,72**	**5,48**
insulation resistance R_{60} [GΩ]	**11,6**	**8,98**	**9,87**	**9,84**	**12,5**	**11,0**
polarization index R_{60}/R_{15}	**3,08**	**1,94**	**3,20**	**2,06**	**3,35**	**2,00**

Table 1: PDC measurement results before (Feb. 2005) and after (Oct. 2005) oil treatment

If it is possible to obtain accurate measurements of the winding's DC resistance during measurement, it is possible to calculate the winding's temperature what gives better approximation to insulation gap temperature than the transformer's temperature gauges, especially during unsteady states. Fig. 5 shows a possible implementation.

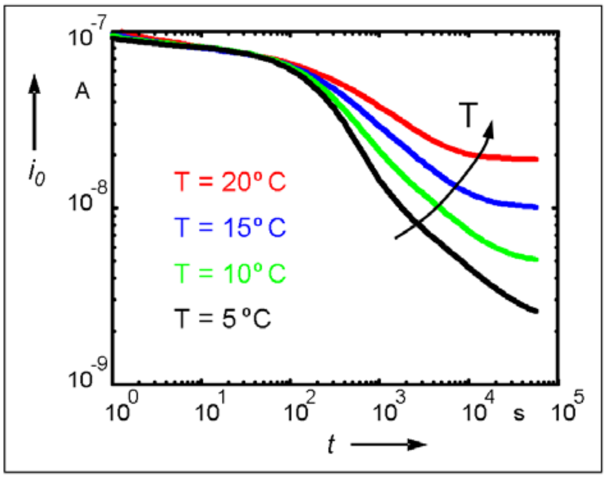

Fig. 4: Influence of temperature on polarization current

Voltage U_0 is the polarization voltage (500 Volts or above), the resulting current through the insulation system is i_0. Voltage source U_1 is for measurement of winding resistance (typically less than 10 V), the resulting current is I_1 (typically 3 to 10 A). The winding voltage U_2 must be measured directly at the winding bushings with a second pair of cables to eliminate voltage drop. As the winding represents a large inductivity in this circuit it is important to control the voltage U_1 that the current I_1 is kept constant, especially a circuit break has to be avoided.

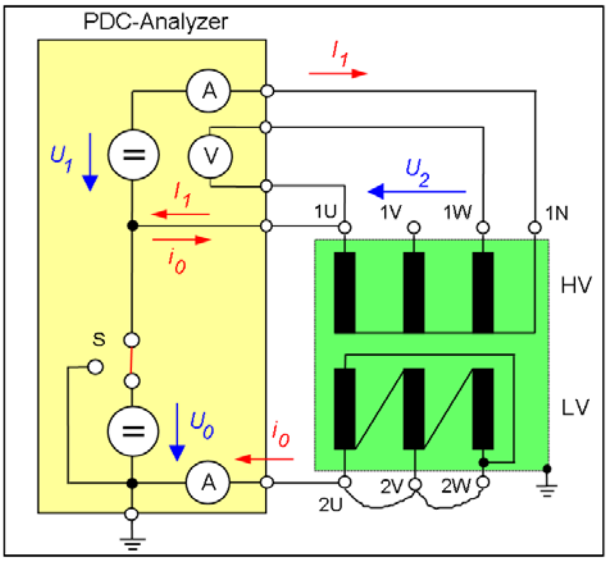

Fig. 5: Dielectric measurement with winding temperature monitoring

CONCLUSION

With precise on-site setup it is possible to perform reproducible measurements which allow calculation of moisture content of the insulation system with an accurateness of 0,5%. For good results, a minimum polarization time of 10.000 seconds should be used on large power transformers.

For better accurateness the influence of marginal electric fields at bottom and top of windings during modelling of insulation system has to be investigated.

Temperature gradients and uncertainty of winding temperature at on-site measurements complicate proper modelling and determination of moisture content.

Recent research proposes shorter measurement time with calculation of stored charges derived from polarization and depolarization currents [4].

Ongoing work is the development of measurement of winding temperature through its DC resistance during dielectric measurements for temperature correction during unsteady temperature states.

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