Diagnosis of Power Transformers via Partial Discharge Detection and Localisation with the Transfer Functions as Basis for Insulation Condition Assessment

Introduction

Transformers are one of the most important and cost-intensive components of electrical energy supply networks. A view on the age structure of the transformers in service for different utilities shows, that many of the transformers already have reached their design age. Fig. 1 shows the age of the transformer population in the voltage range between 110 kV and 400 kV for a large utility in Germany.

Figure 1: Years of operation for transformers of a large German utility in the voltage range of 110 kV to 400 kV [1]

The results are similar in other countries. A large amount of transformers is older than 25 years and a remarkable number is older than 35 years. The evaluation of the transformers regarding service performance, reliability, availability and maintenance strategy needs reliable information on the status of the insulation of the transformer and the partial discharge (PD) measurements can be a tool for such an evaluation, because the survey and research results indicate that load tap changers, the windings, the insulation ageing and the contamination are the key sources of transformer failures [2]. Thus a replacement of some transformers can hardly be postponed, but the deregulation forces the utilities to save costs. As a consequence the need and the interest in measures for the life span
extension and load optimisation of the components of the electrical power supply strongly rose.

The ageing of the insulation is in all cases a major failure mode and the PD measurement is a very useful tool for off-line and on-line measurements [3]. The consequences of PD can be detected by different methods. The well known Buchholzrelay is an integral detector of gases, which can be generated by PD. The newly developed “Electronic Buchholzrelay” indicates the amount of gas as well as the gas rate and is therefore a differential detector of dissolved gases [4]. Furthermore the dissolved gases as result of PD can be detected by the gas-in-oil analysis (DGA) where the gas amount is proportional to the charge or better the energy of the PD [5, 6]. The measurement of the PD according to IEC 60270 [7] is the measurement of the apparent charge at the accessible points of the equipment, e.g. for transformer the high voltage bushing and the neutral or star point. Even if the recommended values for the apparent charge seems to be sufficient for type and routine tests the measurement of the “true” charge and the localisation of the PD origin are desirable requirements for reliable and improved evaluation of the transformer insulation condition.

**Modules of the PD Diagnosis System**

The structure of the developed PD monitoring system consists of two modules: the on-line data acquisition and the off-line data analysis. For the signal decoupling a new, patented sensor has been developed, which consists of a metal plate with defined dimensions and is mounted on the bottom of the bushing, thus a capacitive decoupling of the PD signals is possible [8]. The mounting of the sensor is quite simple and can be used for any kind of transformer, thus measurement taps, which are not available especially on older transformers, are not necessary. As illustrated in Figure 2 the signal transmission is performed via an enhanced fiber optic technology with a bandwidth of about 10 MHz, whereas the used quadripole (QP) and the amplifier cut off frequencies below a few 10 kHz. Due to this new combination of decoupling and transmission technique as well as to the short distances between sensor and optical transmission the influences of noise can be significantly reduced, whereby various parameters like the amplification factor or the dimensions of the sensor can be used to optimize the signal to noise ratio (SNR).

![Diagram](image)

**Figure 2: Scheme of data acquisition**
After the signal digitalization the data processing is started with a digital filtering of continuous noise signals. Sinusoidal noise, caused by e.g. radio and communication services, is suppressed with new developed frequency rejection filters in frequency domain and white noise owing especially to the optical transmission is filtered with wavelet techniques [9]. Afterwards periodically appearing noise pulses can be eliminated using cross correlation methods [10], whereas stochastically occurring pulse shaped noises like corona discharges are separated using a new technique, which is based on the comparison of the relation of frequency spectra of the impulses measured simultaneously at the neutral and the bushing [11].

**Basic of the transfer function**

The transfer function is well known in the signal transmission field and also in the high voltage test and measuring business. The main idea of introduction the transfer function in the high voltage test technique was the impulse test of transformers. The main purpose of this test is the check of the linear behaviour of the transformer and this is done by measuring e.g. the neutral current at 50 % and 100 % lightning impulse voltage and by the comparison of the two current shapes. With an oscilloscope as recording device this requires a attenuation of the factor 2 by the current and voltage measuring channels. Small deviation in the input voltage which may be undetected by the oscillogram leads to changes in the current shape due to the sensitivity and this ends very often in the discussion concerning the linearity of the test object or the test circuit. The transfer function is in this respect not sensitive to small changes in the signal input, because the output changes at the same time assuming a linear behaviour of the test object [12]. The experience with the transfer function shows the reliability and the advantages during transformer impulse tests and also the possibility to use the transfer function as diagnosis tool [13 - 15]. The principle of the transfer function will also be used to detect partial discharges (PD) in transformers and more over to localise the PD origin and to calculate more accurate the true charge amount. Figure 3 shows the principle diagram of the developed method.

![Figure 3: Scheme of the functional principle](image)

The coil of a transformer is divided in numerous winding sections. The PD at an unknown origin generates a signal which travels through the winding sections to the high voltage bushing and to e.g. the neutral or star point. The bushing as well as the neutral point are accessible points or PD measurements and the signal can be recorded. Assuming the transfer function of the transformer coil is known by the sectional transfer functions of the winding sections the change of the signal from the origin point to the measuring point can be calculated. This procedure can be used to calculate the shape of the signal at any point within the coil using the measured signal and the section winding
transfer function. This can be done for both signals measured at the bushing and at the neutral point and calculated at each winding section within the transformer. Figure 4 shows the used model for the transformer and the determination of the section winding transfer function.

Figure 4: Equivalent circuit for the transformer model

The partial differential equation can be solved if the constant coefficients are known and if the terminal conditions at \( x = 0 \) (neutral) and \( x = l \) (bushing) as well as the initial and final conditions at \( t = 0 \) and \( t = \infty \) are met. Due to the fact that the coefficient are not known different mathematical algorithm like “Sequential Quadratic Programming” and “Genetic Algorithm” have to be used to solve the partial differential equation [16].

**Experimental Investigations in the Laboratory**

On a specially prepared distribution transformer (10 kV / 380 V, 200 kVA), which has been pulled out of its vessel, 7 clamps have been mounted along phase V with equidistant spaces comprising 2 winding packages as shown in Figure 5.

Figure 5: Laboratory measurement set-up
Into each clamp 150 PD-pulses have been injected spread equal to three different PD-types generated by a needle-plane arrangement in air, oil and pressboard, in order to simulate different failures. Thus in total 1050 PD-pulses have been digitised at the bushing and at the neutral via a 50 Ω resistor using a sampling rate of 100 MHz and a low-pass filter with a 20 MHz cut-off frequency. Afterwards all sectional transfer functions from each clamp or respectively origin to the bushing and to the neutral including in both cases the termination resistor of 50 Ω have been determined using a network analyser. The transfer functions have been recorded with 1601 equidistant points between 10 kHz and 5 MHz, thus only this frequency range has been considered when the measured signals were calculated back to the 7 clamps along the winding. The result of such a calculation is shown in Figure 6 exemplary, where a discharge has been injected into one clamp using the needle-plane electrode configuration in air.

![Figure 6: Measured and calculated PD signals](image)

On the top diagram in Figure 6 the signals measured at the bushing and at the neutral are displayed, while the other diagrams show the signals at the three other origins calculated back from the measured data. The recalculated signals from the bushing and from the neutral are almost identical at origin 3, thus indicating that there is the actual origin of the measured PD-pulses. The small discrepancies between the signals at the actual origin can be traced back to measurement uncertainty.

**Experimental Investigations on-site**

In order to verify the presented modelling technique measurements on a 40 MVA transformer on-site have been performed, as displayed in Figure 7. The step response of the transformer was measured o-site and later on calculated using the described transformer model. In Figure 8 the measured and calculated step responses are shown and the agreement is reasonable good.
Figure 7: Transformer for on-site PD measurements

Figure 8: Measured and calculated step response

The PD measuring results are shown in Figure 9 together with the off-line evaluation of noise and PD signals in Figure 10.
It is obvious that even without a digital filtering an adequate signal to noise ratio (SNR) can be achieved (Fig. 9a). After the suppression of sinusoidal and white noise (Fig. 9b) a rejection of all signals from outside the transformer, like corona discharges, can be performed (Fig. 9c). Therefore a separation between inner and outer impulses is carried out by comparing the frequency spectra quotient between the signals measured at the bushing and the neutral simultaneously, thus it is possible to divide the frequency spectra into groups as displayed in Figure 10, where signals measured at the 40 MVA transformer are regarded. Furthermore a localisation of the PD is possible due to the determination of the PD origin by calculation of the impulse shape at different points within the transformer from both sides and by the comparison of these calculated signals. The point with identical shapes is the PD origin and the “true” charge can be evaluated.

In a final step the PD signals, which remain in the data stream after the denoising and the pulse separation are analyzed concerning their apparent charges as well as their origins. In this case the highest PD impulses had an apparent charge in the range of 1000 pC. The determination of the origins, which is based on the modeling of the transformer coil and explained comprehensively in [17], leads to the result that there is mainly one defect, which is located close to the beginning of the winding of the middle phase (V) nearby the bushing.

**Conclusions**

The described method allows to detect and localise the PD origin with measurements of the PD signals at two accessible points of the transformer, the high voltage bushing and the neutral point. The section winding transfer function can be evaluated from the step response measurements of the complete coil, which is possible also for transformer in service. With these transfer function a comparison between the two calculated signals, starting at the two measuring points, gives the origin of the true PD signal.
The method allows furthermore to determine the shape of the PD signal at the true origin and therefore the integral of this impulse gives a charge value which is much closer to the real charge compared the measurement of the apparent charge at the accessible points. The knowledge of the PD origin and the true charge can be used to evaluate the harm of the PD on the insulation performance and is therefore a good basis for the assessment of the insulation condition of the transformer. The measuring system uses fibre optic transmission systems which reduces the noise during on-site measurements and therefore it is possible to measure and localise the PD in service. Depending on the maintenance strategy of the utility the system can be used to observe important transformers continuously or to check the transformers from time to time in order to have a basis for the insulation condition assessment.

References

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