New Devices for a Dry Type Transformer Protection and Monitoring System

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Abstract: In this contribution new devices for protecting and monitoring dry type transformers are introduced. An online overheating protection is performed by using an optical fibre sensor, which signals an alarm if a local overheating appears. In this case an offline analysis of the transfer functions of the transformer coils can be usefully applied for the identification of interturn short circuits or similar destructions, that might have caused the local overheating. The developed monitoring system is efficient and cost-effective and can be easily installed on almost all categories of dry type transformers.

Keywords: Transformer, Protection System, Monitoring System, Transfer Function, Partial Discharge (PD)

I. INTRODUCTION

Transformers are indispensable for guaranteeing a flawless power transmission and distribution. Due to their exposed placement at the junctions of energy supply systems a failure of these devices causes dire consequences, which normally can only be compensated by enormous financial and technical efforts. At the distribution level often dry type transformers are used up to voltages of 36 kV and power of 24 MVA. Dry type transformers, which are usually insulated by epoxy resin, have in comparison with paper-oil insulated transformers the advantage that no environmental precautions are required. This is the main reason, why they are assigned instead of paper-oil insulated transformers, beside the fact that for dry type transformers only a minimum of service is needed. However, using these transformers also an uninterruptible power supply has to be ensured, which only can be optimized if the devices are monitored in operation. Up to now such monitoring systems can only be economically applied on large power transformers with some 100 MVA but not for dry type transformers, although they are sensitive to different destructive phenomena due to the characteristics of their solid insulation. Especially partial discharges can be the reason for a failure, because due to the absence of self-healing effects as they exist in liquid or gas insulated high voltage components, partial discharge (PD) activities can damage the insulation over a long period. Thus can lead to interturn short circuits resulting in local overheating, which again enhance due to the temperature extension in the insulation material the appearance of partial discharges. If this chain reaction is once initiated a breakdown of the insulation is unavoidable and may also lead to fire hazards entailing in dreadful damages with expenditures often higher than the transformers cost price.

Therefore in the following different possibilities of monitoring dry type transformers are discussed and a new system is introduced, which can be efficiently used for preventing malfunctions.

II. PARTIAL DISCHARGE MEASUREMENTS

PD measurements are well known as a quality control tool for the insulation and are therefore well investigated and improved. They represent the state of the art, because no other method allows such a precise statement about the condition of the insulation. Measuring partial discharges can be performed using various methods, but for the measurement on dry type transformers mainly acoustic, ultrasonic and electric techniques are applied. Acoustic and ultrasonic measurements are based on the same principle, only the frequency range, in which the mechanical compressional waves caused by the discharges are determined, is different. However, due to the high damping owing to the solid insulation these methods do not have the necessary sensitivity. Furthermore these methods especially are designed for a localization of the PD source, whereas the determination of the apparent charge is usually not possible. The reason therefore is that a calibration measurement, which is necessary for the determination of reference signals, can not be performed. Without such references a comparison of the measurement results is not practicable, thus these techniques are more or less restricted to indicate whether a PD activity exists or not. Consequently electric PD measurements, with which the apparent charge can be detected, are preferable, because with the determination of the apparent charge an appraisal on the extent of the damage inside the insulation can be estimated. Nevertheless, also the conventional narrowband electric PD measurements have various disadvantages, even for measurements on-site, where surrounding noise influences the measurements. Often it is not possible to find a frequency range, in which the noise signals can be suppressed efficiently, thus a sensitive PD measurement can not be performed, although this is necessary especially for dry type transformers, because apparent charges above 20 pC have to be determined, according to the limit defined in the IEC 60726 [1]. Furthermore with the actually used electric PD measurements a localization of the PD source can only be achieved in seldom cases. Therefore a prototype of a new PD detection system has been developed, which allows beside the determination of the apparent charge also a localization of the PD origin. The principle of this patented system is quite simple [2]; by mounting a couple of sensors on the surface of the transformer coils the electromagnetic radiation caused by the partial discharges can be detected. A localization becomes possible, because on sensors, which are close to the PD source a higher signal
can be decoupled than on sensors, which are placed far away, as clarified in Figure 1.

As shown in Figure 1 on a coil of a dry type transformer 7 sensors have been placed, one on each winding package. Into the lowest clamp calibration signals with an apparent charge of 20 pC have been injected, which close to ground via a 50 Ω resistor at the upper clamp. The signals decoupled at the sensors were band-pass filtered, thus only frequencies between 10 kHz and 1 MHz are amplified and recorded. The digitized signals are illustrated in Figure 2 making it obvious, that the amplitude of the recorded signals decrease with increasing distance between sensor and the PD source or respectively the calibration impulse generator. Thus in this case the signal from sensor 7 has the highest amplitude, because it is closest to the PD origin. This system, whose properties and possibilities are described in more details in [3, 4], is still under improvement in order to optimize it for the practical operation under online conditions. However, PD measurements are usually quite extensive, thus a continuous online PD detection seems to be large scaled, comparing the price for such a system and the transformers cost price. In some cases the costs for the PD detection system can top those of the transformer, thus an economical monitoring is not possible in general. A solution of this problem is to monitor the PD activity online in intervals, but due to the characteristics of the solid insulation such a measurement method is unsatisfactory, because PD activities inside solid insulations can be interrupted for a certain period. PD phenomena are accompanied by a generation of gas due to the destruction of the insulation at the PD origin. Therefore inside the defect void the pressure increases, thus enhancing the breakdown strength and suppressing temporarily partial discharges until the gas diffuses into the solid insulation. The pressure inside the cavity thereby decreases resulting in the reduction of the breakdown strength and therefore in the renewed appearance of PD activities. This cycle continuously degrades the solid insulation material until a breakdown appears. However, this recurrent PD occurrence has not to be remarked in regularly performed measurements, thus a monitoring system is needed which enables beside a more economic monitoring a protection against serious damages or even breakdowns. Such a system, which is based on an innovative sensor technology, is introduced in the following chapter.

### III. OVERHEATING PROTECTION

Many dry type transformers are equipped with a PTC (Positive Temperature Coefficient) temperature fuse integrated in the low voltage coils for signalizing a temperature extension due to an excessive current. As explained before local overheatings can also appear at the high voltage coils due to interturn short circuits caused by the destruction of the solid insulation by partial discharges. These local overheatings, which can not be detected by the PTC systems, represent a pre-stage of a breakdown resulting possibly in burns, as it happened on a 400 kVA transformer depicted in Figure 3. Thus it is useful to monitor the temperature distribution at the high voltage phases offering the possibility to disconnect the transformer in time and avoid thereby subsequent damages.

This aim can be reached using the new developed overheating protection system, which guards both the high and low voltage coils as well as the core against overheating. The system consists of a fibre optic sensor and a control unit, which processes the measured data and signalizes an alarm to the control center of the power supply station if an overheating appears.

The patented principle of operation bases on the
temperature dependant modification of the optical transmission properties of an optic fibre cable [5], thus the optic sensor does not cause any electromagnetic interference or influences the operation of the transformer in any other way. If a light signal is injected by an optical transmitter into one side of the fibre optic sensor it can be detected at the opponent end with an optical receiver as shown in Figure 4. If an extended temperature arises at the surface of the fibre optic sensor the damping of the light transmission is increased until a certain temperature limit is reached, where the light transmission is interrupted. In this case an alarm is given, thus the transformer should be disconnected, which also can be automated and controlled by the protection system if necessary.

As shown in Figure 4 the sensors are mounted vertically on the coils, because due to the annular spread out of the overheating inside a winding package, which causes the typical ring-shaped resin color changes, it is not necessary to place the sensor directly on a hot spot but on any position above the overheated winding package. The temperature threshold, at which an alarm is signalized, can be adjusted over a wide range from about 80°C up to 170°C or even more if necessary. The coarse adjustment of this threshold can be performed with the selection of the material of the fibre optic sensor, whereas a fine tuning is possible by modifying the properties of the transmitter and receiver. The function and operation reliability of this method was proven in the laboratory with the model shown in Figure 5.

As described in Figure 5 a heating resistor has been integrated in a segment of a transformer coil, which has been disposaled by a manufacturer. By placing different kinds of sensors on the surface of this segment above the heating resistor properties of various fibre optic materials as well as the adjustment of the transmitter and receiver could be investigated. Based on this examinations a prototype was developed, which has been tested in the laboratory of a manufacturer of dry type transformers. For this purpose a transformer was specially prepared in such a way that a certain winding in one of the high voltage coils has been short circuited. Energizing the transformer the appearing overheating was detected in time by the protection prototype, thus the transformer could be switched off before a serious damage or a fire occurred. Actually this system, which is shown in Figure 6, has been applied on different dry type transformers in Germany for about one year.

In case of an alarm displayed by the overheating protection system it is necessary to check whether this overheating was caused by a winding short or owing to another reason, which can be performed using transfer functions.

IV. TRANSFER FUNCTIONS

The detection of winding shorts can be performed by a comparison of transfer functions recorded before and after a failure has appeared. According to the system theory transfer functions describe the characteristic behavior of a linear shift invariant system unequivocal. Thus modifications of the system, like interturn short circuits, lead to changes of the electrical characteristics and therefore to changes of the transfer functions. However, a transformer does not represent such a linear system due to its nonlinear magnetic hysteresis curve, thus for a whole transformer this method is not applicable. Only the properties of a single coil can be examined using transfer functions, because a coil represents a complex system consisting of resistors, inductors and capacitors, thus a coil belongs to the class of linear electrical circuits.

The determination of transfer functions can be performed with different offline methods, mainly step response analysis and frequency response analysis. Using the frequency response analysis the output signals for sinusoidal input signals with various frequencies are recorded, thus the damping and phase shift for discrete frequencies can be combined to a transfer function. This method is quite time-consuming but has a good reproducibility, because the measurements are less influenced by surrounding noise, which can be suppressed using filters adjusted to the discrete measurement frequencies. In contrast to this method the step response is faster and easier to perform by using a steep input impulse (delta-impulse) for recording the response or output signal of the system. With the help of the convolution theorem the transfer function can then be calculated in the frequency domain. However, the output signal has to be measured in a
wide frequency range, thus noise influences the measurement. Therefore the signal to noise ratio must be as high as possible to guarantee reproducible measurements, thus an input signal with a high amplitude is required. For this reason a special steep impulse generator was developed, which generates delta impulses with a rise time of less than 400 ps and an amplitude up to 250 V with an adjustable impulse duration. The functional principle is based on the switching of a charged cable, which is shown in Figure 7.

As depicted in Figure 7 a cable is at first charged with a DC source, thus the voltage $U_1$ is equal to the voltage $U_0$ from the source, whereas the output voltage $U_2$ remains to 0 V as long as the switch S is open. If the mercury reed switch is closed the voltages $U_1$ and $U_2$ skip to $U_0/2$, because the electromagnetic wave runs at both sides of the switch through an impedance of 50 $\Omega$ ($R$, $Z_L$). If the wave has passed the cable the output voltage decreases to nearly 0 V, due to the voltage division between the resistors $R_i$ and $R$. The duration of the impulse can therefore be adjusted by the cable length, which is decisive for the transit time of the electromagnetic wave.

With the impulse generator, which is battery supplied for easy handling on-site, the transfer functions of one coil of a 400 kVA dry type transformer have been recorded before and after a winding short. The measurement setup as well as the transfer functions are illustrated in Figure 8.

From Figure 8 it becomes obvious that an interturn short circuit of about 8% of all windings causes significant changes in the transfer characteristic. The differences are more visible at lower frequencies, which are defined by the inductive characteristics of the coil, whereas for the higher frequencies the capacitive signal transmission is decisive. The example shows that deformations like winding shorts can be proven using the evaluation of transfer functions.

V. CONCLUSIONS

Since the use of paper-oil insulated transformers is restricted many distribution transformers for power levels up to 24 MVA and voltages up to 36 kV are replaced by dry type transformers usually insulated by epoxy resin. For the protection and monitoring of these transformers a cost-effective and efficient system is required, which is not available on the market at the moment. Therefore such a system has been developed, which monitors online local overheatings using a fibre optic sensor technology. In case of an overheating alarm an offline analysis of the transfer function can give indications if the overheating was caused by interturn winding shorts or similar failures. The introduced system is well tried and installed on different dry type transformers in Germany for about 1 year with the intention to increase the reliability and life expectancy of dry type transformers leading to an ensured power distribution.

VI. ACKNOWLEDGMENTS

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