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Power Transformers Insulation Material Investigations: Partial Discharge

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Abstract**—**There is a great problem in testing and investigations the reliability of different type of transformers insulation materials. It summarized in how to create and simulate the real conditions of working transformer and testing its insulation materials for Partial Discharge PD, typically as in the working mode. A lot of tests may give untrue results as the physical behavior of the insulation material differs under tests from its working condition. In this work, the real working conditions were simulated, and a large number of specimens have been tested. The investigations first stage, begin with choosing samples of different types of insulation materials (papers, pressboards, etc.). The second stage, the samples were dried in ovens at 105 $C^0$and 0.01bar for 48 hours, and then impregnated with dried and gasless oil (the water content less than 6 ppm.) at 105 $C^0$and 0.01bar for 48 hours, after so specimen cooling at room pressure and temperature for 24 hours. The third stage is investigating PD for the samples using ICM PD measuring device. After that, a continuous test on oil-impregnated insulation materials (paper, pressboards) was developed, and the phase resolved partial discharge pattern of PD signals was measured. The important of this work in providing the industrial sector with trusted high accurate measuring results based on real simulated working conditions. All the PD patterns (results) associated with a discharge produced in well-controlled laboratory condition. They compared with other previous and other laboratory results. In addition, the influence of different temperatures condition on the partial discharge activities was studied.

Keywords**—**Transformers, insulation materials, voids, partial discharge (PD).

I. Introduction

TRANSFORMERS are one of the most important Power supply elements. Forethought their weight varies from a few hundred kilograms up to 800 tones. They essentially always consist of the same main materials: copper, electrical steel and insulating materials (insulating paper, pressboard, and laminated wood) [1].

The Transformer Life Management is a completely accurate process of operating, monitoring, diagnostic, and detailed analysis to provide a technical, economic, optimized solution to improve the reliability and availability of the transformer. The transformer life is equal to the life of its insulations. The loss of life or the condition of the whole transformer can be due to: dielectric stresses, chemical stresses, thermal stresses and dynamic stresses. The dielectric stresses refer to the combination of solid and liquid insulation systems for power transformers. Insulation material conditions of power transformers are an important factor for its lifecycle time and the frailer coincidences [2], [12], [22]. Insulation material in a power transformer consists of cellulosic (paper and pressboard) and mineral oil. Cellulose insulation materials have been proven to have desirable chemical and physical properties for use as electrical insulators. Typical operating temperatures for power transformers lie between 65 to 95 ^oC [7].

Cellulose is a good isolator and is also polar having a dielectric constant significantly greater than one. It should be denoted be denoted that the following terms are often used interchangeably in the context of solid transformer insulation: Paper (Kraft paper), pressboard, transformer board, & cellulose. Although in the context of particular transformer insulation they may indicate different parts, paper tape, paper cylinders, transformers board cylinders. They are all refers to electrical grade paper insulation. Fig. 1 shows some samples of different types of insulation papers that have been prepared and used for investigations purposes [8], [15].

Fig. 1 Different types of transformers insulation material

Failure of the inner insulating systems of transformers can lead to a catastrophic failure with serious environmental and economic consequences. Partial Discharge (PD) monitoring and diagnosis are essential to identify the nature of insulation defects causing discharge.

The failures of the insulations can be slowly as a normal result of aging, continues thermal stress, or fast in some transient process. Hover, the statistics and the earlier investigations shows that more 80% of the failures are from the first case [3], [4]. This reason can be investigated and localized by the PD measurements, which is really is the beginning of the dielectric failure [5], [6]. The PD itself is some kind of breakdown of the insulating material (oil and paper or pressboards).

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If the experiments were separated by the paper only without mineral oil, so we got different PD voltage or breakdown voltages. As there will be other factors will affect the experiment such as the holes in the paper, the electrode positions, etc. The breakdown of the oil (separately) also can be fixed and investigated, but it totally differs than when it's working (impregnated) with paper.

The drying temperature besides the vacuum is the most important parameter concerning the drying results and time. The temperature also influences the depolymerization of insulation material. Therefore, an optimal temperature control is essential.

A lot of parameters can affect the researching process in different phases and stages. The main parameters that may have a big influence on the experiment and measurements result summarized as a. Type the electrodes which are dielectric contacts, b. Temperature, c. Drying and degassing of the insulation material, d. Time of impregnation, drying,.., etc. , e. Type of measuring media and it is a condition (oil).
Different samples of the insulating material (paper) that used in the transformers were prepared as in the real transformer conditions (Fig. 1). All the measurements, preparations, setup procedures and measurements performed at *Schering Institute-Hannover / Germany.*

II. Paper the Partial Discharge Theory and Concepts

Partial discharges occur only during the first and third quarter of each cycle. This is the initial rising positive signal and the initial rising negative signal. Effectively, during the initial rising positive signal, all of the capacitive components are being charged until the partial discharge inception voltage is reached across each specific void, and partial discharges commence [8], [10].

A significant method to present and interpret the PD measuring results is phase resolved partial discharge analysis (PRPP) or PD pattern, see Fig. 2. The type of defect and the source of discharge can be identified by the PD pattern [9], [11].

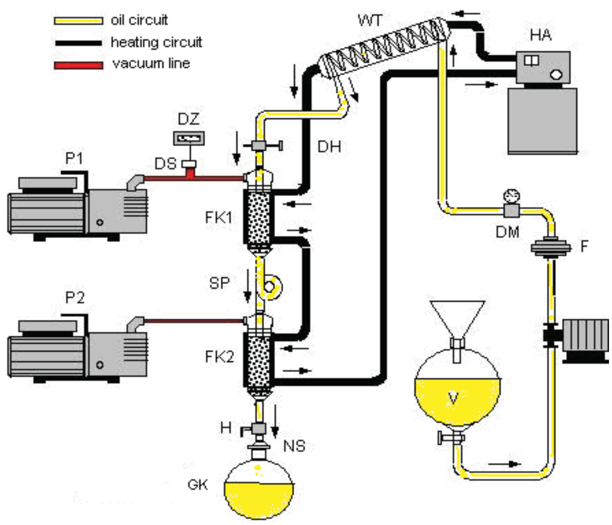
The main parameters of PD patterns are phase angle ***Φ***, discharge magnitude ***q***, and frequency ***n*** (the counts number) [15], [19]. The changes in the PD Φ-q-n pattern and the PD current shape due to the degradation of insulating materials can be investigated with a storage digital oscilloscope and a modern PD measurement system.

The PD patterns are often interpreted by a human engineer's expert, although they contain massive numerical information which can be used by expert systems too.

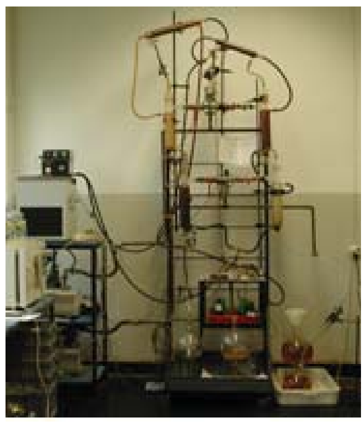
In order to avoid or minimize the gas in oil effects and water contents, the mineral oil for this group of experiments was prepared in the laboratory, also all the paper insulation samples implemented in special drying procedures, as follows: 1-Oil Drying Water content < 6 ppm, 2-Specimen Drying 105 C^0, 0.01bar, 48 hours, 3- Specimen impregnation with dryad oil 105 C^0, 0.001bar, 48 hours 4- Specimen cooling, Room pressure and temperature 24 hours.

III. Mineral Oil Preparation

In the transformer, the oil is used as cooler and insulating liquid. Nearly it is surrounding all the transformer interior parts. The oil should be prepared to face the high industrial standard with minimum water content. For that, the insulation liquid had to be processed, dried and degassed in order to improve electrical and dielectric properties. In Fig. 2, the schematic diagram of the oil drying and degassing system.



(a)



(b)

Fig. 2 (a) Schematic diagram and (b) picture of the drying system for insulating fluids

Fig. 3 Water content analyser devices

After completing this process, a several oil test samples were taken and analyzed for determining the water, as shown in Fig. 3. The mineral oil as in the real transformers was prepared and tested. The test approved the minimum water content.

IV. Drying and Impregnating of Paper Samples

A number of insulating paper samples: paper, pressboards and warped paper that normally used in the transformers was prepared as shown in Fig. 4. The paper is wrapped in several layers in a cylindrical form as it is between the winding. The thickness of this paper 0.1 mm and the wrapped paper in cylindrical form was about 5mm.

Fig. 4 Example of insulation paper samples

V. Drying of the Paper Samples

In order to extract the moisture (humidity) located inside insulting paper. The insulting papers were placed in metallic containers as it is illustrated in Fig. 5. The samples were dried in a special vacuum oven with vacuum pressure ~1 mbar in temperature 105 ºC, for 48 hours which more than enough. According to the standards IEC 60641-2:2005, the minimum time to extract the moisture is 24 hours. It is very important not over the dry samples. Otherwise, its internal structure can be destroyed or deformed.

Fig. 5 The drying furnace and paper samples placed in a preformed metallic container

VI. Impregnation with Prepared Oil in the Lab

To impregnate the paper samples with mineral insulating oil early prepared in the lab (as it was up mentioned). the impregnation process and how the oil was added to the samples from a rear side without disconnecting the process or opening the oven.

The samples were impregnated in the vacuum oven with vacuum pressure ~1 mbar, during temperature 105 ºC, for 48 hours

VII. The Cooling Process

To bring the impregnated insulating paper samples and the oil to the ambient temperature and normal pressure, the oven was switched off. The cooling process was for 24 hours, the average ambient temperature at the experiment time was 20-22 ºC.

VIII. Measurements System and Setup Conditions

The measurement system setup is consisting of two subsystems: the measuring system and the specimen. At the same time, both the measuring systems and the specimen consist of subsystems and different elements. The PD measurements are very sensitive to noise. It is important to have such a distinction between measuring system and specimen. As the measuring system elements itself can also be sources of PD impulses which are detrimental to the accuracy of the PD measurements of the specimen, which in the particular case of the project refers as to the insulation papers and pressboard samples.

The PD measurement device used was the ICM developed by Power Diagnostics Systems GmbH with its corresponding software.

Fig. 6 An example for samples measurements

IX. Results and Observations

For essential comparing purposes, some samples were investigated without oil and as the voids where are filed with gasses (air), the PD voltage was less than when it is impregnated with oil.

In order to measure the PD inception voltage, the high voltage applied to each of the samples was slowly increased still finding the PD inception voltage, that is, the voltage from which the PD activity take place.

For determining the extinction voltage, the voltage applied to the specimen was increased approximately 5% above the PD inception voltage and then this was slowly decreased still the value at which the PD activity stops was reached. PD inception voltage was applied to the specimen during 40 seconds. The average results obtained for the PD extinction and inspection voltage. Table I shows the results for the paper that was firstly measured without oil and then it was in simply impregnated with dried oil and measured [20]. One layer was 1 mm. The importance of these experiments was to realize the efficiency of the heating and impregnation process up illustrated in this work.

It is clear that the paper without oil has a large number of voids comparatively, which allow for the electrical PD charge to go through the insulation material, by impregnation the oil fulfill these voids and the PD voltage becomes higher and higher by more time.

TABLE I
INCEPTION PD VOLTAGES FOR PAPER

Conditions	PD Voltage, V		
	One a layer of Paper	Two layers of Paper	Three layers of paper
Without Oil without drying	200-290	360 - 400	500 - 600
With Oil impregnation without drying after 24 hours	450-510	1320-1380V	2135-2200
With Oil impregnation without drying after 48 hours	740-800	1440- 1500 V	2380-2500
With Oil impregnation without drying after 96 hours	1090-1140	1750-1835	3200-3300

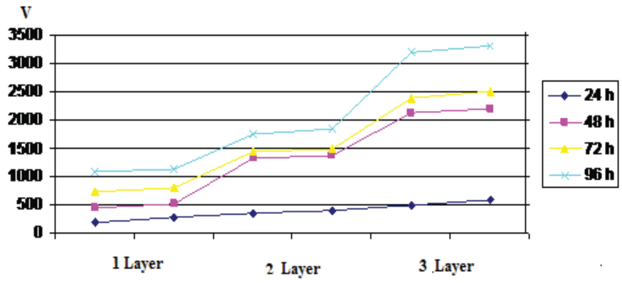


Fig. 7 The inception PD voltages for paper

Also in the mean time, the water from the cellulose (insulation paper) comes out to the oil which was detected by regular testing the water contents of the oil, the analyses show therising of water content in the oil. After about 120- 150 hours the measurements results in highlights only a slight increasing in the PD voltages. These phenomena can be explained because of that some samples voids are not fully degassed. In Table II a number of samples consist of 3 different kinds (types) of insulation paper was measured without oil [14], [21].

TABLE II
THE INCEPTION PD VOLTAGES WITHOUT OIL

Type of insulation Paper	Thinks of one layer, mm	PD Voltage, V		
		One layer	Two layers	Three layers
1	0.1	260	520	760
2	0.15	500	955	1310
3	1.0	1110	1840	2500

The relation between the PD voltage and the layers number is nearly linear. In Table III the insulation's paper samples were heated for 48 hours, impregnated under pressure for 48 hours and cooled for 24 hours by the procedures mentioned in the the 4th section of this work.

Comparing the results in Tables II and III, it is clear that the impregnation process has a big influence on the PD voltage for the paper was increased in about 13 times for 1, 2, and 3 layers.

For the Paper type, 2, PD voltage was increased about 6 times. For the Paper type 3 as the PD voltage has been increased by about 28 times. Theoretically, if the insulation material (paper) was good impregnated the PD phenomena absent and the voltage can reach to the breakdown voltage without any PD [13].

The results also show that the PD increased in nonlinear form by adding the layers as there is there maybe a small space between the layers where the oil did not reach.

For building the phase-resolved pattern of the partial discharge activity of each of the samples under study, the previously measured PD inception voltage was applied to the insulation paper during 100 seconds. These diagrams are shown in Fig. 9.

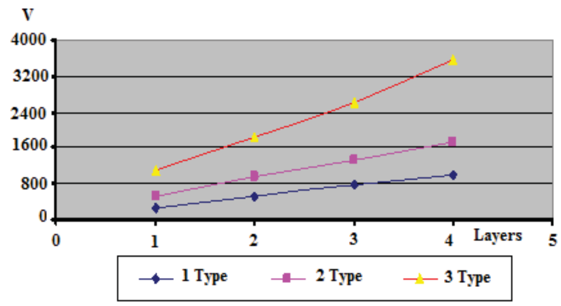


Fig. 8 The inception PD the 3 types of paper impregnated with drying

TABLE III
THE INCEPTION PD VOLTAGES IMPREGNATED WITH OIL

Type of insulation Paper	Thinks of one layer mm	PD Voltage, V		
		One layer	Two layers	Three layers
1	0.1	3310	6700	9100
2	0.15	5930	11500	15640
3	1.0	14300	28450	37150

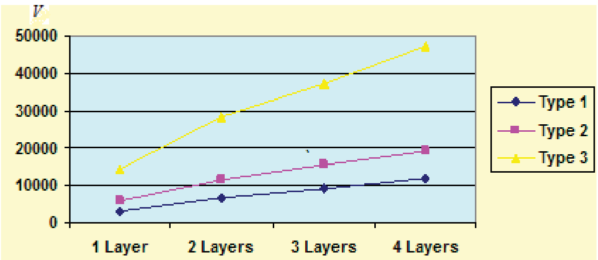
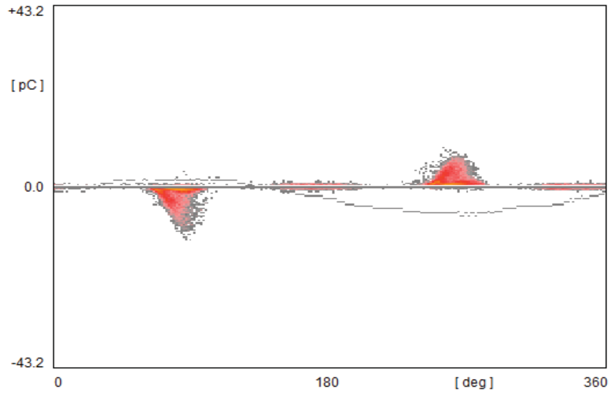
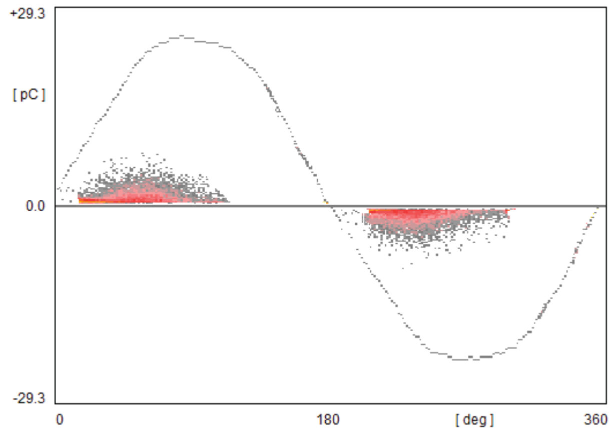


Fig. 9 The inception PD the 3 types of paper impregnated with drying and cooling



(a)



(b)

Fig. 10 (a) and (b) are Measured PD pattern by inception voltage time

It can be observed in Fig. 10, the partial discharge patterns of the samples without oil and with oil are not similar as the PD inception is differed. The area of red color indicates a high density of PD impulses. At the inception voltage of the PD, both pictures show charge pulses are symmetrical in the positive and negative half-cycles of the alternating voltage.

The analysis and the interpretation of the PD patterns were according to power diagnostics supplementary handbooks and software [16], [17]. In both 2D and 3 D which give a clearer picture (Figs. 10 and 11), the discharge amplitude with the counts number in the phase. The total count number and level in 3D reflect the real density of the PD voltage region (red color).

Analyzing the 3D patterns of the insulation material samples (Fig. 11). It was observed that the positive and the negative amplitudes are symmetrical as it was mentioned in Fig. 10, but the counts number and level counts levels are not the same (they don't have the same height). Depending on the PD density increased or decreased according to the direction of the applied voltage. These phenomena can be interpreted as: either the voids in the sample near electrodes parts (positive and negative) are not symmetrical (the same number of voids) or because of the appearance of small amount gas bubbles in liquids (oil) between the sample and the metallic parts (electrode). But on the average, pulses have the same amplitude in both half-cycle. The charge transferred from the void to electrodes surrounding the insulating materials is always smaller than the actual charge [14], [18].

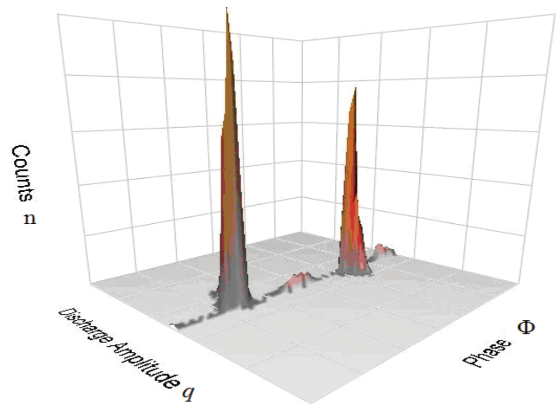


Fig. 11 Example of the 3 D pattern for the paper with oil 3310V

The 3D analyses were applied to the all entire specimen's samples that have been measured in this work. The charge and counts number (pulses number) are illustrated for Cluster. The larger void volume leads to larger PD magnitude.

The parameters in different stages have been studied as well as the insight into the physical changes in the void during electrical aging. The results provide rules for the identification of the electrical aging stage through the partial discharge measurements.

X. Conclusions

PD behavior under different applied voltages for different kinds of insulation materials has been studied. PD behavior was observed through phase resolved partial discharge patterns under AC sinusoidal.

PD activity within a void in a dielectric material is strongly influenced by the applied voltage waveform because the electric field magnitude in the void is determined by the applied voltage. It was noticed that there are some factors that affect the experiments, and these notices exist in the real transformers such as:

1) The number of voids in the paper cannot be the same for all the samples even from the same type.
2) The electrode positions cannot be the same 100% for all the samples.
3) Water from surrounding air comes to oil then from oil to cellulose in this case the PD voltage should go down Past impregnation close rest of air holes (voids) in cellulose this makes the Pd voltage goes up the relative water content on the surface of the oil, not the same as in the depth of the measuring cells.

4) The charge transferred from the void to electrodes surrounding the insulating materials is always smaller than the actual charge. The transfer factor should be investigated in the future works, and it differs from case to case and sample to sample.
5) The origination location of the PD based on the partial discharge picture is unique only in few cases. It can be seen only as an indication of the location where the material is defective and where improvements in manufacturing are necessary. The PD magnitude plays here the same role as during a test according to specifications.
6) If the oil was so dry the breakdown or PD inspection voltage goes down, and if we dried the cellulose so much, it would be the structure of the mechanical stress can go down.
7) The changes in the PD Φ-q-n pattern and the PD current shape due to the degradation of insulating materials have been investigated with and a PD measurement system. In order to verify the effect of the gas change, the volume of gas in a void was observed with the Φ-q-n pattern.

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