Studying the Aging Evolution of Oil-Paper Insulation Comprising of a Gas Cavity Under the Stress of AC and DC Voltage Depending on Partial Discharge and Dissolved Gases Measurements

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ABSTRACT The oil-paper insulation system is widely used for the insulation purposes of power transformers as a result of its ability to withstand high thermal and electrical stresses. The presence of a gas cavity between impregnated papers layer is a serious problem. When localized breakdown takes place within this cavity, partial discharge (PD) occurs and ages the rest of the insulation system. This aging phenomenon declines the expected life time of the insulation system and subsequently the life time of the power transformers. Dissolved gas analysis is a recommended technique that is used in order to assess the state of the insulation system inside the transformers. In this paper, PD is recorded in the case of gas cavity presence between the layers of the impregnated papers under the effect of AC and DC voltage stress. This record is extended from the instance of PD inception until the breakdown of the whole insulation system. Furthermore, the concentration of the gases that dissolve in the insulating oil due to the aging of the impregnated paper is measured eight times during the record of the PD. Finally, the degradation of the insulating papers is studied optically through the use of a microscope at different stages of the aging test. Depending on PD measurements, dissolved gas analysis (DGA) results, and the optical study of the paper aging, the evolution of the aging of oil-paper insulation system as a result of internal PD is declared when AC and DC voltage stresses are applied. It is obtained that the aging evolutionary process totally differs with the alteration of the applied voltage.

INDEX TERMS Partial discharge, internal cavity, oil-paper, dissolved gas analysis, insulation aging.

I. INTRODUCTION

In consequence of aging problems on the hand, and imperfect impregnation process of oil-paper insulation system on the other hand, small gas cavities can be emerged between the layers of the impregnated papers. During operation conditions, the electric stress over these cavities is high compared with surrounding insulating system. Furthermore, the dielectric strength of the gas inside these cavities is lower than the dielectric strength of the surrounding insulating materials. Thus, discharges may occur inside these cavities before they erode the rest of the insulation system. This phenomenon is called internal PD. By time, these PD activities age the oil impregnated paper layers and will eventually lead to a complete breakdown [1]–[3]. 

Studying internal PD remains a challenging issue because of many reasons. First of all, the presence of small gas cavities inside electrical insulation system can be considered a common problem. Second reason is that, internal PD always occurs accompanied by chemical reactions, local heat emissions, etc. These chemical reactions produce chemical byproducts such as carbon oxides and hydrocarbon gases. These byproducts greatly affect the aging process of the surrounding insulation system [4], [5]. Third reason is that the electrical properties such as complex relative permittivity and surface conductivity of the insulation system that surrounds the gas cavity are influenced during PD reoccurrence [6]–[8]. Fourth reason is the stochastic nature that distinguishes the PD [9], [10].
As a result of the increasing demand to transmit electric energy over long distances with low losses, HVDC transmission systems spread through many regions worldwide. The converter transformer is one of the most important and expensive components in this power system. Thus, the insulation system within these transformers must be as reliable as possible [11]. As a result, PD measurements on HVDC equipment with oil-paper insulation systems are considered worth to be studied extensively. Internal PD characteristics of oil-paper insulation systems with regard to DC voltage application have not been sufficiently investigated. Thus, the differences between aging evolutionary processes due to internal PD when either AC or DC voltage stress is applied require further clarifications.

Due to the ability to withstand high mechanical, thermal, and electrical stresses, oil-paper can be considered the main insulation system that is used to isolate the transformer windings [12], [13]. Many researches have correlated the remaining age of the operating transformers with the state of oil-paper insulation system [14]–[18].

Insulating paper is a composite material that is manufactured from various organic substances. Cellulose represents approximately 90% of the chemical structure of the insulating paper. The other 10% is divided between hemicellulose and lignin [19], [20]. As shown in Fig. 1, cellulose is a polymeric linear chain of glucose molecules that are linked together by glycosidic bond [21]–[23]. During the aging process of the insulating papers these polymeric linear chains breakdown into other chemical products. Due to the weakness of not only carbon-oxygen (C-O) bonds but also glycosidic bonds, different gases such as hydrogen, oxygen, carbon monoxide, carbon dioxide and hydrocarbon gases are emitted and dissolved in transformer oil with different concentrations during the aging process. These concentrations depend on the nature of the fault that causes the degradation of the insulating papers [24]–[26].

Different methods are used in order to distinguish the faults within the transformer by analysing the percentage of the dissolved gases in the insulating oil. These methods can be classified into three main categories. The first category contains key gas method that classifies the faults according to the dominant emitted gas. The second category includes the methods that rely on different gases ratios such as Dornenburg’s ratio method, Rogers’s ratio method, and IEC ratio method. The third category includes the graphical methods that can be represented either by a triangle form or a pentagon form [27]–[29]. These three categories are well known as DGA. Table 1 illustrates the faults that can be detected by DGA.

In this investigation, PD will be recorded in the case of a gas cavity presence between the layers of the impregnated paper under the effect of AC and DC voltage stress. The PD will be recorded from the instance of its inception until the whole insulation system breakdown. Moreover, the dissolved gases will be measured eight times during PD aging by using chromatography analysis according to IEC 60567 [30]. The degradation of the insulating papers is studied optically by using a microscope. PD measurements, DGA, and aging process monitoring will be studied in order to understand the mechanism behind the breakdown of oil-paper insulation system due to internal PD. The main aim of this investigation is to clarify the differences in the oil-paper aging evolution process due to internal PD when either AC or DC voltage stress is applied.

**II. EXPERIMENTAL SETUP**

As shown in Fig. 2, ten layers of insulating presspaper have been inserted between two identical brass plate electrodes.
trodes. Each layer is 0.15 mm thickness. Because of its wide usage in the insulation system of the transformer windings, KREMPBEL Presspaper PSP 3055 has been used in the current research. Table 2 illustrates the technical data of the used presspaper samples that has been measured in accordance with IEC 60641-2 [31]. A 5 mm diameter cavity has been artificially created in the middle of the insulating presspaper as shown in Fig. 3 in order to simulate the embedded cavity between the insulating layers. The thickness of the cavity changes between 0.45, 0.6, 0.75, and 0.9 mm by arranging three, four, five, and six insulating paper layers respectively with a cavity in the middle of these layers. This arrangement has been selected in order to simulate the presence of gas cavity between the impregnated paper layers according to CIGRE method II and ASTM-D149-09 [32], [33]. In order to check the quality of the insulating paper samples, the degree of polymerization (DP) has been measured before implementing the aging tests. The DP before any stress for all samples was $1100 ± 15$.

The insulating presspaper samples have been impregnated with Shell Diala oil according to DIN EN 60763-2. This oil has been chosen in the current research based on its wide deployment and good physical characteristics. It is clear from Table 3 that the oil fulfils the requirements of the IEC 60296 [34]. The insulating papers have been dried at temperature of 105°C and pressure lower than 100 Pa. for 24 hours in a heating cabinet. Then, these dried papers have been impregnated with the oil in a pressure lower than 100 Pa. for another 24 hours. Finally, the oil-paper insulation system is kept another 24 hours before implementing any PD measurements as recommended previously in [35], [36]. This preparation process of oil-paper insulation system is repeated before PD aging tests in order to provide consistent conditions.

PD has been measured through the use of Omicron MPD-600 PD measuring system according to the IEC 60270 standard. As it is shown in Fig. 4, the measuring impedance ($Z_m$) is connected in series with the coupling capacitor ($C_k$) and both are connected in parallel with the test object. The AC voltage source frequency is 50 Hz. In case of DC voltage application, a Greinacher circuit has been connected to the secondary winding of the high voltage transformer as explained in [37].

All measurements have been recorded with an external noise limit 5 pC. Voltage application procedures consist of two main stages. Firstly, the voltage has been raised with a constant rate of $0.25 \text{kV/s}$ until reaching the level of 1.2 of PD inception voltage (PDIV). Then, the voltage is kept constant until the insulation system breakdown. The difference in the definition between PDIV in AC and DC cases has been taken into account during the measurements. PDIV in AC case is defined as the minimum applied voltage required to initiate single discharge event inside the cavity per each cycle of the power frequency. However, the minimum applied voltage required to initiate one discharge event inside the gas cavity per one minute, is the definition of PDIV in DC case [38], [39]. Following these two definitions, PDIV has been measured in the current research to be approximately...
equal in all cavity thicknesses in AC and DC aging tests. This can be explained according to the fact that, the electric field in both AC and DC during voltage boosting stage depends mainly on the permittivity of the insulating materials [40]–[42]. Thus, the minimum electric stress required to initiate PD events inside the cavity is the same between AC and DC voltage stress. It is recommended to measure PD magnitude and repetition rate at a voltage level 1.2 of PDIV because of the fact that the PD repetition rate is so low just above the PDIV.

As shown in Fig. 5, a temperature control unit has been connected to the external brooder that contains the test vessel in order to maintain constant temperature during all aging tests. The temperature has been adjusted to be 60 °C inside the external brooder as it represents the temperature of the in service transformers [43]. Temperature sensor has been used as a way to indicate any change in the temperature during aging tests. In order to simulate the circulation of the insulating oil inside the in-service transformers, external oil loop has been designed with the using of oil pump. Regarding this oil loop, the dissolved gases are distributed equally within the internal test vessel [44]–[46].

Oil samples have been extracted from the test vessel through the use of a drain valve as explained in [47], [48]. Following IEC 60567, these oil samples have been kept in glass tubes. Argon has been used as a carrier gas in order to extract gases from oil samples. A gas chromatograph Shimadzu GC2014 is used in order to analyse the extracted gases. The processes of oil sampling, extraction, and chromatographic analysis have been explained in details in previous publications [49]–[51].

III. EXPERIMENTAL RESULT

A. PD CHARACTERISTICS IN AC AND DC CONDITIONS

PD apparent charge, PD pulses peaks, and PD repetition rate have been recorded in case of AC voltage from the instance of PD inception until the breakdown of the whole insulation system. Figs. 6, 7 and 8 illustrate the PD characteristics recorded in case of cylindrical cavity presence in the center of the oil-paper insulating system sample. The cylindrical cavity is 5 mm in diameter and 0.6 mm in height. The whole distance between the electrodes is 1.5 mm. It can be concluded that the PD lasts 127 hours until the breakdown of the insulation system. Referring to Figs. 6 and 7, it is clear that PD magnitude is significant just after the PD initiation. After about two hours, the PD magnitude level decreases. By time, PD occurs with approximately constant magnitude until the occurrence of the final increase. This increase in PD magnitude has been recorded after 70-80 hours from PD inception. This ascending manner of PD magnitude remains up to the failure of the whole insulation system. The green circles in Fig. 6 indicate the time marks when oil samples have been taken to perform the DGA.

PD initiates inside the cavity with a relatively high repetition rate at a voltage level 1.2 of PDIV. Later, this rate decreases after a short time as shown in Fig. 8. Then, the PD rate increases again for 30-40 minutes. Finally, PD occurrence rate inside the cavity declines while the charge increases until the breakdown of the insulation...
system. This scenario agrees with previous results introduced in [6], [13].

PD pulses peaks and repetition rate have been also recorded in case of DC voltage application from the instance of PD inception until the breakdown of the whole insulation system. The cavity dimensions are the same as in AC case. The measured PDIV in case of DC voltage application is 12.3 kV. PDIV is approximately constant in AC and DC cases at the same cavity dimensions as it has been measured during constant voltage rising stage. It is clear from Figs. 9 and 10 that the breakdown in DC aging test takes longer time than in AC aging test. This result can be explained according to the difference in the PD magnitude and repetition rate. The PD magnitude and repetition rate in AC case is greater than in DC. This result totally agrees with previous results compared between PD magnitude and repetition rate in a gas cavity inside polyethylene solid insulating specimen under the effect of AC and DC voltage stresses [52], [53]. The green time marks in Fig. 9 indicate the time when DGA has been performed in DC case.

The highest rate of PD has been detected in DC voltage case just after reaching the inception voltage level. This rate decreases gradually until the breakdown of the insulation system. This descending trend of PD rate is attributed to two main explanations. On one hand, high magnitude leakage current passes through the insulating sample when the applied voltage attains PDIV level. This current causes fast recharging inside the embedded cavity. Consequently, the highest PD rate is detected in this period [53], [54]. On the other hand, the occurrence of PD inside the cavity causes the accumulation of charges on the cavity walls. As a result, the voltage inside the cavity drops to the residual voltage ($V_r$) [55], [56]. The time interval between successive PD pulses is given by equation (1) [38], [56]. Due to the fast recharging process inside the cavity after PD inception, $V_r$ value is high. Thus, the time interval between the successive pulses is so short in this stage. In conjunction with the PD propagation and the accompanied insulating paper aging, $V_r$ drops and as a consequence longer time is required in order to initiate PD events inside the cavity [57].

$$T_{int.} \approx \tau(V_{min.} - V_r)/(V_{c\infty})$$

where:

- $T_{int.}$: time interval between successive PD pulses.
- $V_{min.}$: minimum required voltage for PD inception.
- $V_{c\infty}$: the final value of the voltage inside the cavity.

Due to the difference between PD magnitude and repetition rate in AC and DC cases, the insulating medium surrounding the cavity is expected to be degraded at a faster rate in AC case. The time of insulation system breakdown has been measured in AC and DC cases for different cavity thickness at a voltage level 1.2 of PDIV. In order to obtain reliable
results, the aging tests have been repeated six times for each cavity thickness. Fig. 11 shows that, the breakdown occurs in AC case faster than in DC case regardless of the thickness of the cavity. As the PDIV is approximately equal in AC and DC cases, the difference in the time of insulation system breakdown has been attributed mainly to the different PD magnitude and repetition rate. Of the results illustrated in Fig. 11, the margin of error in the breakdown time in all measurements did not exceed 9%.

B. DGA RESULTS (CONCENTRATION OF DISSOLVED GASES)

As indicated in Figs. 6 and 9, oil samples have been taken eight times under each AC and DC voltage aging tests in order to perform DGA. In AC case, oil samples have been taken every 15 hours. However oil samples have been taken every 18 hours in DC case. The time interval between successive oil sampling differs between AC and DC cases because of that the breakdown of the whole insulation system in DC case takes longer time than in AC. The purpose of the first and second oil samples is to analyse the generated gases in the early stage of PD. The third, fourth, and fifth samples, aim to assess the dissolved gases generated in the period when PD occurs with approximately constant magnitude. The purpose of the last three oil samples is to study the dissolved gases during the period that indicates the insulation system pre-breakdown.

The concentration of hydrogen (H₂), methane (CH₄), acetylene (C₂H₂), ethylene (C₂H₄), ethane (C₂H₆), carbon monoxide (CO), and carbon dioxide (CO₂) gases have been measured in AC and DC cases in order to predict the complete scenario of oil-paper insulation system degradation due to the presence of gas cavity. Furthermore, the gas generation rate (GGR) has been calculated for the dissolved gases in AC and DC voltages by using equation (2) [58].

\[ GGR = \frac{1}{T} \left( \frac{S_2 - S_1}{S_1} \right) \times 100 \] (2)

where:

- \( T \): time between the successive samples in hour.
- \( S_2 \): the gas concentration of the second oil sample in part per million (ppm).
- \( S_1 \): the gas concentration of the first oil sample (ppm).

Figs. 12 and 13 illustrate the concentration of the dissolved gases in the collected oil samples in AC and DC cases respectively. Dual axis figures have been used for clear representation of the gases concentration. A higher generation rate can be observed for AC voltage when compared to DC voltage. CO₂ is generated and dissolves in oil with high quantity more than the other gases in all stages. CO gas is generated with a high rate in the first, sixth, seventh, and eighth oil samples when AC voltage is applied. However in DC case, CO gas is generated with an approximately constant rate in all samples. C₂H₂ gas has been detected in all stages of PD not only in AC aging test but also in DC aging test. Figure 12, illustrates that C₂H₄ is produced in AC test in the first, seventh, and eighth oil samples only. However in DC test, it is produced with a
C. DGA RESULTS (GGR OF DISSOLVED GASES)

On the basis of DGA results it can be concluded that CO$_2$, CO, C$_2$H$_2$, and C$_2$H$_4$ can be the considered the main generated gases in the case of internal PD activities between the impregnated paper layers. Consequently, GGR has been calculated for these gases in every stage in AC and DC cases. These calculations help to gain clearer understanding of presspaper aging due to PD activities. In order to represent the results in a clear manner, GGR values have been recorded for C$_2$H$_2$ and C$_2$H$_4$ as hydrocarbon gases in one figure, and for CO$_2$ and CO as carbon oxide gases in another figure for both AC and DC cases.

Figs. 14 and 15 show that CO$_2$ has the highest GGR in the early stage of PD, however C$_2$H$_4$ has the highest GGR prior to the insulation system breakdown in AC aging test. C$_2$H$_4$ is a gas generated mostly in the cases of thermal problems [59], [26]. C$_2$H$_2$ is also generated with high rate in the first stage. CO is generated with a relatively balanced GGR in comparison to the other three gases.

The high value of GGR in the first sample of DGA in all gases can be explained on the basis of two reasons. Firstly most of gases dissolve in the oil after the impregnation process and before PD inception with a concentration lower than 1 ppm as shown in table 4. As a result ($S_1$) value in equation (2) is so small in the first sample. Secondly, PD occurs in the first stage with high magnitude and high repetition rate as it is shown in Figs. 6 and 7. Consequently, the insulating presspapers are supposed to be degraded extensively in this stage. Because of this extensive deterioration gases are generated and dissolve in oil with high concentration as shown in Fig. 12. As a result ($S_2$) value in equation (1) is so high in comparison with ($S_1$) in the first sample of DGA. Thus, the numerator of equation (2) is so high for the first oil sample while the dominator is so small. This difference leads to high GGR of dissolved gases in this sample.

Figs. 16 and 17 show the GGR values of the four gases in DC voltage case. It is clear that the GGR values in DC voltage case are lower than their values in AC voltage case for all gases. The lower of dissolved gases concentrations and GGR in case of DC voltage application can be explained as a result of the lower PD magnitude and repetition rate. C$_2$H$_2$ has the highest GGR in the early stage of PD. However C$_2$H$_4$ has the highest GGR before the insulation system breakdown. GGR of CO$_2$ gas is higher than GGR of CO in all stages in DC case. However in AC case, GGR of CO is higher than GGR of CO$_2$ in the second, third, and fourth oil samples. GGR of C$_2$H$_2$ and C$_2$H$_4$ in the second, third, fourth, fifth, and sixth oil samples in DC case is not as small as in AC case.

Depending on GGR calculation, it can be estimated that the insulating papers degrade under AC voltage stress mostly in the early stage of PD and prior to the insulation system breakdown. However under DC voltage stress, the insulating papers appear to be degraded gradually during all PD stages. In order to validate this estimation, CO$_2$/CO ratio has been calculated in the eight oil samples for both AC and DC.

### Table 4. Concentration of the dissolved gases in the oil before PD inception.

| Gas   | C$_2$H$_2$ | C$_2$H$_4$ | CH$_4$ | C$_2$H$_6$ | CO   | CO$_2$ | H$_2$ |
|-------|------------|------------|--------|------------|------|--------|------|
| ppm   | 0.2        | 0.2        | 0.4    | 0.3        | 0.8  | 2      | 2    |
The degradation in the last PD stage takes place accompanied by high temperature. Depending on GGR calculations and CO\textsubscript{2}/CO ratio, it can be concluded that the degradation of presspapers in AC case occurs predominantly after PD inception and before the whole insulation system breakdown. However, in DC case the insulating papers degrade with high rate prior to breakdown of the insulation system.

In order to present more reliable results, the degradation of the insulating papers has been investigated three times with the using of a microscope. The degradation of the presspapery samples have been recorded firstly after 30 hours from PD inception. This investigation aims to identify the resulting degradation level in the primary stage of PD occurrence. Then, the degradation of the presspapers have been recorded another time after 100 hours in order to identify the aging level in AC and DC cases during the pre-breakdown stage of the insulation system. Finally, the degradation of the insulating presspapers has been recorded just after the insulation system breakdown. The aim of these three records is to identify the aging scenario of the insulating papers in AC and DC cases through different stages of PD.

**E. PRESSPAPER DEGRADATION WITH AC AND DC VOLTAGE STRESS**

According to previous researches, PD magnitude increases to a high value after PD inception. Later, this high PD magnitude
drops [6], [13]. This increase in PD magnitude is explained due to the conduction mechanism that occurs along the cavity walls. This mechanism occurs mainly as a result of not only the formation of conductive carbonised channels along the cavity edges, but also the conductive acids and gases production due to PD. The increase in surface conductivity implies that a larger area of the insulating surface is subjected to discharge events. Thus larger capacitance is discharged with a higher PD magnitude [7], [8], [63]–[65].

Fig. 20 illustrates that the cavity edge is obviously degraded by the PD events within the cavity after 30 hours of PD inception. It is also clear that this degradation occurs to the papers that are in vicinity of the cavity. Remarkably, the degradation is evident in case of AC voltage application more than in DC case in this stage of PD. The carbonized tracks around the cavity edges occur due to PD events and also greatly affect PD magnitude level. A direct proportional relation is considered between PD erosion time and paper aging.

Fig. 21 illustrates the degradation of the insulating papers after 100 hours of PD aging. It can be observed that the presspapres degradation with DC voltage stress is more obvious after 100 hours rather than after 30 hours of PD inception. A significant carbonized edge is found then for both AC and DC voltage stressed specimen. It can be also concluded that the difference between the degradation level after 100 hours and 30 hours is so remarkable in DC case rather than in AC case.

After the whole insulation system breakdown, the degradation of presspapres has been investigated too. This investigation has been implemented with the unaided eye and with the using of microscope zoom. It is clear from Fig. 22 that the puncture point of the breakdown can be determined by the unaided eye in the papers located in vicinity of the cavity. The deterioration of the cavity edges cannot be determined in AC case by the unaided eye even after complete insulation system breakdown. Thus a microscopic 10x-zoom has been used in order to record the degradation of the cavity edges in this case.
In DC case the cavity shape is completely deformed by the PD erosion until the insulation system breakdown. Fig 23 illustrates that the upper and lower edges of the cavity totally degrade and the cavity do not remain in the cylindrical shape. This degradation is so obvious without using a microscopic zoom. The carbonized area in the presspapers that locate in vicinity of the cavity in DC voltage is greater than in AC voltage. The varying erosion level is a clear indication on the unalike field stress in the defect under AC and DC voltage load. This will lead to future investigations in order to explain the acting mechanisms.

By analysing the detected presspapers degradation in the previously mentioned three stages, not only in AC aging test but also in DC aging test, many important results can be obtained. In case of AC voltage application, PD occurs in the early stage with high magnitude and repetition rate. This PD extensively deteriorates the insulating presspapers not only that locate next to the initially punctured papers but also the edge of the artificial defect. This deterioration occurs accompanied with a high rate of dissolved gases generation. The carbonized cracks around the cavity that result from PD event greatly affect PD propagation. Then, this deterioration rate decreases with the decline of PD magnitude and repetition rate. Finally PD magnitude rises again and the insulating papers in vicinity of the cavity degrade until the complete breakdown of the insulating system.

In DC case, PD occurs in the early stage with high magnitude but not as high as under AC voltage. Thus, the dissolved gases are emitted with lower concentration in case of DC voltage application. The detected paper degradation with DC voltage is not so clear in the early stages. This degradation increases gradually while the progressing PD ascends in magnitude. This degradation reaches its maximum before the insulation system failure. It can be detected with unaided eyes along the border of the cavity.

F. DGA RESULTS VALIDATION

In order to validate DGA results that have been obtained in the current research, it will be compared with a model that has been presented in a previous publication. W. Chen et al. introduced a model that contains one general condition and three secondary conditions [46]. The general condition is used in order to identify whether the dissolved gases are emitted due to surface discharge or due to a cavity presence between the impregnated paper layers in case of AC voltage application. Then, the three secondary conditions are used to identify the stages of PD depending on DGA results. Other models have studied the DGA in case of gas cavity presence between impregnated paper layers in case of AC-DC combined voltages application [44], [45].

In W. Chen’s model, 40 mm diameter cavity has been artificially installed between two identical Kraft pressboard layers. Each layer was 80 mm in diameter and 1 mm thickness. The temperature of the test cell during the measurements was 60°C and PD was recorded in a frequency 50 Hz. PD measuring circuit was designed according to IEC 60270 standard. A 1000 pF coupling capacitor was used in order to measure the high frequency PD impulses. DGA procedures were carried out depending on IEC 60567. Oil samples were taken out from the test vessel for DGA every six hours during aging tests.

Table 5 introduces a comparison between the conditions of W. Chen’s model and the obtained results in the current article. Remarkably, the general condition has been fulfilled in all DGA measurements. The condition of the early stage has not been fulfilled. However the condition of the late stage of PD has been fulfilled. The condition of the middle stage of PD has been fulfilled in the third, fourth, fifth, and seventh DGA measurements.

The first dissolved gases measurement has been implemented in the current research in AC case after 15 hours of PD

| Condition                        | W. Chen's model conditions | Obtained results     |
|----------------------------------|----------------------------|----------------------|
| General condition                | $C_2H_4/C_2H_2 \leq 0.1$  | Fulfilled in all measurement |
| PD early stage condition         | $C_2H_4/C_2H_2 \leq 0.5$  | Not Fulfilled        |
| PD middle stage condition        | $0.5 \leq C_2H_4/C_2H_2 \leq 3$ | Fulfilled in 66% of the measurement |
| PD late stage condition          | $C_2H_4/C_2H_2 < 0.2$     | Fulfilled            |
aging. However, the first dissolved gases measurement in W. Chen’s model has been implemented only after 6 hours from PD inception. As a result, the condition of the PD early stage in W. Chen’s model has not been fulfilled in this investigation.

Depending on the comparison between the obtained DGA results in the current research and W. Chen’s model it can be concluded that the obtained result corresponds to W. Chen’s model in most cases. It can be also concluded that the condition of the late PD stage is the most compatible condition with the obtained results.

IV. CONCLUSION

The paper focuses mainly on the aging evolution of oil-paper insulation in case of gas cavity presence. The obtained results in this paper can be classified to four main points. Firstly, the paper introduced records of PD events in case of gas cavity presence between the impregnated paper layers in AC and DC cases. It has been obtained that PD occurs in AC voltage case with magnitude and repetition rate higher than in DC voltage case. The breakdown of the oil-paper insulation system require more time in DC voltage case rather than in AC voltage case.

Secondly, dissolved gases have been measured eight times during PD measurements when AC and DC voltages are being applied. DGA results show that CO₂, CO, C₂H₆, and C₂H₄ can be considered the most generated gases correlated to the case of gas cavity presence between impregnated paper layers. These gases are generated with high rate in the early stage of PD in AC and DC aging tests. Not only GGR but also CO₂/CO ratio showed that the insulating paper degrades with high rate in AC case in the early and late stages of PD. However it degrades gradually during PD events in DC case. The highest rate of presspaper degradation in DC case has been detected before the breakdown of the insulation system.

Thirdly the degradation of the presspapers has been recorded three times not only during AC aging test but also in DC aging test in order to prove the DGA results. It has been recorded 30 hours after the PD aging, 100 hours after the PD aging, and after the insulation system breakdown. It has been concluded that the degradation is so clear in the early stage of PD in AC aging test however in DC aging test the insulating papers degrade extensively before the whole insulation system breakdown.

Finally the DGA results have been compared with a model that has been presented in a previous publication. This model is used to assay the PD stages depending on DGA results when AC voltage is being applied. DGA findings of the current article support the model that has been presented in the previous publication.

The paper aims to identify the main features of gas cavity presence defect between the layers of the impregnated paper within the transformers. This defect has been chosen to be studied because of its danger and commonness Moreover the aging evolutionary process of the insulating papers surrounding the cavity has been investigated in case of AC and DC voltage application.

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