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Effect of Temperature on Creeping Flashover Voltage of Nanofilled Oil-Pressboard Insulation

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ABSTRACT Creeping flashover (surface discharge) at oil-pressboard interface is considered a serious failure of the insulation system in power transformers. In this paper, creeping flashover voltage at oil-pressboard interface using the concept of nanofluids is experimentally evaluated. The creeping flashover test is carried out using a needle-plate electrode configuration considering 5 mm gap spacing. Three different types of nanofiller (CuO, MgO and ZnO) with different concentration levels (0.05, 0.1, 0.2 g/l) are used for enhancing oil-pressboard creeping flashover voltage. The effect of temperature on creeping flashover voltage is experimentally studied for all nanofiller types at the adopted concentration levels. The considered temperatures are room temperature (30 ^{o}C), 50 ^{o}C, 80 ^{o}C and 120 ^{o}C. These temperatures are considered to study their effect on creeping flashover voltage taking into consideration a wide range of transformer loading. Average of ten creeping flashover voltages is investigated for all studied conditions. Also, Weibull distribution is used for analyzing the creeping flashover voltages at 10% and 50% probabilities for the studied conditions. Finally, interpretations of the obtained results are presented through a proposed mechanism.

INDEX TERMS Creeping flashover voltage, oil-pressboard, nanoparticles, CuO, MgO, ZnO, needle-plate electrode, Weibull distribution.

I. INTRODUCTION

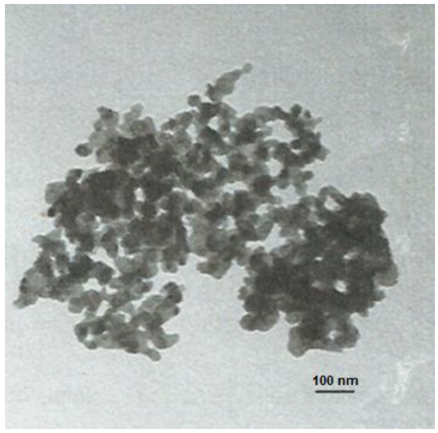
Power transformers are considered vital parts in electric power system; generation, transmission or distribution. Oil immersed transformers are widely used in these systems. The insulating system for these transformers depends largely on oil-pressboard combination which has a high dielectric strength. Transformer oil is used for the purposes of insulation and cooling, while the pressboard is used for insulation between transformer windings. Oil-pressboard interface is considered the weakest insulation point. As this interface has the lowest creeping flashover dielectric strength. This comes due to the difference in the relative permittivities of transformer oil and the impregnated pressboard, which supports charge growth under high voltage stresses. Creeping flashover stresses are responsible for serious damage of transformer insulating system under normal AC voltage operating conditions [1-7]. So, it is important to enhance creeping flashover voltage of oil-pressboard interface.

It is found that adding few percentages of nanoparticles to transformer oil forming nanofluid, improving various electrical properties of oil and oil impregnated pressboard. This improvement comes as nanoparticles attract electrons and hindering their motion. Also, it comes due to the increase in electron trap energy by nanoparticles and the decrease in moisture content in oil [8-9]. There are many researches that concerned with studying the effect of nanoparticles on dielectric properties of transformer oil [11-17]. However, few ones deal with their effect on creeping flashover voltage of oil-pressboard insulation. The concept of mixing two types of vegetable oil with the base mineral transformer oil (3-element mixed insulation oil, 3EMO) for enhancing flashover voltage at oil pressboard interface is studied in [18]. It is also reported that using 3EMO impregnated pressboard has a slightly higher relative permittivity and a lower percentage of dissolved gases during flashover. Hence, the AC flashover tests are performed using needle-plate and finger-finger electrodes in order to simulate both extremely and slightly non-uniform electric fields, respectively. In [19], the creeping flashover voltage is improved under lightning impulse stresses using Fe_3O_4 nanoparticles. As the nanofluid impregnated pressboard offers high resistance to creeping discharge than base one for the different studied electrode gaps. Also, TiO_2 nanoparticles enhance both the creeping flashover voltage and partial discharge inception voltage of oil-pressboard interface under either AC or impulse voltage stresses as reported in [11]. Two types of nanoparticles (TiO_2 and Al_2O_3) are found to be effective for enhancing the flashover voltage of oil-pressboard interface under static and dynamic conditions [9]. This improvement is explained by the interface double layer for Al_2O_3 nanoparticles and the electron trapping ability for TiO_2 nanoparticles [9]. It is also shown that using Al_2O_3 nanoparticles delay the aging of both transformer oil and oil impregnated pressboard [20]. The average AC and positive lightning impulse breakdown voltages are increased with 11% in case of using nanofluid than base one. Also, the average positive and negative creeping flashover voltages are elevated by 6% when using nanofilled oil impregnated pressboard. In [8], three different nanofiller materials with different concentrations are used for improving the creeping flashover voltage at oil-pressboard interface. It is shown that adding nanoparticles of Pb_3O_4 is more effective in improving the creeping flashover voltage at oil-pressboard interface as compared to Al_2O_3 and SiO_2. The effect of temperature on breakdown voltage of nanofilled transformer oil is studied [12]. It is found that the increase in oil temperature increases its breakdown voltage for three different nanoparticles (TiO_2, ZrO_2, and SiO_2). Up till now, the effect of temperature on creeping flashover voltage of nanofilled oil-pressboard interface is not studied.

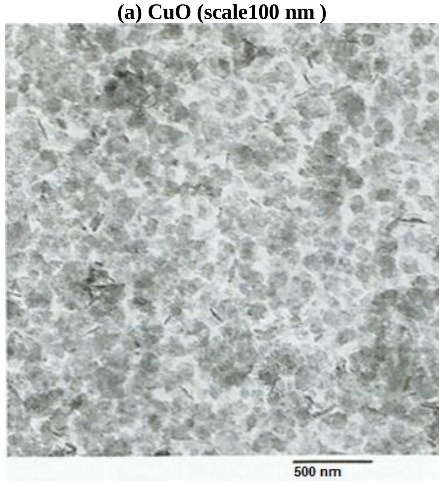
In this paper, the effect of temperature on creeping flashover voltage of nanofilled oil-pressboard is experimentally evaluated. The creeping flashover tests are carried out at room temperature, 50 C^o, 80 C^o and 120 C^o. Three different nanomaterials are used for enhancing oil-pressboard creeping flashover voltage. These nanoparticle materials are CuO, MgO and ZnO. For each nanoparticle type, three different concentrations are studied (0.05, 0.1, and 0.2) g/l. The evaluation of creeping flashover voltage is based on average as well as voltage at 10% and 50% probabilities.

II. CHARACTERIZATION OF NANOPARTICLES

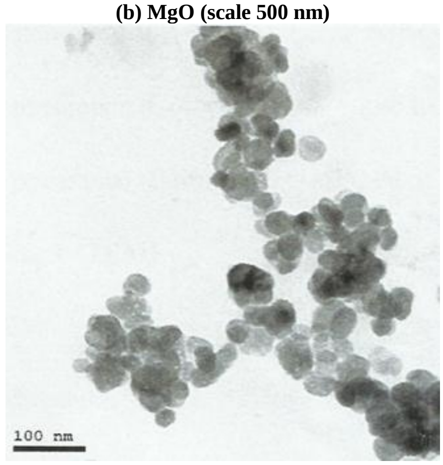
In this section, characterization of nanoparticles for the adopted three nanomaterials is presented. The characterization is carried out based on transmission electron microscopy (TEM) as well as X-Ray diffraction (XRD). The adopted three nanomaterials (CuO, MgO, and ZnO) are supplied from EUROMEDEX, France. The three materials are supplied with their relative datasheets. Fig. 1 shows TEM images for the adopted three nano-materials. TEM images are carried out using JEOL JEM-2100 high resolution transmission electron microscope at an accelerating voltage of 200 kV. From this figure, the nanoparticles have spherical like shapes with as average nanoparticle size of 35±5 nm for CuO and ZnO nanoparticles. However, the average nanoparticle size is found to be 35±3 nm for MgO nanoparticles. Fig. 2 shows XRD patterns for the three nanomatrials. XRD patterns are obtained using XPERT-PRO powder diffractometer system, with 2 Theta (20^o - 80^o), with minimum step size 2 Theta: 0.001, and at wavelength (Kα= 1.54614^o). From the results of this figure, the purity of nanomaterials is greater than 99%.



(a) CuO (scale100 nm)



(b) MgO (scale 500 nm)



(c) ZnO (scale100 nm)

FIGURE 1. TEM image for CuO, MgO, and ZnO nanoparticles.

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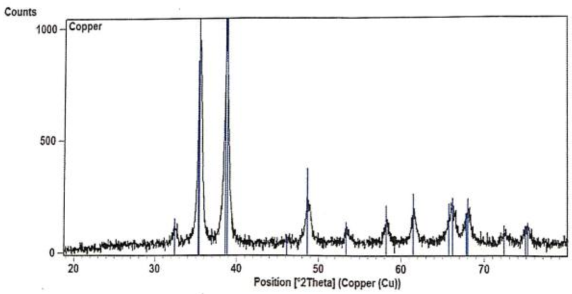
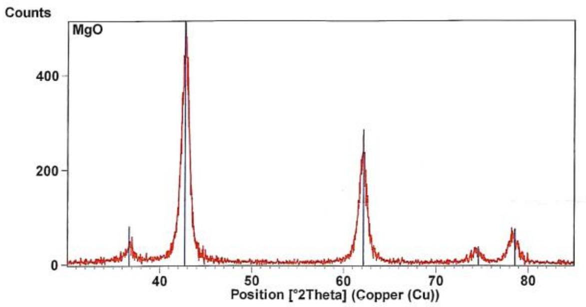
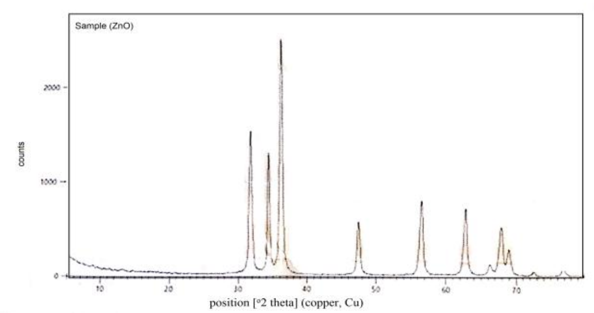


(a) CuO



(b) MgO



(c) ZnO

FIGURE 2. XRD pattern of CuO, MgO, and ZnO samples.

III. EXPERIMENTAL PROCEDURES

In this section, the procedures of nanofilled oil-pressboard samples are introduced. Also, the creeping flashover voltage test is discussed. Finally, the measurement of relative permittivities of oil, nanofilled oil, oil-pressboard and nanofilled oil-pressboard samples is investigated considering the adopted temperatures.

A. SAMPLE PREPARATION

The nanofilled oil-pressboard samples used in this study are prepared considering the three adopted nanomaterials. The flowchart shown in Fig. 3 describes the nanofilled oil-pressboard preparation procedures. Firstly, nanofilled transformer oil is prepared considering three different concentration levels 0.05, 0.1 and 0.2 g/l in addition to the base oil. The nanoparticles with the aimed concentrations are dipped in the base transformer oil and mixed by a magnetic stirrer for 10 minutes. Then, the nanofilled transformer oil is sonicated using an ultrasonic homogenizer for other 10 minutes. The obtained nanofilled oil is set for 24 hours in a vacuum chamber to extract micro voids. The used pressboard is cut into rectangles with dimensions of 30 mm × 40 mm and 2 mm thickness. The pressboard is dipped into the prepared transformer oil samples at all adopted concentration levels for the three nanomaterials for 5 minutes. The adopted pressboard is made from a structured network of wood fibres. The pressboard is made by pressing paper sheets together and drying them under heat and high pressure in a specially designed hydraulic press. The density of the adopted pressboard is 1200 kg/m^3.

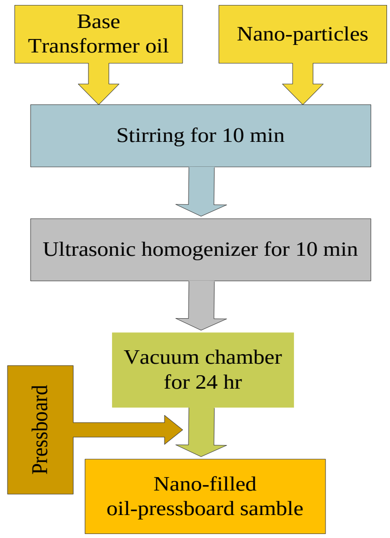


FIGURE 3. Sample preparation procedure.

B. CREEPING FLASHOVER VOLTAGE TEST

The creeping flashover test is carried out considering a needle-plate electrode configuration as declared in Fig. 4. The needle electrode (tip radius 3 μm) is attached on the pressboard surface and connected to the high voltage side. However, the plate electrode is connected to the ground side. The gap length between the electrodes is adjusted at 5 mm. A liquid dielectric tester with 60 kV, 50 Hz rating is used in this experiment. The voltage rise rate is adjusted at 500 V/s. Each measured result is the average of ten values of creeping flashover voltages with 1 minute interval between each two consecutive flashover occurrence. Also, the evaluation is carried out considering creeping flashover at 10% and 50% probabilities. The creeping flashover voltage at 10% probability is related to the creeping flashover voltage at lowest probability. However, the creeping flashover voltage at 50% probability is related to the critical creeping flashover voltage [17]. The creeping flashover at 10% and 50% are analysed using cumulative probability function of Weibull distribution illustrated in Equation (1). Weibull distribution analysis is used to produce creeping flashover voltage at all probabilities considering small number of tests [21].

$$F(v)=1-e^{-(v/\lambda)\xi} \quad (1)$$

where, *F(v)* is the cumulative probability function of weibull distribution, v is the creeping flashover voltage in kV, λ is the scale parameter in kV and ξ is the shape parameter.

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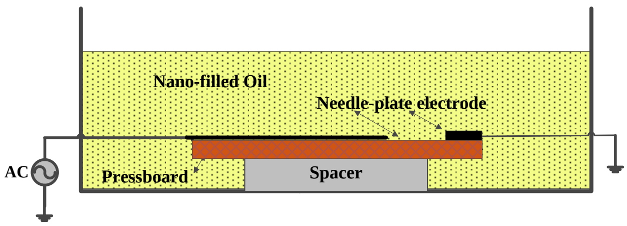
C. Relative Permittivity Measurements

In this work, the effect of temperature on the relative permittivity oil, nanofilled oil, oil-pressboard and nanofilled oil-pressboard samples is investigated. Hence, the relative permittivities of oil, nanofilled oil, oil-pressboard and nanofilled oil-pressboard samples are measured considering the adopted temperatures (30, 50, 80 and 120 ^{o}C). The relative permittivity of both nano-filled oil and nano-filled oil-pressboard are measured using an accurate LCR Meter considering a frequency range of 20 Hz to 2 MHz.



FFIGURE 4. Creeping flashover voltage test set up.

IV. EXPERIMENTAL RESULTS

In this section, experimental results considering the effect of temperature on breakdown voltage of nanofilled oil as well as nanofilled oil-pressboard is investigated. Also, the effect of temperature on creeping flashover voltage of nanofilled oil-pressboard is presented considering the three adopted nanomaterials at different concentration levels. Finally, the effect of temperature on relative permittivities of nanofilled oil and nanofilled oil-pressboard is studied.

A. BEHAVIOR OF CREEPING FLASHOVER VOLTAGE OF NANOFILLED OIL AND OIL-PRESSBOARD INSULATION UNDER DIFFERENT TEMPERATURES

In [11,12] it is reported that, the breakdown voltage of the transformer oil either base oil or nanofilled is increased with the increase in oil temperature. In this paper, the effect of temperature on breakdown voltage of base oil and nanofilled oil is presented considering only a concentration level of 0.05 g/l of MgO nanoparticles. Also, the creeping flashover voltage considering oil-pressboard and nanofilled oil-pressboard is introduced considering the same concentration level of the same nanomaterial. This study is performed in order to clarify the difference between the effect of temperature on breakdown voltage with and without pressboard.

As cleared from Fig. 5, the creeping flashover voltage without pressboard is increased with increasing temperature for both base transformer oil and nanofilled oil. The breakdown voltage increased from 17.2 kV at 30 ^{o}C to 28.4 kV at 120 ^{o}C for base oil. In the case of nanofilled oil with MgO nanoparticles, the breakdown voltage is increased from 20.5 kV to 31.5 kV at 120 ^{o}C. The percentage increase in breakdown voltage is about 65 % and 54% for base and nanofilled oil, respectively. The results match with the results presented in [11,12], where the relative humidity of the transformer oil is decreased with increasing temperature that causes increase in the breakdown voltage. On the other hand, the creeping flashover voltage is decreased with increasing temperature with oil-impregnated pressboard for both base transformer oil and nanofilled oil as illustrated in Fig. 5. The creeping flashover voltage is decreased from 15.2 kV at 30 ^{o}C to 10.4 kV at 120 ^{o}C for base oil-pressboard. However, the creeping flashover voltage is increased from 19.1 kV to 12.5 kV at 120 ^{o}C for nanofilled oil-pressboard modified by 0.05 g/L of MgO nanoparticles. The percentage reductions in creeping flashover voltage for base and nanofilled oil-pressboard are 31.6% and 34.6%, respectively. The obtained behavior of creeping flashover voltage with the presence of pressboard at different temperatures opposes the behavior without the presence of pressboard. This point needs to be clearly discussed. This discussion will be presented in the next section.

Further results on the effect of temperature on creeping flashover voltage at oil-pressboard interface are clarified in the next subsection.

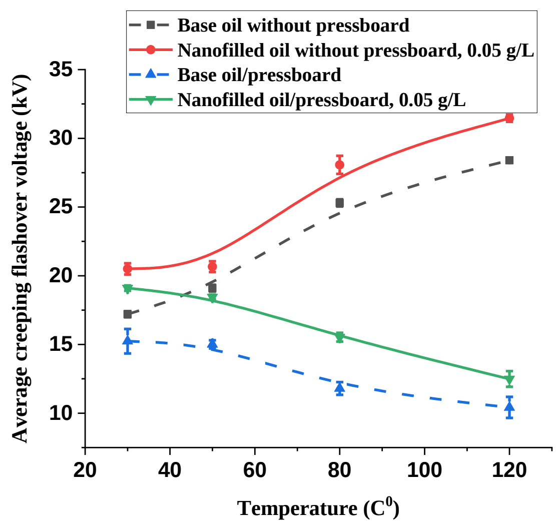


FIGURE 5. Effect of temperature on creeping flashover voltage of nanofilled oil with and without pressboard considering MgO nanoparticles.

B. EFFECT OF TEMPERATURE ON CREEPING FLASHOVER VOLTAGE OF NANOFILLED OIL-PRESSBOARD INSULATION

The effect of temperature on the average creeping flashover voltage, 10% and 50% creeping flashover voltage probabilities is carried out considering different nanofiller material types of CuO, MgO, and ZnO at different concentration levels. Fig. 6 shows the effect of temperature on the creeping flashover voltage of nanofilled oil-pressboard considering the adopted nanofillers. The temperature is significantly affecting creeping flashover voltage of nanofilled oil-pressboard. The average creeping flashover voltage is decreased by increasing temperature considering all concentration levels of base, 0.05, 0.1, and 0.2 g/l. From

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Fig. 6.a, the creeping flashover voltage is decreased from 15.2, 20.4, 21.8, 22.6 kV at 30 °C to 10.4, 17.1, 12.9, and 15.11 kV at 120 °C considering base, 0.05, 0.1, and 0.2 g/l concentration levels of CuO, respectively. The percentage reductions in average creeping flashover voltage are 31.6%, 21.5%, 30.7%, and 43% for base, 0.05, 0.1, and 0.2 g/l concentration levels, respectively. In the case of MgO nanoparticles, the average creeping flashover voltage is also decreased with increasing temperature considering all concentration levels as shown in Fig. 6.b. The percentage reductions in average creeping flashover voltage of nanofilled oil-pressboard modified by 0.05, 0.1, and 0.2 g/l of MgO nanoparticles are 34.6%, 28%, and 24.7%, respectively. However, the percentage reductions in creeping flashover of nanofilled oil-pressboard modified by ZnO nanoparticles are 64.4%, 21.9%, and 41.2%, respectively.

The evaluation of creeping flashover voltage at 10% and 50 % probabilities is carried out. Weibull probability function is analysed using MATLAB software. Figs. 7.a and 7.b show the effect of temperature on creeping flashover voltage considering all creeping flashover probabilities for base and nanofilled oil-pressboard modified by 0.2 g/l of CuO, respectively. From this figure, creeping flashover voltage at 10% and 50% probabilities are obtained. The same procedures are adopted with the two other nanofiller materials. Fig. 8 shows the effect of temperature on creeping flashover voltage at 10% probability considering CuO nanoparticles. It is declared that the creeping flashover at 10% probability is decreased by increasing temperature considering all concentration levels and nanofiller types. The percentage reductions in creeping flashover voltage at 10% probability are 38.8%, 24.6%, 41.7%, and 16.3% considering base, 0.05, 0.1, and 0.2 g/L of CuO nanoparticles, respectively as declared in Fig. 8.a. However, the percentage reductions in creeping flashover voltage at 10% probability considering 0.05, 0.1, and 0.2 g/L of MgO nanoparticles are 44%, 58.2%, and 46.2%, respectively as declared in Fig. 8.b. In the case of ZnO nanoparticles, the percentage reductions are 45.5%, 36.9%, and 47%, respectively as declared in Fig. 8.c. The effect of temperature on the 50% probability creeping flashover voltage is declared in Fig. 9. In the same manner of average and creeping flashover at 10% probability, the creeping flashover at 50% probability is affected by temperature. The creeping flashover at 50% probability is decreased by increasing temperature considering all concentration levels and nanofiller types as declared in Fig.9.

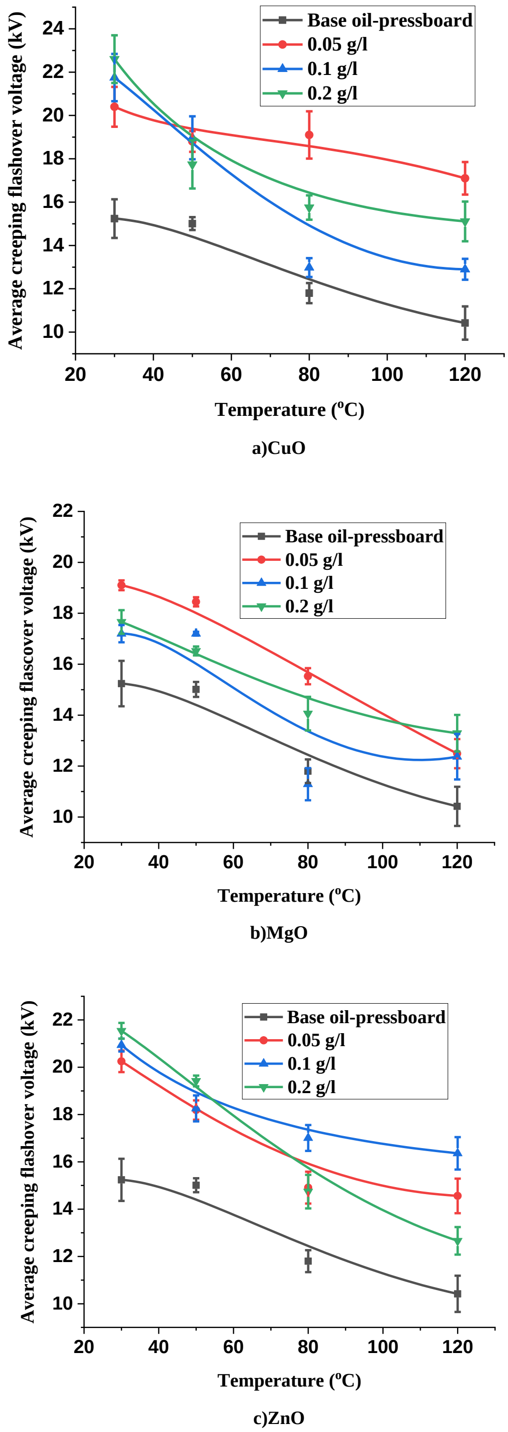

FIGURE 6. **Effect of temperature on average creeping flashover voltage.**

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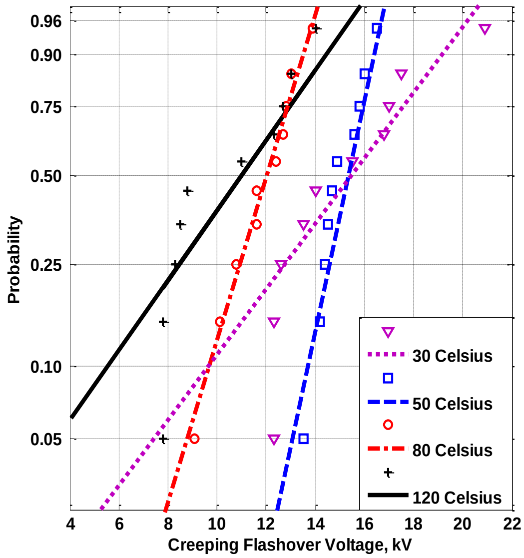
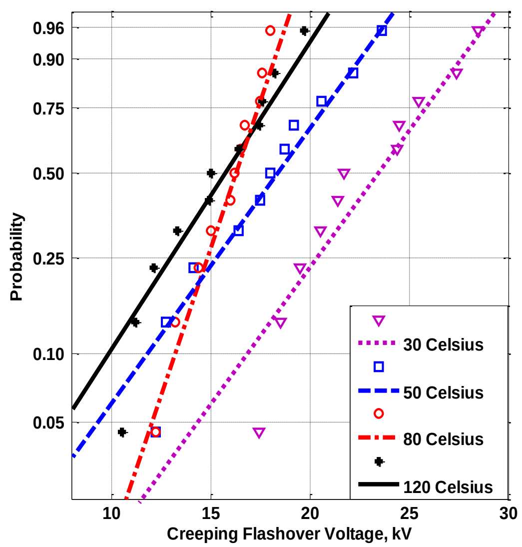
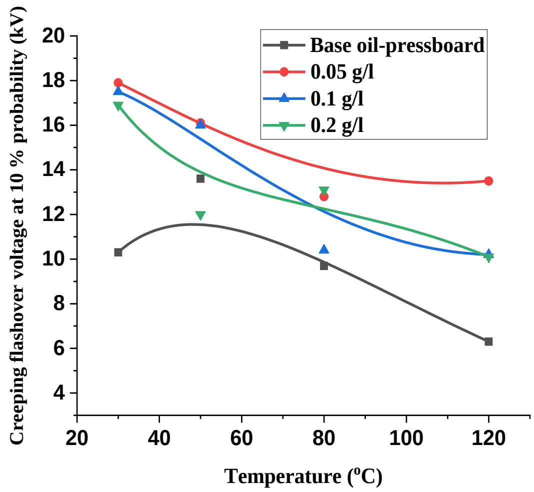


a)Base oil-pressboard

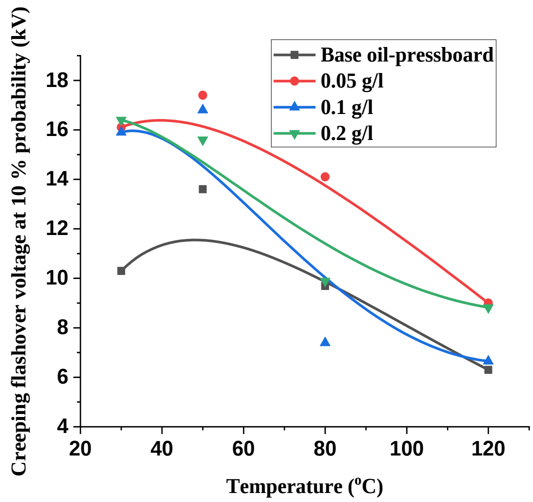


b) Nanofilled oil-pressboard (0.2 g/l of CuO)

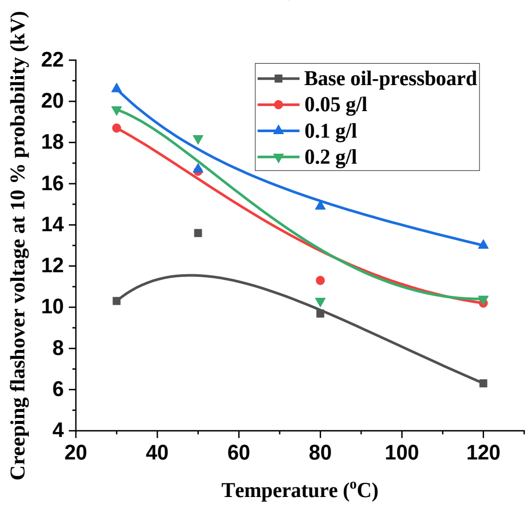
FIGURE 7. Weibull probability curves of creeping flashover voltage for base and nanofilled oil-pressboard insulation considering 0.2 g/l of CuO.



a) CuO



b)MgO



c)ZnO

FIGURE 8. Effect of temperature on creeping flashover voltage at 10% probability.

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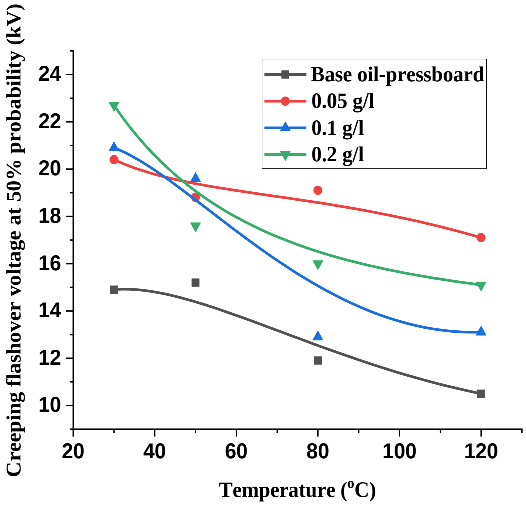
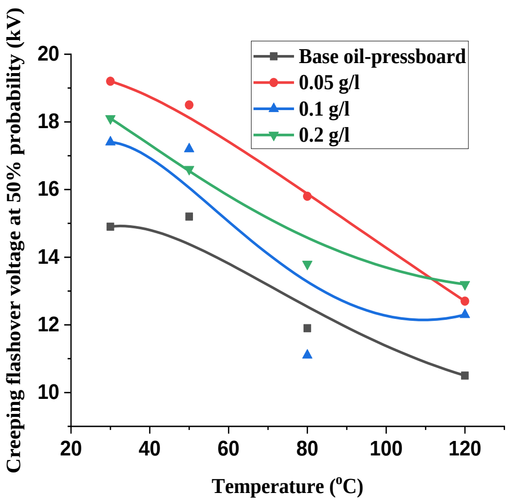
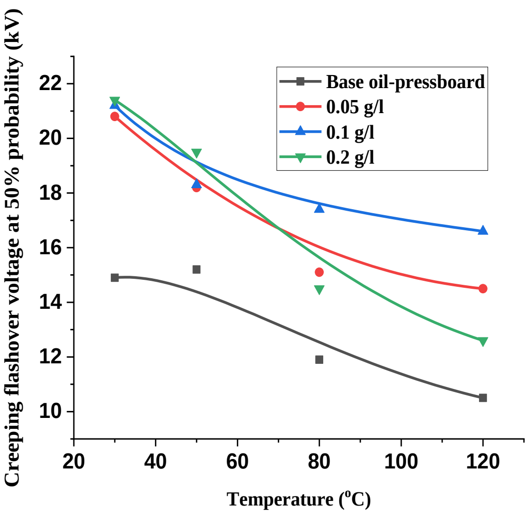


a)CuO



b)MgO



c)ZnO

FIGURE 9. Effect of temperature on creeping flash overvoltage at 50% probability.

C. EFFECT OF TEMPERATURE ON RELATIVE PERMITTIVITIES OF NANOFILLED OIL AND OIL-PRESSBOARD INSULATION

The effect of temperature on relative permittivities of oil, nanofilled oil, oil-pressboard and nanofilled oil pressboard is investigated considering one concentration of CuO nanoparticles (0.2 g/l). Fig. 10.a shows the variation of relative permittivity of base and nanofiled oil (0.2 g/l of CuO). From this figure, a decrease in relative permittivity is achieved either with base or nanofilled oil. However, the relative permittivity increases with the increase in temperature considering oil-pressboard and nanofilled oil-pressboard as declared in Fig. 10.b. This results in increasing the difference between relative permittivities of oil-pressboard and oil as shown in Fig. 10.c. The increase in difference between oil and oil-pressboard permittivities can significantly affect the electric field distribution at oil-pressboard interface. Therefore, the creeping flashover voltage at oil-pressboard interface is also affected as declared in the next section.

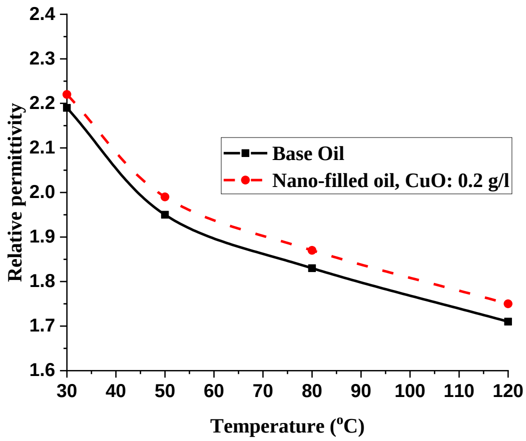
V. DISCUSSION

In this section, the effect of temperature on creeping flashover voltage is discussed. Also, the effect of adding nanofillers to oil-pressboard insulation on creeping flashover voltage is interpreted.

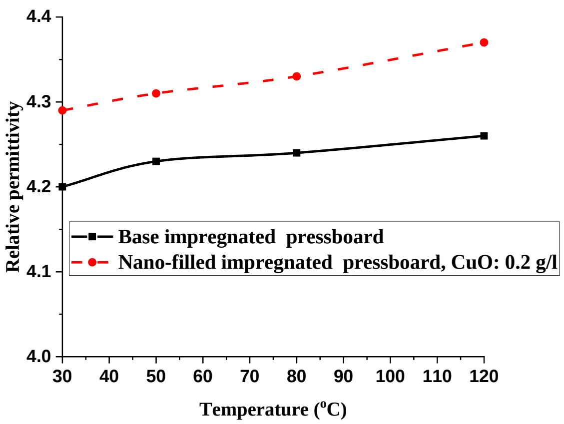
A. EFFECT OF TEMPERATURE

Fig. 11 describes the mechanism of creeping flashover voltage occurrence along oil-pressboard interface. Negative charges are formed within the pressboard as it has the higher relative permitivitty than the transformer oil [18]. Then, positive surface charges are attached to the pressboard surface due to the attraction force with the negative charges within the pressboard. The main space charge density is due to the positive ions in the streamer head. Generally, creeping flashover voltage at oil-pressboard interface mainly occurs due to electric field distortion at oil-pressboard interface. This distortion is due to the difference in permittivity between pressboard and transformer oil. This causes accumulation of space charges on the interface region, which plays an important role in accelerating creeping flashover voltage due to the increase in attractive force exerted on streamer charges.

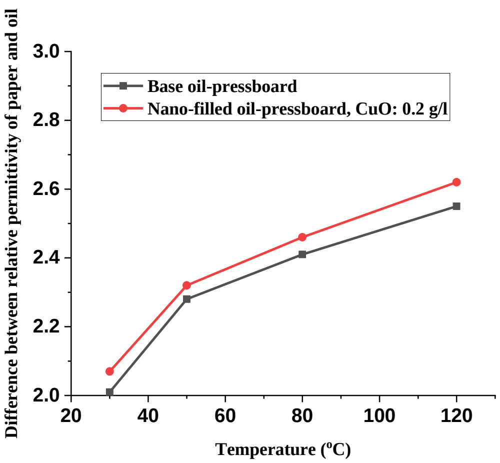
Regarding the effect of oil temperature, the breakdown voltage of transformer oil or its modified nanofluid (without pressboard) increased with increasing temperature as shown previously in Fig. 5. Hence, increasing temperature increases solubility that causes a decrease in the relative humidity of the transformer oil. On the other hand as described previously in Fig. 6, the average creeping flashover voltage along oil-pressboard interface decreases with the increase in operating temperature. This decrease comes due to the increase in attraction force that exerted on streamer charges. The increase in attraction force comes due to the increase in negative accumulated charges at oil pressboard interface. These charges increase due to the increase in relative permittivity difference between oil and pressboard with the increase in oil temperature as declared previously in Fig. 10.c.



(a) Measured relative permittivity of oil and nano-filled oil.



(b) Measured relative permittivity of oil-pressboard with and without nano-particles.



(c) Relative permittivity difference for base oi-pressboard and nano-filled oil-pressboard.

FIGURE 10. Effect of temperature on the relative permittivity.

B. EFFECT OF NANOPARTICLES

Considering the base oil-pressboard insulation, the attraction force that result from the accumulated space charges along the interface accelerates the streamer as shown schematically in Fig. 12.a. Therefore, a lower creeping flashover voltage is obtained. However, the obtained results show that adding nanofillers to oil-pressboard insulation leads to obvious improvement in the creeping flashover voltage at oil-pressboard interface. This improvement has been achieved with all concentration levels of the three used nanomaterials, regardless the difference in the percentage of the improvement. It is reported that, supplement of nanoparticles to transformer oil increases charge trapping [8,10]. The charge trapping process results in motion of streamer in a zigzag manner as illustrated schematically in Fig. 12.b. The scenario of the charging trapping process can explained as, under the application of the electric field, the nanoparticle is exposed to charge dynamic process as declared in Fig. 13. Faces to the positive electrode, hemisphere negative charges are formed. However, positive charges are formed at the other hemisphere that faces to the negative electrode. The negative and positive charges are formed due to the polarisation for semiconducting and insulating nanoparticles. On other hand, charge induction is occurred considering the conductive nanoparticles. The positive charges are trapped the negative electrons that formed due to the ionisation of transformer oil. This process is continued until the nanoparticle is fully saturated with negative charges. The saturation charge of conductive and dielectric nanoparticles can be computed from (2) and (3), respectively [22]. This decelerates the propagation of streamer as well as reduces the energy of its charges. Also, motion of streamer in zigzag manner results in a decrease in electric filed distortion at streamer head. Therefore, the creeping flashover voltage of oil-pressboard is increased.

$$Q_s = -12\pi\varepsilon_1 E_o R^2 \quad \text{for conductive nanoparticle} \quad (2)$$

$$Q_s = -12\pi\varepsilon_1 E_o R^2 \frac{\varepsilon_2}{2\varepsilon_1 + \varepsilon_2} \quad \text{for dielectric nanoparticle} \quad (3)$$

where, E_o is the external electric field strength in V/m, R is the nanoparticle radius in m, and ε_1 and ε_2 are the transformer oil and nanoparticle permittivities, respectively.

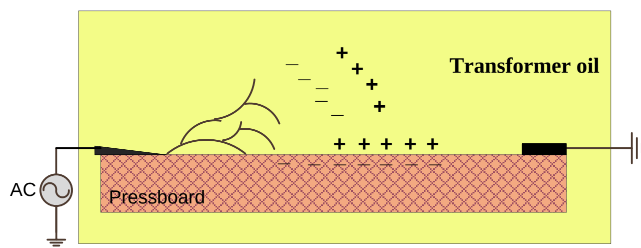


FIGURE 11. Mechanism of creeping flashover of oil-pressboard.

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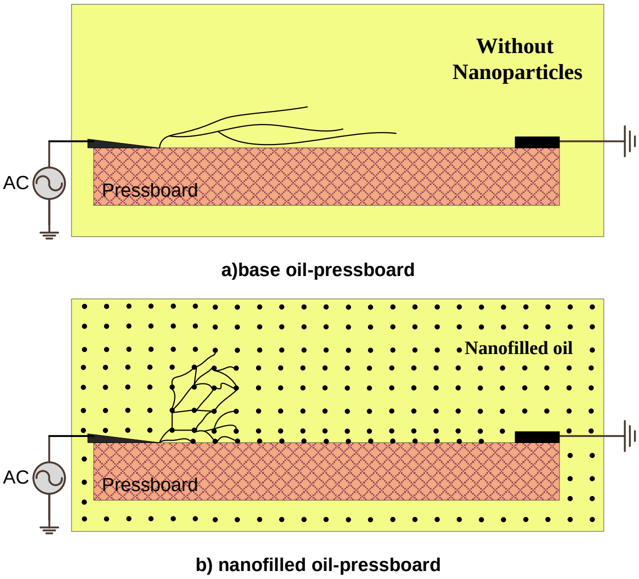

FIGURE 12. Effect of nanoparticles on streamer behavior of oil-pressboard.

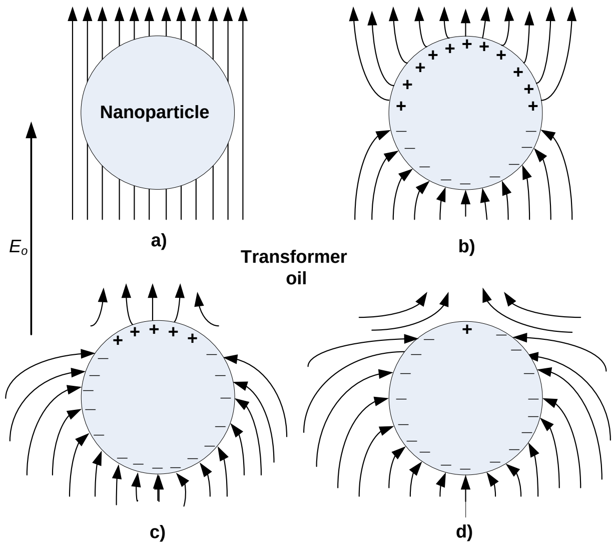

FIGURE 13. Particle charging mechanism [22].

VI. CONCLUSION

Improving the creeping flashover voltage along oil-pressboard interface has been achieved using three different nanomaterials. Three concentration levels of each material have been used for improvement. Average, 10% and 50% probabilities of creeping flashover voltages are evaluated. The experiments have been done at room temperature, 50 ^oC, 80 ^oC and 120 ^oC in order to study the effect of operating temperature on the creeping flashover voltage. It is concluded that:

- The breakdown voltage of the transformer oil without pressboard increases with increasing temperature.
- The creeping flashover voltage of base and nanofilled oil-pressboard decreases with the increase in oil temperature.
- The relative permittivity of oil and nanofilled oil decreases with the increase in temperature. However, the relative permittivity of base and nano-filled oil-pressboard increases with the increase in temperature.
- The used nanoparticles improve the creeping flashover voltage of oil-pressboard insulation system.
- A proposed creeping flashover mechanism considering the effect of oil temperature has been presented.

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