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Impact of Temperature on Dissipation Oil-Paper Insulation Factors Used In Distribution Oil-Paper Insulation Transformers Simulated by Various Isolation Oil Levels

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Abstract: *The temperature in a distribution transformer can vary depending on the season of the year and load it possesses. This temperature change influences the dielectric response of the distribution transformer. This paper presents the results of the impact of temperature on dissipation factors of oil-paper insulation simulated by varying oil level and temperature values. The dissipation factors were obtained by using AC/DC electric current application mode in Finite Element Method software (COMSOL Multiphysics). The results show that when insulating oil is at the same level, the dissipation factor values are sensitive to temperature change.*
Key Word*: COMSOL Multiphysics, dissipation factor, distribution transformer, insulating oil level, insulation temperature, oil-paper insulation.*

I. Introduction

The oil-paper insulation system may be designed to operate continuously up to 55 °C or 65 °C above ambient temperature [1]. Historical climatic data show that the ambient temperature may vary from year to year. For example, in the United Republic of Tanzania, the ambient temperature may be from 20 °C to 24 °C from year to year [2]. This means that the temperature of oil-paper insulation for distribution transformers installed in the National Grid in Tanzania may reach to about 80 °C for commercially available insulation systems designed to operate continuously up to 55 °C above ambient temperature and to about 90 ^{o}C for commercially available insulation systems designed to operate continuously up to 65 °C above ambient temperature. Different studies have already been done on the effect of temperature on dissipation factors measured over wide frequency range [3-5]. In these studies it was indicated that, for example in [5], an increase in temperature shifts the dissipation factor curve along the frequency axis towards higher frequencies. In all the studies done so far, there is no study among them that combined both the effect of temperature in one hand and the insulating oil level on the other. In his previous paper [6], the author proposes the use of dissipation factors measured over wide frequency range to predict oil level in distribution transformer. The results which were obtained in [6] showed that there is clear difference in dissipation factors in the low frequency region when the insulating oil drops below the position of paper layers. As the load given to the distribution transformer is not always constant, the temperature of oil-paper insulation will therefore change with the change of the transformer load. This work, therefore, assesses the effect of temperature on dissipation factors of oil-paper insulation in distribution transformer by combining both the change in temperature value and the change of oil level in a distribution transformer.

II. Methodology

This section provides brief information on the set-up of the configuration used to model the oil-paper insulation. The section also presents modelling requirements in Finite Element Method software (COMSOL Multiphysics) and some other information on how the simulation results were validated.

Set-Up Of Oil-Paper Insulation Model

The set-up of oil-paper insulation model is shown in Fig. 1. The model has paper layers of thickness of 20 mm between two electrodes. The outer domain for which this set-up was placed had insulating oil properties in order to represent the transformer tank. This model was used in [6] in the investigation of the effect of insulating oil level on dissipation factors over wide frequency range. The simulation in [6], however, did not incorporate the effect of temperature. This work is an extension of the work in [6] by incorporating the effect of temperature. The detailed explanation of this setup can, therefore, be found in [6].

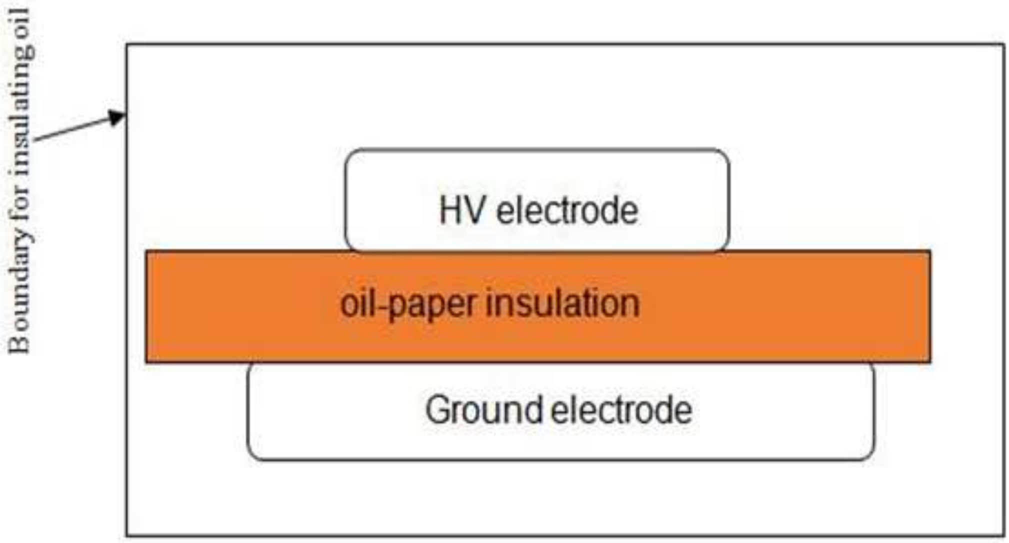

Figure 1 A schematic diagram showing part of set-up used in the investigation of the dielectric response of oil-paper insulation under different insulating oil levels. The diagram is not drawn according to the scale. The detailed set-up was presented in [6].

Validation of Simulation Results

The effect of temperature on dissipation factors of oil-paper insulation over wide frequency range (from 0.1 mHz up to 1 kHz) through measurements were presented in [5]. In this work, the simulations were done in the frequency range of 1 mHz up to 1 kHz. The measurement results in [5] were, therefore, used to validate the simulation results in this work.

Governing Equations For Implementation Of Oil-Paper Insulation In Finite Element Method (COMSOL Multiphysics)

The dissipation factor of oil-paper insulation is computed by dividing the real to imaginary part of the current through the insulation [6]. In Finite Element Method (COMSOL Multiphysics), the current through the insulation can be obtained by using an AC/DC electric current application mode [7]. The governing equations which are necessary to implement oil-paper insulation in Finite Element Method (COMSOL Multiphysics) were presented in my earlier paper [6].

In this paper, the equations in which were used in [6] have been modified by expressing electrical conductivity in terms of temperature. The expression which defines electrical conductivity in terms of temperature, as seen in [8], is shown in equation (1). In equation (1 □T 0 refers to the electrical conductivity of material at the reference temperature (T0). In most of the references consulted, the reference dielectric parameters, e.g. electrical conductivity values are provided at 20^{o}C [8, 9]. □T refers to the electrical conductivity that corresponds to new temperature (T), which is greater than the reference temperature. The electrical conductivity value of oil is from 0.05 to 1 pS/m when the oil is new [5]. It was further reported in [5] that after oil is aged, its electrical conductivity value may become more than 1000 pS/m. In the simulation which was done at room temperature of (20 ^{o}C); 0.08 pS/m for the case of new oil and 8 pS/m for the case of aged oil, the electrical conductivity value of paper was lower than the electrical conductivity of oil [10-12] and in [13] the simulation dissipation factor curves matched well with the experimental dissipation factor curves for a case of new oil-paper insulation when the electrical conductivity of oil and paper were 0.08 pS/m and 0.05 pS/m respectively. In this work, therefore, 0.05 pS/m was used as paper electrical conductivity value.

The parameter E_a refers to an activation energy. By definition an activation energy is the minimum energy necessary for a specific chemical reaction to occur [14]. The activation energy of insulating oil ranges from 0.32 eV (for an aged oil) to 0.54 eV (for new oil) [8]. The activation energy of paper insulation is about 0.9 eV [15]. The inside of the distribution transformer is usually intended to be free from air. The air is usually removed from the transformer tank by using the special technique which is known as vacuum treatment [16]. Therefore, in the simulation, the electrical conductivity of a space with no any insulating oil should be practically equal to zero. For simulation purpose, however, it was set to low value ($10^{□20}$ S/m). In equation (1), k_B refers to the Boltzmann constant, its value is equal to 8.617385□10^{-5} eV / K [8].

III. Results

This section presents the dissipation factor curves obtained through computer simulations by using the Finite Element Method Software which is known as COMSOL Multiphysics. The simulations considered two cases of oil electrical conductivity values, i.e. 0.08 pS/m and 8 pS/m in order to simulate cases of new and aged insulating oil. In each case, the simulations were carried out when the oil was assumed to be at its maximum level and when it was at 20% of its maximum level. The temperature value was set to 20 ^oC, 40 ^oC or 80 ^oC to simulate different insulation temperature values in the distribution transformer when supplying different load conditions.

Oil at its Maximum Level

As it has been stated earlier in this paper, the set-up as shown in Fig. 1 was placed in insulating oil subdomain of 40 cm by 20 cm in order to simulate a case of oil-paper insulation inside oil immersed in the distribution transformer. The oil at its maximum level, therefore, was at the height of 20 cm from the base. The material properties used were 0.05 pS/m for paper electrical conductivity and 0.08 pS/m and 8 pS/m for oil electrical conductivity when the oil is new and when the oil is aged respectively. The values of permittivity and governing equations were presented in my earlier paper [6]. Dissipation factor curves which were obtained for oil electrical conductivity value of 0.08 pS/m are shown in Fig. 2. On the other hand, dissipation factor curves which were obtained for oil electrical conductivity value of 8 pS/m are shown in Fig. 3. From Fig. 2, it can be observed that the dissipation factor curves of oil-paper insulation for a case of new oil shifted upwards with an increasing temperature. The curves at all temperature values decayed almost exponentially with an increasing frequency. The significant difference of dissipation factor values at different temperature values can be observed clearly at low frequencies. For example, the difference between dissipation factor values for T = 20 □C and T = 80 □C is 200.

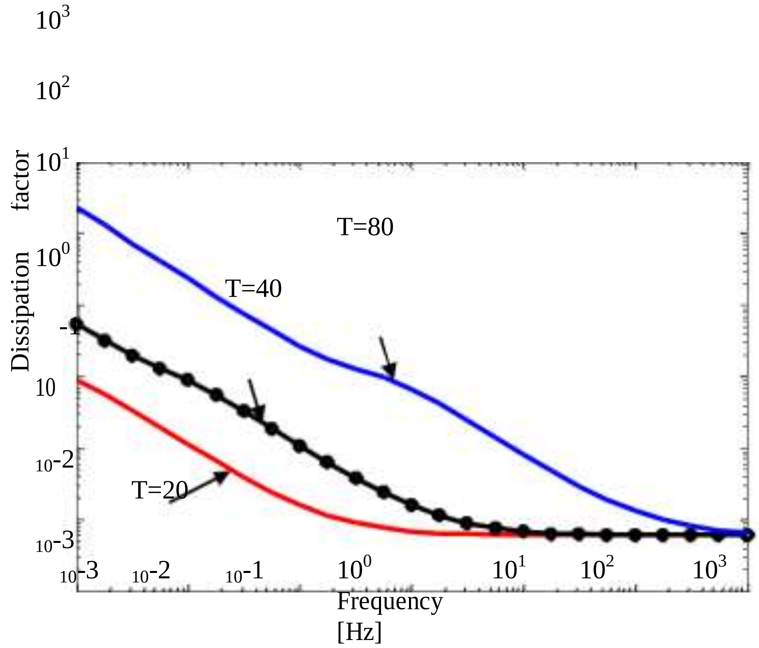

Figure 2 The dissipation factor curves of oil-paper insulation for oil level at its maximum value for T = 20 □C, 40 □C and 80 □C. Oil electrical conductivity value = 0.08 pS/m (new oil).

For a case of aged oil, i.e. when oil electrical conductivity value is 8 pS/m, there was also clear difference in dissipation factor values which was simulated at different temperature values, especially at low frequencies. At 1 mHz, the difference in dissipation factor values at 20 □C and 80 □C, was about 400. Unlike for a case of new oil, in the aged oil, the loss peaks were observed. The loss peaks shift towards the higher frequency with an increasing temperature. In this case the loss peaks have the same values, irrespective of the frequencies of their occurrence. Example, in Fig. 3, it was observed that three loss peaks for T = 20 □C, T=40 □C and T = 80 □C have dissipation factor value of 0.9. Similar characteristics of the loss peaks of dissipation factor curves shift towards the higher frequency with an increasing temperature was also observed in measurement results in [8]. The measurement results in [8] were, therefore, used to validate the simulation results in this paper.

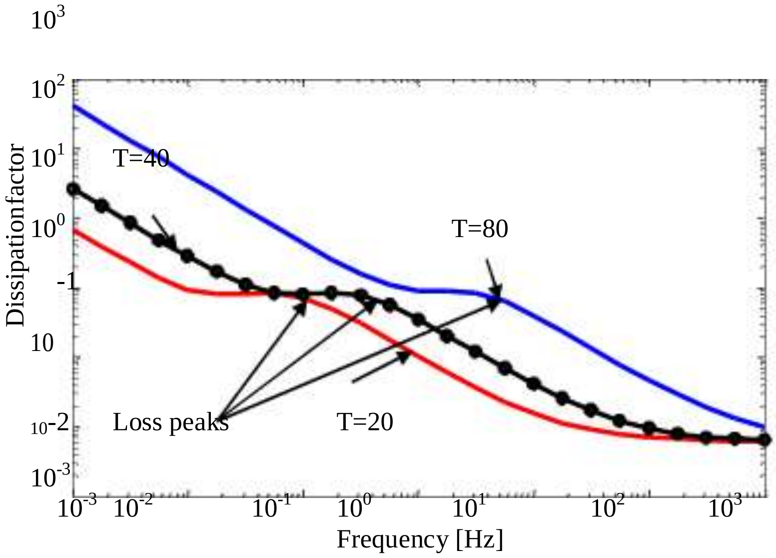

Figure 3 The dissipation factor curves of oil-paper insulation for oil level at its maximum value for T = 20 C, 40 C and 80 C. Oil electrical conductivity value = 8 pS/m (aged oil)

Oil at 20% of its Maximum Level

Oil at 20% of its maximum value represents a condition in which the paper layers are not covered with insulating oil. This means that the oil has dropped below the paper layers. The results for oil electrical conductivity value of 0.08 pS/m and 8 pS/m are shown in Fig. 4 and Fig. 5, respectively. As it can be seen from these figures (Fig. 4 and Fig. 5), the dissipation factor curves are the same for both two cases. When the oil level is at 20% of its maximum value, the difference between dissipation factor values were observed at low frequencies. Example, at 1 mHz, the difference between dissipation factor values for T = 20 C and T = 80 C is about 0.067 (7 $\times 10^{-2}$ − 3 $\times 10^{-3}$). The loss peaks of dissipation factor value of 0.15were observed for temperature values of 40 C and 80 C.

Effect of Temperature on Dissipation Factors of Oil-Paper Insulation Used in Distribution Transformers Simulated by Varying Insulating Oil Levels

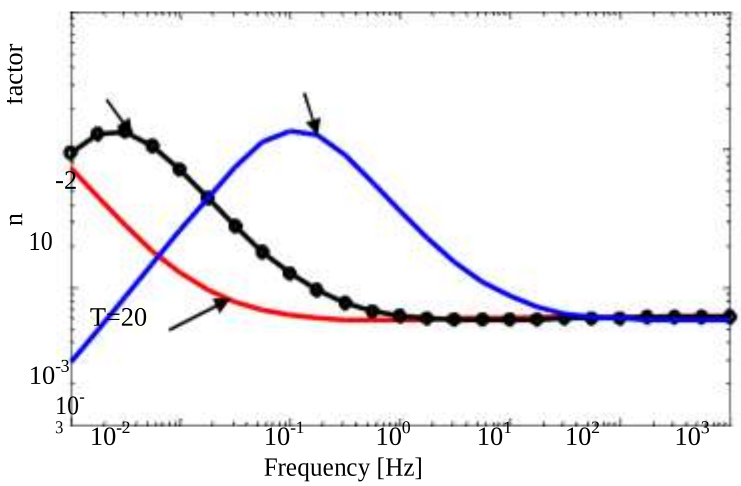

Figure 4 The dissipation factor curves of oil-paper insulation for oil level at 20% of its maximum value for T = 20 C, 40 C and 80 C. Oil electrical conductivity value = 0.08 pS/m (when the oil is new)

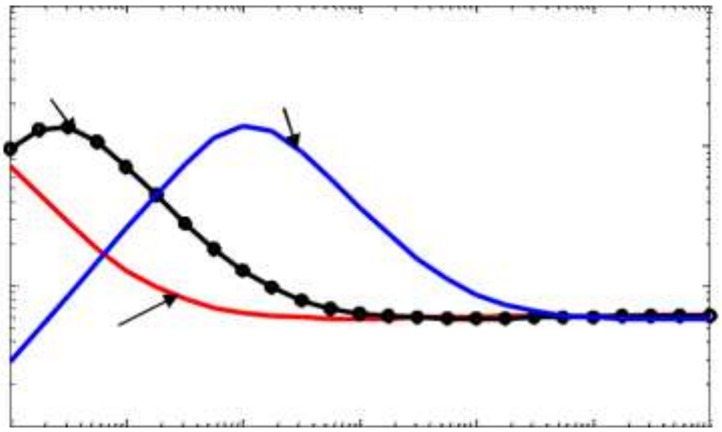

Figure 5 The dissipation factor curves of oil-paper insulation for oil level at 20% of its maximum value for T = 20 C, 40 C and 80 C. Oil electrical conductivity value = 8 pS/m (when the oil is aged)

IV. Discussion Of The Results

The nature of the dissipation factor curves in Fig. 4 and Fig. 5 indicate that the properties of oil do not affect dissipation factor curve when the oil level has dropped below the paper layers position. In this case there was a vacuum between paper layers whose electrical conductivity value was not influenced by change in winding temperature. This is because thermal conductivity in the vacuum was zero [17]. The results, therefore, indicate that the change in the characteristics of the dissipation factor curve was influenced by the type of the dielectrics between paper layers. To further confirm this fact, the oil which is below paper layers may not affect the dissipation factor of the insulation in the distribution transformer, an empty insulating oil condition (i.e. when oil level was dropped to 0% of its maximum value) was simulated. The results under this case are shown in Fig. 6. From this figure it is clearly observed that the shapes and magnitudes of the dissipation factor curves are similar to that when the oil level was at 20% of its maximum level. The characteristics of the dissipation factor curve can, therefore, be used to determine the type of dielectrics between paper layers. In my earlier paper [6], I proposed the use of dissipation factor values measured over wide frequency range in order to predict the insulating oil level in the distribution transformer. In this work, it has been observed that at the same oil level, the dissipation factor curves are not the same in different temperature values. This implies that dissipation factor values which are measured when the temperature values for insulation are different cannot be comparable for prediction of change in oil level if the temperature values will not be incorporated in the design of the oil level indicators. This means that if the on-line measurement systems for determining insulating oil level are desired, both dissipation factor and temperature values are important parameters to be considered in oil level indicators. For the off-line measurements in controlled environment, the oil level indicators designed based on dissipation factor values alone can be used.

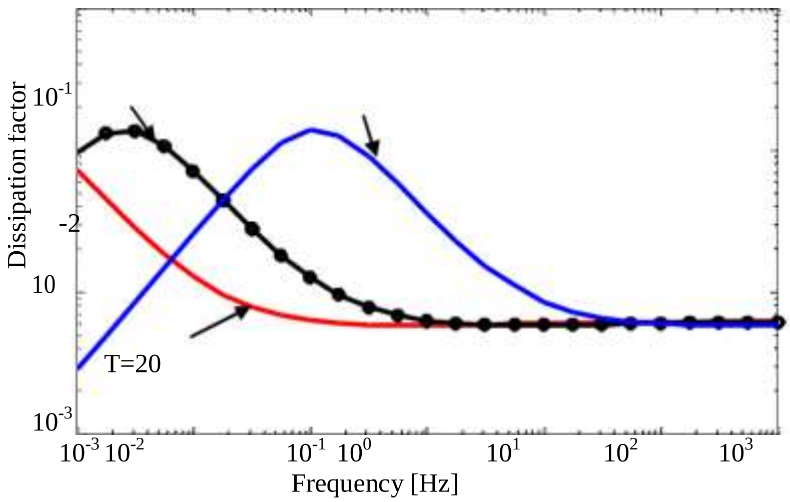

Figure 6 The dissipation factor curves of oil-paper insulation for oil level at 0% of its maximum value (i.e. when the transformer tank is empty) for T = 20 C, 40 C and 80 C. Oil electrical conductivity value = 0.08 pS/m (when the oil is new)

V. Conclusions

This study reports the results of the effect of temperature on the dissipation factors of oil-paper insulation over wide frequency range for cases of the distribution transformer at different oil levels. The results show that at the same oil level, the dissipation factor curves over wide frequency range are influenced by change in temperature values. An accurate oil level can therefore be determined when dissipation factor measurements are performed in off-line conditions in a controlled environment. In case, one would like to design on-line oil indicator. This on-line indicator must be able to give oil level based on temperature and dissipation factor values.

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