Studies on the effects of moisture and ageing on charge de-trapping properties of oil-impregnated pressboard based on IRC measurement

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Abstract: The dielectric properties of oil-paper insulation degrade due to moisture ingress and ageing. This degradation significantly impacts the space charge accumulation and charge trapping behaviour in the insulation, which are vital parameters for insulation health under the high-voltage direct current environment. In this work, an improved model based on the isothermal relaxation current (IRC) has been developed to study the charge trapping behaviour of an oil pressboard under the influence of moisture and ageing. The conventional IRC model considers the total relaxation current because of charge de-trapping only. However, in the case of a composite dielectric like oil pressboard, dipolar relaxation also affects the relaxation current. In this work, a methodology has been proposed to investigate charge de-trapping behaviour of oil-pressboard insulation considering the dipole relaxation process from IRC measurements. For this purpose, frequency domain spectroscopy measurements and IRC measurements have been performed on oil-impregnated pressboard specimens carefully prepared in the laboratory having different ageing conditions and moisture contents. Results presented in this work depict that charge trapping parameters, i.e. the trap depth and trapped charge distribution are highly affected both by ageing and moisture. It was observed that ageing leads to the generation of deeper traps, while moisture mainly enhances the density of shallow traps.

1 Introduction

Oil-paper insulation has been a popular choice for electrical insulation in transformers, power cables, and high-voltage equipment for its low cost and excellent mechanical and electrical properties [1, 2]. With the advancement of high-voltage direct current (HVDC) systems, oil-paper insulation has been extensively used in HVDC cables and converter transformers. However, a major problem with this type of insulation is that with time, moisture and other ageing by-products accumulate in the insulation due to thermal, electrical, mechanical, and chemical stresses [3, 4]. This leads to the strong degradation of the insulation. It has been well established that with the increase in the moisture content, the mechanical strength of the paper insulation steeply declines, which makes it prone to failure under lightning and switching surges [4]. Furthermore, moisture desorbed from paper may lead to bubble formation, which can cause the dielectric breakdown of the transformer [5]. However, under HVDC conditions, another significant cause of worry is the accumulation of space charge. The accumulation of space charge results in the localised enhancement of the electric field. This may lead to partial discharges, treeing, and other insulation degradation processes [6]. In comparison to polymeric insulations (i.e. Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), Cross-Linked Polyethylene (XLPE)), there has been significantly less amount of research on space charge investigations in oil-paper insulation [7–9]. In the present work, it has been tried to bridge this gap and extract information regarding the effect of moisture and ageing on charge trapping–de-trapping in oil-pressboard insulation from isothermal relaxation current (IRC) measurements.

IRC is a diagnostic method that provides the distribution of traps in a dielectric material [10, 11]. Traps or localised ‘defects’ are distributed across the energy band in particularly polymeric dielectrics [12]. Pressboard and Kraft paper are porous materials. The cellulose fibres present in the Kraft paper and pressboard consist of glucose units repeatedly arranged through a spacing of nearly 1 nm. Even in a single cellulose fibre, there exist pores having dimension ~1 nm [13]. After the impregnation process, oil, cellulose fibres, and aforementioned pores in fibres together create a complicated microscopic arrangement, with lots of interfacial regions. The interfacial region between two dielectrics is characterised by the high presence of ‘traps’ where space charges get confined [14]. Moreover, with ageing, the polymer chain breaks down, and the broken bonds produce new trapping sites [15]. These traps often capture electrons and confine them for the indefinite amount of time, giving rise to the phenomena of space charge. The time spent by the carrier inside the trap depends on the trap depth or trap energy. If the trapped charge carrier obtains this energy through thermal collision or other means (photon bombardment, very high electric field, etc) [16], it will be released to the conduction band, thereby contributing to the conduction process. Depending upon the trap depth, the trap release time may be in the order of milliseconds (shallow traps) to few hours (deep traps). The subsequent trapping and de-trapping of charge is instrumental in the conduction process of the dielectric under stressed conditions [16]. However, if the stressed dielectric specimen is discharged, then there is no more charge injection into the dielectric. Instead, the de-trapped charges are now extracted through the electrodes. This results in a current, which can be termed as the de-trapping current. As the accumulated space charge slowly decays due to charge extraction through electrodes, the de-trapping current monotonically decreases with time. Quite naturally, a large presence of deep traps will lead to a very slow decay of space charge. For this reason, information regarding the density of traps versus trap energy is highly valuable.

In the conventional IRC model, the relaxation current is supposed due to the de-trapping of previously trapped carriers only. This holds true only for non-polar dielectrics. For polar dielectrics, in addition to charge de-trapping, the relaxation of dipoles will also contribute to the relaxation current. In the case of moisture-impregnated oil-pressboard insulation, there is a strong presence of polar compounds and permanent dipoles. Therefore, in order to characterise the trap distribution from IRC analysis, it is important to identify the contribution of dipolar polarisation in the relaxation current.
In the present work, a methodology has been developed to separate the effect of dipolar polarisation in IRC from charge de-trapping using frequency domain dielectric spectroscopy. For this purpose, the Hamon approximation [17] is utilised for converting time frequency domain response to time domain response. After subtracting the current component due to dipolar relaxation from IRC, the current due to charge de-trapping is identified. The aim of the present work is to investigate the effect of moisture and ageing on charge trapping in oil-impregnated pressboard insulation from dielectric response measurements. For this purpose, several oil-impregnated pressboard samples having different moisture contents and ageing conditions were prepared in the laboratory and relaxation current and frequency domain spectroscopy (FDS) measurements were performed on them. For ageing analysis, the samples were made to undergo through accelerated thermal ageing. Results presented in this work depicted that IRC measurements can effectively identify the effect of moisture and ageing on charge de-trapping behaviour of oil-pressboard insulation.

2 Theory

2.1 Frequency domain spectroscopy and Hamon approximation

In frequency domain dielectric response, more commonly known as FDS, the dielectric specimen is excited with alternating voltage $U_i(t)$, thereby producing an alternating current. From the phase difference of the applied voltage and recorded current, the dissipation factor can be calculated. The dissipation factor is expressed as [18]

$$\tan \delta = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)}$$

where $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ are the real part and imaginary part of the complex dielectric relative permittivity, respectively. $\varepsilon'(\omega)$ represents the energy storage or capacitive properties of the dielectric, whereas $\varepsilon''(\omega)$ corresponds to the energy losses in the dielectric. The energy loss inside the dielectric is due to DC conduction and frictional losses between different dipole groups during the sinusoidal excitation process [19]. When the excitation frequency is very low, the DC conduction is predominant over other losses. This is due to the fact that at very low frequencies, the duration of half-cycle is long enough to cause ionic charge transport from one electrode to another, thus resembling the conduction process in a dielectric under the DC voltage. The dominance of DC conduction can be identified by a slope of $-1$ in the log–log scale in $\varepsilon''(\omega)$ characteristics, which is typically observed in the 0.1–1 mHz region.

Time domain and frequency domain responses of a dielectric are inadvertently related to each other, and response in one domain can be predicted if the response in the other domain is known. The common tools employed for this conversion of response domain are Fourier transform, transfer function analysis, etc. Compared to these approaches, a much easier way for the calculation of frequency domain dielectric response from time domain measurements is the Hamon approximation [17]. The Hamon approximation provides the frequency characteristics of $\varepsilon''(\omega)$ from charging–discharging currents. The main requirement for the application of the Hamon approximation is that the charging–discharging current should follow the $A^r\tau^n$ form, where $A$ is constant, $r$ is time, and $n$ is a coefficient having values between 0.3 and 1.2. The Hamon approximation is based on a simple relation between the imaginary part of the complex relative permittivity and relaxation current due to the dielectric polarisation current given by

$$\varepsilon''(\omega) = \varepsilon_0 \frac{\sigma_0}{\varepsilon_0 \omega} + \frac{i q \nu}{k T f C_0 U_i}$$

where $f$ is the frequency at which the imaginary permittivity will be calculated. Alternatively, if the imaginary permittivity at a frequency is known, then using (2), the corresponding dipolar relaxation current at the corresponding time instant ($0.1/f$) under the step voltage $U_i$ can be predicted. It is noteworthy that the corresponding time instant is 10 times higher than the inverse of the concerned frequency, i.e. from the imaginary permittivity data at 0.1 mHz, the dipolar relaxation current at 1000 s can be evaluated.

2.2 IRC measurements

It has been already discussed that the trapped charges require a certain amount of energy to get released to the conduction band. This energy is also known as trap depth. If the re-trapping of charge carriers is ignored, then the rate of release of electrons in a trap depth range $dE$ can be given as

$$\delta n = f_d(E) n(E) \exp(-\int_{E}^{E_f} e_d dr) dE$$

where $n_f$ is the rate of release (de-trapping) of electrons, $f_d(E)$ is the initial occupancy of electrons, $N(E)$ is the energy distribution of traps throughout the energy gap, $e_d$ is the probability of de-trapping of an electron per unit time from a trap level to energy $E$. $e_n$ can be given as

$$e_n = v \exp(-\frac{E_t}{k T})$$

where $v$ is the attempt to escape frequency, $E_t$ is the trap depth, $k$ is Boltzmann’s constant, and $T$ is temperature.

Summing up the contribution of all traps between the valence band ($E_v$) and conduction band ($E_c$), (3) can be rewritten as

$$n_f = \int_{E_v}^{E_c} f_d(E) N(E) e_n(E, T) \exp(-\int_{E}^{E_c} e_d dr) dE$$

As all de-trapped charge carriers are swept out of the dielectric, they induce a current in the external circuit. If the current per unit electrode area is $I(t)$, then $I(t)$ is related to the trap distribution through the following equation [10]:

$$I(t) = \frac{q k T E}{2} f_d(E) N(E) \int_{E_v}^{E_c} \exp(-\int_{E}^{E_c} e_d dr) dE$$

where $q$ is the amount of electronic charge and $l$ is the depth of the electron injection. The current per unit electrode surface can be easily calculated by dividing the total measured current by the electrode area.

From the time at which a particular amount of charge is extracted ($t_a$), the corresponding trap depth ($E_{t_a}$) can be evaluated through the following equation:

$$E_{t_a} = k T \ln(v t_a)$$

From (6), the trap density at the trap depth $E_t$ can be calculated as

$$N(E) = \frac{2 n_f t_a}{q k T \int_{E_v}^{E_c} f_d(E) N(E)}$$

Using (7) and (8), the trap density at the trap depth $E_t$ can be easily calculated. In the present work, the values of $f_d$ and $v$ have been taken as 1/2 [10] and $6.2 \times 10^{12}$ [20], respectively.

2.3 Combining IRC model with FDS measurements

If polar compounds are present in the dielectric specimen under study, the relaxation current can be given as

$$I(t) = I_{\text{cap}}(t) + I_d(t)$$
where $I_d(t)$, $I_{dc\text{-trap}}(t)$, and $I_d(t)$ are the total relaxation current, current due to charge de-trapping, and current due to dipolar relaxation, respectively.

The methodology of separating the dipolar relaxation current and de-trapping current is discussed through the following steps.

(i) It has been already discussed in Section 2.1 that the $\varepsilon_r'(\omega)$ characteristics are due to dipolar relaxation and DC conduction. As the DC conduction process becomes very dominant, over dipolar relaxation process. Therefore, the value of $\varepsilon_r'(\omega)$ at very low frequencies (typically 0.1–1 mHz) can be approximated as

$$\varepsilon_r'(\omega) \approx \frac{C_{dc}}{\varepsilon_0}$$  (10)

where $C_{dc} = (\varepsilon_0/\varepsilon_t)$.

Using (10), $C_{dc}$ can be estimated. $C_{dc}$ basically represents the contribution of DC conduction in $\varepsilon_r'(\omega)$ characteristics.

(ii) Once $C_{dc}$ is estimated, the contribution of DC conductivity at any frequency can be estimated by $(C_{dc}/\omega)$. This DC contribution is subtracted from the $\varepsilon_r''(\omega)$ characteristics, thereby giving the contribution of dipolar polarisation in $\varepsilon_r''(\omega)$.

(iii) After the dipolar contribution is evaluated, the relaxation current solely due to the dipolar relaxation $I_d$ can be estimated by the following equation:

$$\varepsilon_r''(\omega) - \frac{\sigma_0}{\varepsilon_0\omega} \approx \frac{I_d(0.1/f)}{2\pi f C_d U_c} \approx \frac{I_d(0.1/f)}{2\pi f C_d U_c}$$  (11)

where $I_d$ is the charging current, $\sigma_0$ is the DC conductivity, $C_d$ is the geometric capacitance, and $U_c$ is the applied DC voltage. It should be mentioned here that using (10), from the value of $\varepsilon_r''(\omega)$ at $f$ frequency, the relaxation current (due to dipolar relaxation) at $0.1/f$ time instant can be computed.

(iv) Once the dipolar polarisation current $I_d$ is identified, the current component due to charge de-trapping ($I_{dc\text{-trap}}$) in the relaxation current $I_d$ can be identified using (5) and (9). After $I_{dc\text{-trap}}$ is identified, the trap density ($N_t$) at the trap depth $E_t$ can be calculated using (7) and (8).

3 Experimental set-up

Pressboard specimens having a thickness of 0.5 mm and other dimensions of 8 × 8 cm² were used for sample preparation. At first, to desorb the moisture present in the pressboard, the specimens were heated at 105°C, and its weight was monitored at regular intervals. Once a steady value in weight is obtained, the sample under heating was considered as dry and de-moisturised. Then, for preparing samples having different ageing condition, some dry samples were impregnated with transformer oil in vacuum and kept in a sealed container. Prior to impregnation, the transformer oil was heated and degassed. The sealed container was put in a thermal oven, where accelerated thermal ageing was performed. The temperature of the thermal oven was kept at 140°C. The heat oven used in this experiment can provide heating temperature with an accuracy of 0.5°C. After each 200 h ageing interval, the oven was stopped, followed by the cooling of the sealed container for a sufficient period, and then a pressboard specimen was taken out from its FDS and IRC measurements.

For the moisture-related study, the dry specimens were kept in open air for moisture absorption, and their weights were monitored continuously. Due to moisture ingress from open air, the weight of the samples will increase. From this increase, the percentage of moisture (by weight) can be calculated. After the sample obtained the desired moisture percentage, it was impregnated with degassed transformer oil and kept in a sealed container for a few weeks to obtain moisture equilibrium. In this way, oil-impregnated pressboard specimens with 1, 2, and 3% were prepared. It should be mentioned that when a pressboard specimen with a particular moisture content was impregnated with mineral oil, some amount of moisture migrated to oil from the pressboard. For this reason, prior to current and FDS measurements, the moisture content in oil of sealed containers was measured with an oil-moisture sensor. The moisture sensor used can measure the moisture content in oil with an accuracy of 1 ppm. In all containers, the moisture content in oil was observed to be <50 ppm. From this information, the total weight of moisture in oil is calculated. This moisture has come from the pressboard. Therefore, the reduction in the pressboard moisture content due to moisture migration can be calculated now. It was observed that the reduction in the moisture content in pressboard samples is extremely small and hence it was ignored in further analysis. A schematic of the whole process is given in Fig. 1.

After sample preparation is over, imaginary permittivity (FDS) measurements were performed on the specimens having different moisture contents and ageing conditions. After FDS measurements, the samples were stressed under 10 kV/mm electric stress for around 1 h. After this, the external electric field was removed and IRC measurements were performed on the samples. The experimental set-up consisted of a HVDC source, an electrometer (Keithley 6517 A), and data acquisition. The schematic of the experimental measurements for IRC and FDS are shown in Figs. 2a and b, respectively.

4 Results and discussions

At first, FDS measurements were performed on pressboard specimens with different moisture contents and ageing conditions at 140 V for obtaining imaginary permittivity characteristics. The obtained $\varepsilon_r''$ characteristics of pressboard specimens having different ageing conditions and moisture contents are depicted in Figs. 3a and b. It is observed from these figures that with an increase in ageing and moisture content, imaginary permittivity increases, particularly at low frequencies. The imaginary permittivity signifies the lossy nature of a dielectric. Therefore, with ageing and moisture content, dielectric losses increase in the oil pressboard. This can be attributed to increasing
conductivity. Another noteworthy observation is that in all plots, at very low frequencies (~0.1 mHz), the nature of the curve is very close to a straight line with −1 slope. Therefore, from the value of imaginary permittivity at 0.1 mHz, the DC conductivity can be estimated using (10). The values of DC conductivities for specimens having different ageing status and moisture contents are given in Tables 1(A) and (B), respectively. It can be observed from Tables 1(A) and (B) that the unaged new sample depicted the lowest conductivity, ~0.036 pS/m. After 400 h of accelerated thermal ageing, conductivity increased nearly four times to 0.16 pS/m. However, as the moisture content increased from 1 to 3%, conductivity increases almost 10 times.

From Fig. 4a, it can be seen that with ageing, IRC increases, although the increase is more pronounced during the initial part of the measurement. During the final part of measurement, there is not much difference between the recorded relaxation currents of the fresh sample and thermally aged sample. However, as shown in Fig. 4b, ingress of moisture significantly affects the relaxation current throughout almost the entire measurement span.

For understanding the effect of thermal ageing and moisture on charge de-trapping, the current component corresponding to dipolar relaxation was separated using the methodology described in Section 2.3. Using imaginary permittivity values at discrete frequencies, the value of the dipolar relaxation current at discrete time instants at 5 kV voltage was estimated using (7). Let these discrete current values are denoted as $I_{\text{discrete}}$. After this, $I_{\text{discrete}}$ was curve fitted in the form of $At^−n$ mentioned in Section 2.2. This provided the continuous dipolar relaxation current $I_d$. The calculated values of $A$ and $n$ obtained from the curve fitting for specimens having different moisture contents and ageing are given in Tables 2(A) and (B). Finally, $I_d$ is subtracted from the measured depolarisation current $I_{\text{dis}}$, thereby giving the de-trapping current $I_{\text{de-trap}}$ from (8).

The separated de-trapping and dipolar relaxation current components for fresh samples and the sample after 400 h of thermal ageing are shown in Fig. 5a. It should be noted from Fig. 5a that the de-trapping current of the fresh sample and the 400 h thermally aged sample significantly differs from each other, particularly at the final stages of measurement. However, this feature is completely overshadowed in Fig. 4a, where the relaxation currents of all samples were found to be almost the same during the final stages of measurement. Therefore, it is clear that the assumption of considering the whole relaxation current due to charge de-trapping only may lead to the incorrect diagnosis of oil-pressboard insulation. The separated de-trapping and dipolar relaxation current components of the sample with the 1% moisture content and the sample with the 3% moisture content are shown in Fig. 5b.

In [21], the changes bought by thermal ageing in the microscopic morphology of the pressboard were studied using scanning electron microscope (SEM) measurements. The SEM images of the pressboard having different ageing conditions were shown in Fig. 10 of [21]. The thermal ageing procedure adopted in [21] is very much similar to the present work. It was observed in

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**Table 1** Effect of ageing condition and moisture on DC conductivity of oil impregnated pressboard

| Ageing condition | Conductivity, S/m |
|------------------|------------------|
| (A) Effect of ageing condition on DC conductivity. | |
| new sample | $3.66 \times 10^{-14}$ |
| 200 h ageing | $7.17 \times 10^{-14}$ |
| 400 h ageing | $1.6 \times 10^{-13}$ |
| (B) Effect of moisture on DC conductivity | |
| 1% | $4.94 \times 10^{-14}$ |
| 2% | $1.16 \times 10^{-13}$ |
| 3% | $5.45 \times 10^{-13}$ |
that as thermal ageing progresses, the roughness and cellulose fibre surface increase. At the same time, the average fibre length decreases. This can be attributed to the breaking of polymeric chains due to thermal ageing.

![Fig. 4](image)

**Fig. 4** Effect of thermal aging and moisture on IRC of oil impregnated pressboard
(a) Effect of ageing on the isothermal relaxation current (IRC), (b) Effect of moisture on IRC

| Ageing condition | A (V/mC) | n |
|------------------|---------|---|
| new sample       | $2.05 \times 10^{-8}$ | 0.85 |
| 200 h ageing     | $3.31 \times 10^{-8}$ | 0.93 |
| 400 h ageing     | $3.09 \times 10^{-7}$ | 1.18 |

| Moisture content | A (V/mC) | n |
|------------------|---------|---|
| 1%               | $5.25 \times 10^{-8}$ | 0.87 |
| 2%               | $9.31 \times 10^{-8}$ | 0.77 |
| 3%               | $3.14 \times 10^{-7}$ | 0.62 |

charge de-trapping only. In Fig. 6b, two peaks in the trap distribution are clearly recognisable. With an increase in ageing, both peaks shifted towards a higher value of the trap depth. However, such a clear trend is missing in Fig. 6a. For example, in Fig. 6a, for the new and 200 h thermally aged samples, two peaks in the trap distribution are clearly visible, but for the 400 h thermally aged sample, there is an indication of a shallow trap peak around 0.75 eV. It is difficult to explain the sudden emergence of a new peak in the shallow trap region. Comparatively, Fig. 6b offers a much straightforward trend. With ageing, the polymeric chains get broken, leading to the generation of new traps. These traps have a higher trap depth. As a result, the trap distribution slightly shifts towards right. Overall, it can be said that both trap density and trap depth increase with ageing. A higher trap density will ensure the presence of larger space charge density.

With deeper traps, this space charge will remain in the insulation for longer durations even under discharging conditions. Indeed, such features have been observed using pulsed electro acoustic (PEA) space charge measurement systems in thermally aged oil-paper insulation [22].

The calculated trap distribution using the improvised IRC model for moisture ingressed samples is depicted in Fig. 6c. With an increase in the moisture content, the trap distribution changed significantly. For the specimen with the 1% moisture, the two peaks are clearly recognisable. However, with an increase in the moisture content, the trap distribution peak corresponding to shallow traps increases rapidly, overshadowing the deep trap peak. Quite contrary to Fig. 6b, the shallow trap peak shifted towards lower values of the trap depth. It clearly shows that moisture increases the shallow trap density in the oil pressboard. It should be mentioned here that the trapping analysis can also be conducted by the direct measurement of space charge through the PEA.
In the present work, an improvised IRC model has been proposed to understand the effect of ageing and moisture content on oil-pressboard insulation in the HVDC environment. The developed model identifies and separates the dipolar relaxation component and charge de-trapping component from the relaxation current and determines the trap distribution. The major observations of the work are discussed in brief below.

(i) For a composite dielectric-like oil pressboard containing polar compounds, considering the whole relaxation current for charge de-trapping only may offer the incorrect evaluation of trapping characteristics of the dielectric system.

(ii) Both ageing and moisture lead to the formation of new traps, thereby increasing trap density.

(iii) Thermal ageing leads to the generation of more deep traps. This leads to a slow decay of accumulated space charge under HVDC conditions, eventually triggering insulation degradation [27]. On the other hand, moisture accumulation leads to the formation of shallow traps which enhances the conductivity several times.

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Table 3  Comparison of trap density obtained from the improved IRC model with other published results.

| Research work | Trap density, m⁻³ |
|---------------|------------------|
| present work  | 10⁻¹⁸–10⁻¹⁹      |
| Wei et al. [23]| 10⁻¹⁸–10⁻¹⁹      |
| Yang et al. [24]| 10⁻¹⁸–10⁻¹⁹    |
| Wei et al. [25]| 10⁻¹⁹–10⁻²⁰    |
| Zhou et al. [26]| 10⁻¹⁹–10⁻²⁰   |

Fig. 6 Trapped charge distribution of samples having different aging status and moisture content

(a) Trapped charge distribution of samples with different ageing conditions using the conventional IRC model. (b) Trapped charge distribution of samples with different ageing condition using the modified IRC model, (c) Normalised trapped charge distribution of samples with different moisture contents.
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