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AN EXPERIMENTAL STUDY ON DIELECTRIC PARAMETERS OF XLPE INSULATED HIGH VOLTAGE CABLES UNDER DIFFERENT OPERATING CONDITIONS

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Keywords

High Voltage Cables, Dielectric Loss, Dielectric Loss Factor, Energy Distribution.

Abstract

High voltage underground cables used in distribution systems provide benefits including aesthetics, reliability, low maintenance costs, and resistance to environmental factors. However, their initial installation expenses are considerably higher than overhead lines, and fault detection is quite challenging. Thus, a deep analysis of dielectric parameters is crucial. Typically, electrical specifications of high voltage underground cables provided by the manufacturer are used for nominal operating conditions. However, it is essential to acknowledge that variations in operational conditions have a discernible impact on the dielectric characteristics of cable insulation. This phenomenon results in an accelerated aging process of the insulation material and contributes to unexpected failures. Hence, it is imperative to determine dielectric parameters of cable insulation under varying operational conditions and elucidate the impact of these operational states on insulation properties. This study involved experimental determination of the dielectric parameters, including capacitance, relative dielectric constant, dielectric loss, and tanδ, for a XLPE insulated high voltage underground cable, designed for a nominal voltage of 12/20 kV. These assessments were performed under varying operating conditions, specifically for distinct voltage, temperature, and frequency. Based on the acquired findings, it is evident that the dielectric characteristics of the cable insulation exhibit substantial variations in response to alterations in voltage, temperature, and frequency, even when operating within the defined nominal limits.

XLPE İZOLELİ YÜKSEK GERİLİM KABLOLARININ FARKLI İŞLETME KOŞULLARI ALTINDA DİELEKTRİK PARAMETRELERİ ÜZERİNE BİR ÇALIŞMA

Anahtar Kelimeler

Yüksek Gerilim Kabloları, Dielektrik Kayıp, Dielektrik Kayıp Faktörü, Enerji Dağıtımı.

Öz

Dağıtım sistemlerinde kullanılan yüksek gerilim yer altı kabloları estetik, güvenilirlik, düşük bakım maliyetleri ve çevresel faktörlere dayanıklılık gibi avantajlar sağlar. Ancak bunların ilk kurulum maliyetleri, havai hatlara göre oldukça yüksektir ve arıza tespiti zordur. Bu nedenle dielektrik parametrelerinin derinlemesine analizi oldukça önemlidir. Yüksek gerilim yeraltı kablolarının üretici firma tarafından verilen elektriksel değerleri genellikle nominal işletme şartları için kullanılmaktadır. Ancak değişken işletme şartları, kablo yalıtımının dielektrik dielektrik parametrelerini de değiştirmekte olup yalıtımın daha hızlı yaşlanmasına ve beklenmeyen arızalara neden olmaktadır. Ancak değişken işletme şartlarında, kablo yalıtımının dielektrik parametreleri de değişmekte olup, sistemin çalışmasında aksamalara ve beklenmeyen arızalara neden olabilmektedir. Bu nedenle, kablo yalıtımının dielektrik parametrelerinin farklı işletme koşulları altında belirlenmesi ve bu işletme koşullarının yalıtım üzerindeki etkilerinin ortaya konması önem arz etmektedir. Bu çalışmada, 12/20 kV nominal gerilimli, XLPE izoleli bir yüksek gerilim yeraltı kablosunun, farklı işletme koşullarındaki (gerilim, sıcaklık ve frekans) dielektrik parametreleri (kapasite, bağıl dielektrik katsayısı, dielektrik kayıp, tanδ) deneysel olarak belirlenmiştir. Elde edilen sonuçlara göre, nominal çalışma sınırları içerisinde dahi kablo yalıtımının dielektrik özelliklerinin farklı gerilim, frekans ve sıcaklık ile önemli ölçüde değiştiği gözlemlenmiştir.

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AN EXPERIMENTAL STUDY ON DIELECTRIC PARAMETERS OF XLPE INSULATED HIGH VOLTAGE CABLES UNDER DIFFERENT OPERATING CONDITIONS

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Highlights

- Dielectric performance of XLPE insulated high voltage cables varies due to the operating conditions.
- Voltage magnitude and frequency, along with conductor temperature affect dielectric properties.
- It is essential to consider dielectric properties for high voltage cable operational limits.

Graphical Abstract

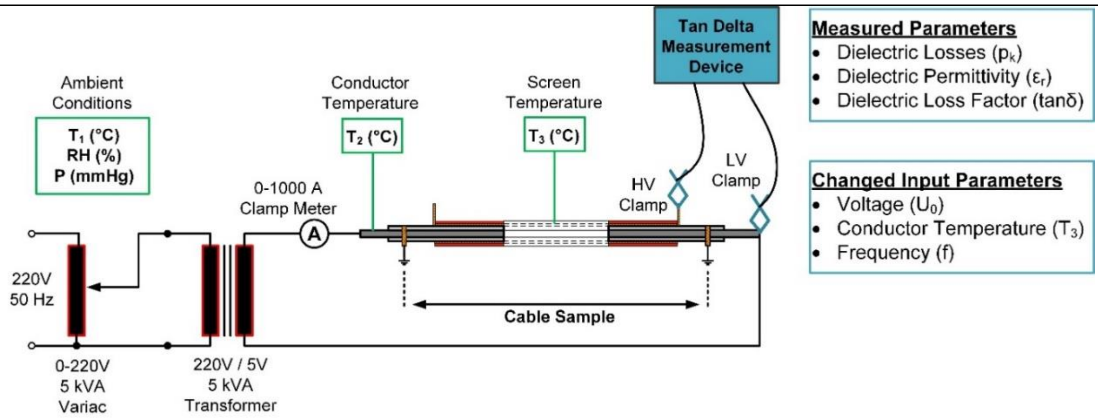

Figure. Graphical Abstract

Purpose and Scope

The objective of this study is to experimentally analyze how high voltage cables' dielectric properties change under different operating conditions. The study focuses on XLPE insulated high voltage cables and involves measurements on unaged cables in real operating conditions

Design/methodology/approach

The study investigated how dielectric properties respond to changes in voltage, temperature, and frequency. Voltage ranged from 1 kV to 12 kV, temperature from 30°C to 80°C, and frequency from 50 Hz to 400 Hz. Dielectric loss (p_k), dielectric permittivity (ε_r) and dielectric loss factor (tanδ) values under varying voltage, temperature and frequency were determined by measurements. CPC-100, CP-TD1 measuring device was used for different frequencies and voltages. To control the cable temperature, an electrical test setup is employed that regulates the current flowing through the conductor.

Findings

The study found that the voltage level impacts dielectric losses and the dielectric loss factor. However, it doesn't alter the cable's capacitance. Temperature and frequency adjustments influence all dielectric parameters. This suggests that the loading ratio of the cable and voltage harmonics play a crucial role in its dielectric properties more than voltage amplitude.

Practical implications

The dielectric properties of MV cables are regularly assessed while in operation. This practice enables a comparison between the dielectric quality parameters of a MV cable that has been operational for a specific duration with those of a newly manufactured MV cable. This comparison highlights that examining dielectric parameters both prior to the MV cable's operation and during its service life allows for an in-depth analysis of the cable's dielectric lifespan and capacitance.

Originality

Previous studies in the literature have typically investigated the impact of voltage, frequency, and temperature on dielectric material quality parameters individually. In contrast, this study offers a more comprehensive and thorough examination of the quality parameters of MV cables.

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1. Introduction

To meet rapidly increasing energy demand, new investments and studies have been carried out in recent years (Kaplan et al., 2012). However, solving the problem of increasing energy demand has led to the emergence of problems in the accurate, reliable and efficient transmission, distribution, and delivery of energy to the consumers. As the size of the energy transported increases and alternative energy sources are connected to the network, transmission and distribution networks have become more complex. However, it is a fact that the equipment used in the power system will be exposed to different and more challenging operating conditions. Correct and reliable management of this complex network is an issue of great importance in terms of energy continuity (Wang et al., 2001; Zaengl, 2003b). One of the issues that should be emphasized in order to ensure this continuity and reliability is the correct selection of the equipment in the power system, the ability to examine their behavior under difficult operating conditions, and the ability to instantly monitor their quality performance (Chan et al., 1993; Wang et al., 2001; Werelius et al., 2012). Studying the medium voltage (MV) network and its high voltage components in the power system is crucial. The MV network is closely connected to residential areas, where electrical faults are more common (Lelak et al., 2002; Ponniran & Kamarudin, 2008). To ensure a consistent power supply in the MV distribution network, proper operation of the equipment is essential (Hampton, 2008; Peng et al., 2009; Arikan et al., 2023). In newly installed systems, high voltage equipment must pass standardized tests to operate within specific limits. However, like all systems, aging affects distribution systems (Vahedy, 2006). Consequently, regular testing and maintenance of aging equipment are necessary. Extending the electrical life of power system equipment by a few years can result in significant economic benefits for the power industry (Werelius et al., 2012). Power cables play a crucial role in transmitting energy within the MV distribution system. They are fundamental equipment for energy transportation and come with a significant investment cost. In case of a failure, these issues can result in significant financial losses for both the distribution network and consumers. (Chan et al., 1993). Hence, it is imperative to ensure the reliable operation of MV cables throughout their lifespan. The end-of-life or failure of an MV cable typically stems from deterioration, degradation, and aging of the cable's insulation material (Cookson, 1990; Malpure & Baburao, 2008; Suwarno & Salim, 2006). Several key factors contribute to the aging of MV cables, including chemical degradation, water tree formation, and exposure to electrical and thermal stress (Hvidsten et al., 1990; Malpure & Baburao, 2008; Mazzanti et al., 1997). It's essential to conduct a comprehensive analysis of these flaws and the factors affecting the cable's insulation. To this end, a variety of methods are employed today for conducting condition, performance, and quality analyses of MV cables within enterprises (Boggs & Kuang, 1998). In addition to assessing cables in active operation, it is equally important to conduct measurements and analyses on undamaged or newly manufactured cables. This enables a more comprehensive understanding of the influence of the aforementioned factors on the cable's integrity and aids in comprehending the effects of deteriorating elements. In a power system, MV cables don't always operate under nominal conditions during their service life. The cable's temperature varies due to the continuously changing electrical loads in the system. Typically, MV cables are designed to work at their nominal current capacity because of their high installation and operating expenses. However, during periods of high demand, they can be overloaded, causing the cable temperature to exceed the maximum level. Conversely, during low-demand times, the cable may carry less current than it's designed for (Mazzanti et al., 1997).

MV cables can experience changes in both temperature and voltage. When demand for electricity is low, the cable may have higher voltage than its normal level. Conversely, during high-demand periods, it might have lower voltage. Additionally, if there are irregular patterns in the voltage supply, the cable's insulation is exposed to a non-standard voltage with different frequency components [20]. Numerous studies in the literature have aimed to measure the quality of dielectric parameters in cables under different working conditions (Chmura et al., 2012; Oyegoke et al., 2003; Zaengl, 2003a). Among these parameters, the one most frequently employed is the dielectric loss factor, commonly denoted as tan δ (Gockenbach & Hauschild, 2000; Mahalik, 1997). Measuring tan δ in MV cables can be done using various techniques. One method involves using very low frequencies, typically in the range of 0.001Hz to 1Hz (Hou et al., 2023; Morsalin et al., 2019; Ďurman & Lelák, 2010; Hernandez-mejia et al., 2009; Hernandez-Mejia et al., 2009; Hvidsten et al., 1990). However, this method takes time due to the lengthy measurement period, and low frequencies can lead to additional polarization losses in the dielectric material. Another approach is the dielectric spectrum method, which measures the dielectric loss factor at frequencies in the kHz or MHz range with low voltages (Bolivar et al., 2003; Liu et al., 2009). Although this approach offers insights into material quality, it fails to disclose how high voltage impacts the dielectric material because of the use of low test voltage. Furthermore, the higher measurement frequency compared to the grid frequency reduces polarization losses. An alternative way to measure the dielectric loss factor is by conducting measurements at the mains frequency while applying high voltage (Pascoli et al., 2008; Song et al., 2007, Arikan et al., 2022). According to the IEC 60502-2 standard, for tan δ measurements in MV cables with specified nominal voltage values (ranging from 7.2 kV to 36 kV), the measurement voltage must be at least 2 kV. This method obtains measurements under the cable's operational voltage and frequency using the "Schering Bridge" technique. These measurement techniques are commonly employed in numerous research studies. They usually examine how the quality of cable insulation material alters as voltage changes, with consistent frequency and temperature. Typically, the voltage levels employed in these studies are whole-number multiples of the cable's rated voltage (Pascoli et al., 2008). It's important to recognize that the amplitudes of voltage harmonics in the network can vary considerably and may not consistently align with whole numbers. Another aspect explored in these studies is how temperature affects the insulation material (Lelak et al., 2002). These studies often observe how the dielectric loss factor behaves as the temperature increases from lower values to the normal operating temperature. Temperature increases are typically done in 10°C steps, ranging from 30°C to 90 - 110°C, and the material's properties are measured at each of these temperatures.

This study involved conducting experiments in the laboratory to measure the dielectric loss, parallel equivalent capacitance, relative dielectric permittivity, and dielectric loss factor of a 12/20kV MV cable. The cable was tested under different operating conditions, including variations in voltage, temperature, and frequency. The obtained measurements were then analyzed to understand how the dielectric material of MV cable responds to changes in voltage, temperature, and frequency. The methodology part includes details about the experimental setup, cable samples used, and measurement procedures. In the results & discussion section, the results gathered from the measurements are shown and analyzed. In the conclusion section, the study's outcomes are included.

2. Methodology

In order to determine the behavior of dielectric material parameters of MV cables under different operating conditions, 12/20 kV, 1x150/25 mm^2, cross-linked polyethylene (XLPE) insulated, single core, aluminum conductor, copper screened cable was used as the test sample and its properties are given in Table 1.

Table 1. Technical specifications of the cable sample

Properties	**Value**
VDE Code	NA2XSY
Rated voltage [kV]	12 / 20
Cross-section-Conductor (Al) [mm^2]	150
Cross-section-Screen (Cu) [mm^2]	25
Diameter of conductor [mm]	6,18
DC resistance@20^{0}C [ohm/km]	0,206
Inductance [mH/km]	0,63
Capacitance [μF/km]	0,25
Ampacity [A]	353
Cable length [m]	11
Overall diameter [mm]	38
Operating temperature [^{0}C]	90
Short circuit temperature (max. 5 second) [°C]	250
Cable Condition	Unaged

The experimental arrangement depicted in Figure 1 was established to assess the dielectric properties of the cable sample utilized in this investigation across various voltages, temperatures, and frequencies.

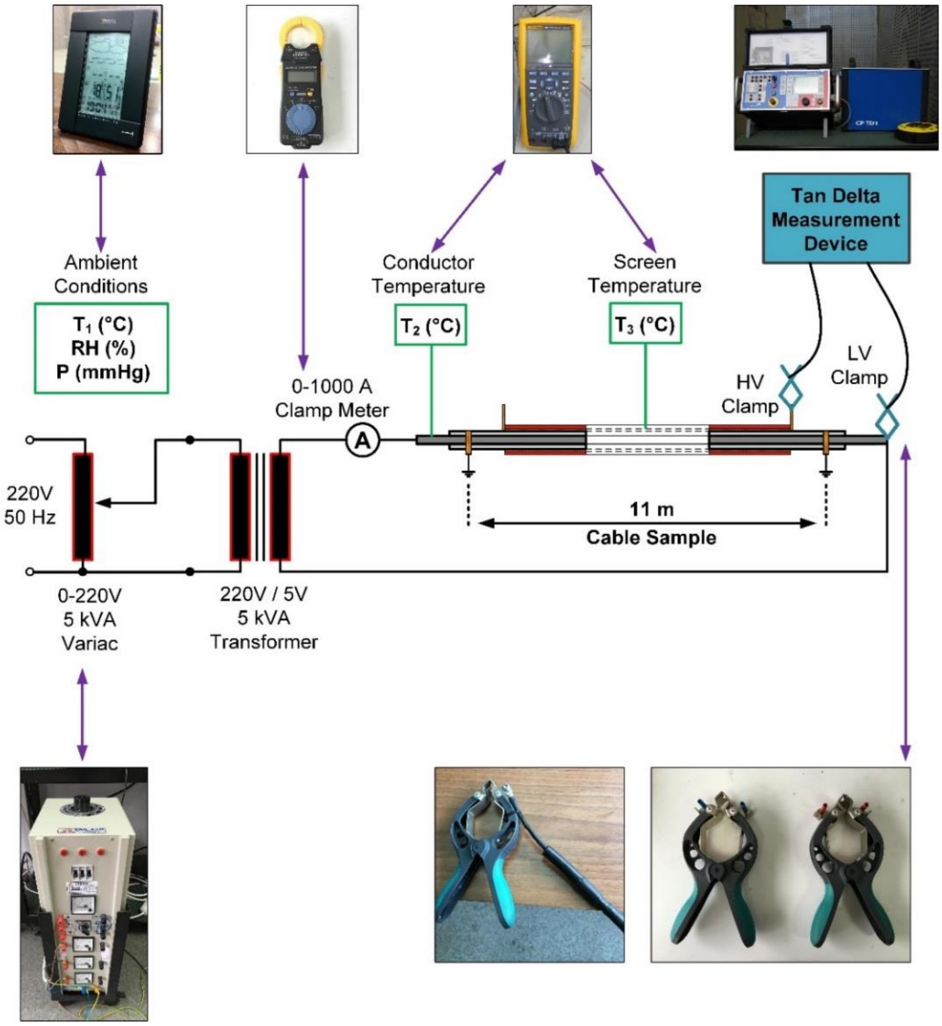

Figure 1. The experimental test arrangement employed in the study

To measure the cable's temperature, thermocouples are positioned at specific points. In this study, two temperature measurements were taken on the cable. The first was at the cable's conductor where it connected to the secondary winding output of the transformer, and the second was at the screen's temperature in the cable's midpoint. The screen temperature in the middle of the cable was chosen as the reference point during the cable's heating process. This location is the least affected by temperature increases due to relatively high contact resistances at connection points. Measuring the conductor's temperature at the cable's connection point served to monitor any overheating caused by contact resistance and allowed for necessary precautions. Figure 2 illustrates a sample variation in the temperature from the midpoint of the cable as it was heated to 40°C.

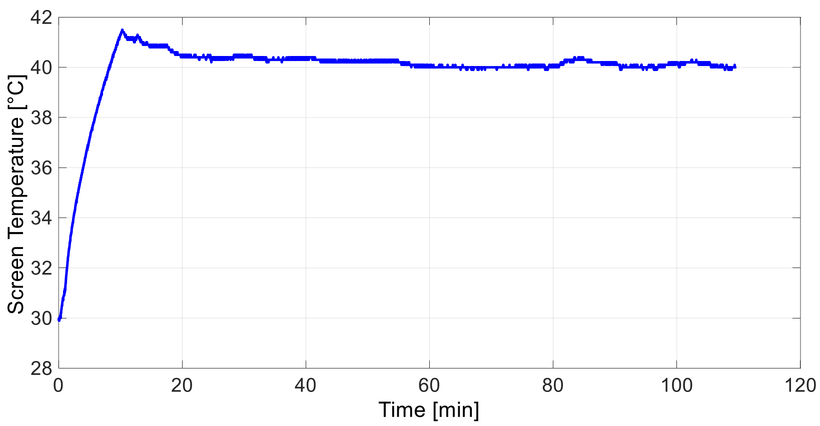

Figure 2. Variation in temperature recorded from the middle of the cable during the heating process up to 40°C

Prior to connecting the cable sample to the transformer, thermal insulation material was applied to cover the entire cable. This was done to hinder the dissipation of heat generated within the cable conductor as a result of

losses associated with current flow. Consequently, this approach diminishes the duration needed for the cable sample to attain the intended temperature, expediting the measurement process and conserving heat.
To pass current through the cable conductor, a transformer with a primary voltage of 220 V, secondary voltage of 5 V, and a nominal power of 5 kVA was employed. The input voltage of the transformer was regulated by a variac with nominal values of 220V/0-220V and 5 kVA. By utilizing the variac, the primary voltage (V_1) of the transformer could be adjusted, consequently controlling the amplitude of the secondary voltage (V_2) in accordance with the transformer's conversion ratio. This enabled the management of current flow through the conductor. A clamp meter capable of measuring alternating currents between 0 – 1000 A was used to measure the current flowing through the conductor. The cable's temperature, which increases due to the current passing through the conductor, was measured at two distinct points: within the conductor at the cable connection point (T_2) and from the screen surface located at the midpoint of the cable (T_3). To carry out these measurements, two Fluke 289/FVF multimeters and K type thermocouples were employed. The thermocouples are capable of measuring temperatures between -40°C and 260°C with an accuracy of ±1.1°C. Meanwhile, the multimeters provide a sensitivity of ±0.1°C and an accuracy of ±1%+1°C.

T_1 temperature represents the ambient temperature within the laboratory and was measured using a laboratory type weather station. In addition to ambient temperature, measurements also included recording relative humidity and pressure values within the laboratory environment, as detailed in Table 2.

Table 2. Average values of the laboratory conditions observed during the measurement procedures

Temperature	Relative Humidity	Pressure
25 ± 1°C	%35 - 40	756 – 758 mmHg

During the measurements, there are surface currents that flow through the dielectric material from the screen to the conductor. This occurs because the dielectric material's surface possesses a particular surface resistance. To avoid these leakage currents from affecting the measurements or introducing measurement errors, copper strips were placed on the dielectric material's surface at both ends. These copper strips were connected to the ground probe of the device and brought to the same potential using a cable. This approach involves measuring only the current passing through the dielectric material, effectively isolating surface currents from the intended measurements. After the measurement setup was established, dielectric parameters of the cable insulation were measured. To carry out the measurement process, the desired temperature was achieved by passing current through the cable conductor. After reaching this temperature, it was carefully maintained for approximately three hours by continuously regulating the cable current using the variac. Following this, the cable's temperature was stabilized within a range of ±1°C, and the dielectric properties were then measured. Table 3 presents the dielectric parameters and their corresponding measurement ranges as determined in this study.

Table 3. Dielectric parameters and their corresponding measurement ranges

Changed Parameters	**Measurement Range**	**Measurement Steps**	**Measured Parameters**
Voltage	1 kV – 12 kV	0,5 kV	Dielectric loss (p_k) Dielectric loss factor (tan δ) Parallel Equivalent Capacitance (C_p)
Frequency	50 Hz – 400 Hz	25 Hz	
Temperature	30°C - 80°C	10 °C	

As per the IEC 60502-2 standard, it is specified that a minimum test voltage of 2 kV should be used for measuring the dielectric loss factor (IEC 60502-2, 2014). The study's test voltage range was set to cover the relevant standard, and test voltages ranging from 1 kV to 12 kV, increasing by 0.5 kV increments, were utilized to observe the effects of higher voltage levels on the dielectric material. Measurements were conducted using the CPC-100, CP-TD1 measuring device, which allows adjustment of the output frequency from 50Hz to 400Hz in increments of 25 Hz. This range enabled observation of how the dielectric material is affected by voltage harmonics up to the eighth harmonic, as well as the fundamental component. Furthermore, a maximum test temperature of 80°C was chosen to prevent damage to the cable's insulation caused by overheating due to contact resistance between the cable conductors and the transformer, despite the nominal operating temperature of underground cables being 90°C.

3. Results and Discussion

In this section of the study, the outcomes of cable measurements and the assessments derived from these results are discussed. The measurements were aimed at revealing how the cable's dielectric material responds to different operational conditions by examining variations in voltage, temperature, and frequency.

3.1 Measurement Results Based on Test Voltage

Due to the extensive amount of measurement data, the examined ranges were restricted, and the change curve in only one case was provided to facilitate a clearer evaluation of the observed changes, especially in the ranges exhibiting similar behavior.

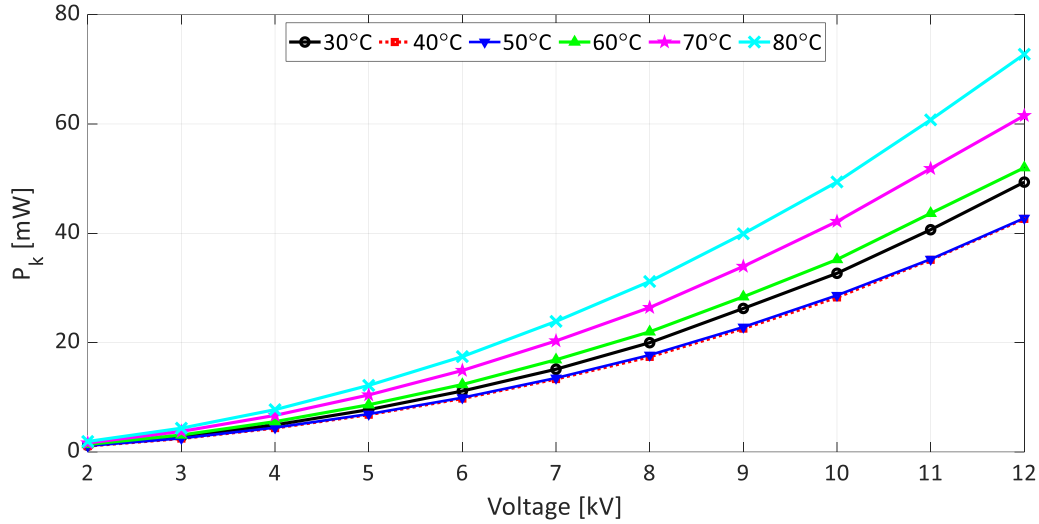

Figure 3. Voltage-dependent change of dielectric loss (p_k) at various screen temperatures (f = 50 Hz)

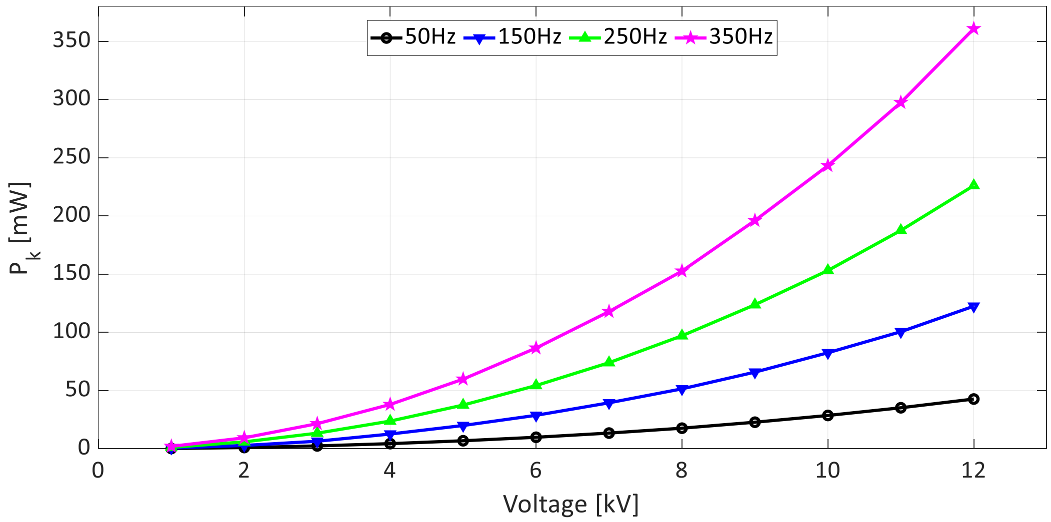

Figure 4. Voltage-dependent change of dielectric loss (p_k) at various frequencies (T = 50°C)

Figure 3 illustrates the results of dielectric loss measurements, showing how they change as the voltage increases from 1 kV to 12 kV. These measurements were conducted at different shield temperatures (30°C, 40°C, 50°C, 60°C, 70°C, and 80°C), all at a constant frequency of 50 Hz. In general, when considering all temperatures, it's evident that dielectric losses increase quadratically as both voltage and current increase. At 12 kV nominal U0 voltage, the lowest dielectric loss was observed at 40°C, measuring 42.64 mW. The highest dielectric loss at the same voltage level was recorded at 80°C, with a value of 72.75 mW. Figure 4 displays how dielectric losses vary with voltage at a constant cable screen temperature of 50°C, but with different frequencies. Various harmonic frequencies, including the 3rd, 5th, and 7th harmonics, were investigated. The data reveals that dielectric loss increases with rising voltage for each frequency. At U_0 (12 kV) voltage level, dielectric loss values are as follows: 42.77 mW at 50 Hz, 122.53 mW at 150 Hz, 226.13 mW at 250 Hz, and 360.92 mW at 350 Hz. When the frequency is increased by three times (150 Hz), the dielectric loss becomes 2.86 times the value at 50 Hz. When the frequency is increased by five times (250 Hz), the dielectric loss rises to 5.29 times the value, and when increased by seven times (350 Hz), the dielectric loss reaches 8.44 times. It's noticeable that this increase is not linear, as one might expect based on the series equivalent circuit of the dielectric loss factor (tanδ). These findings suggest that the dielectric material's response to changes in frequency isn't consistent with traditional series and parallel equivalent circuit models. Additionally, it appears that voltage harmonics cause additional losses inside the dielectric material.

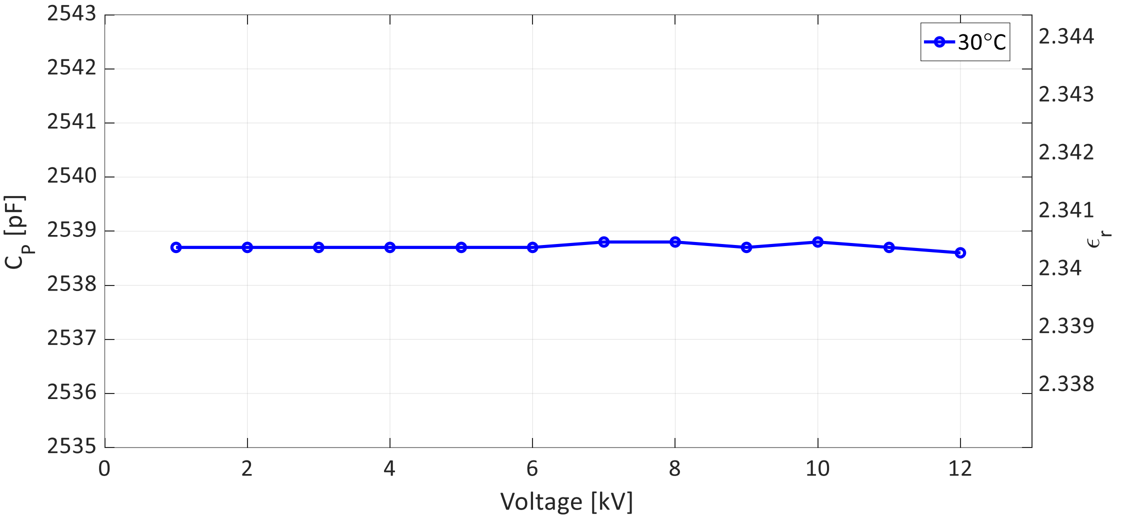

Figure 5. Voltage-dependent change of parallel equivalent capacitance (C_p) and relative dielectric permittivity (ε_r) at 30°C screen temperature (f = 50 Hz)

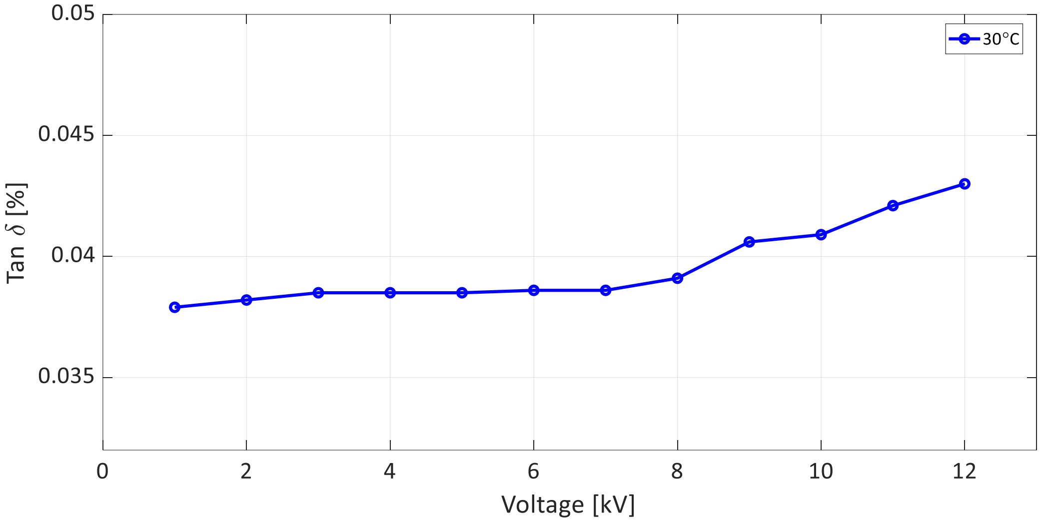

Figure 6. Voltage-dependent change of dielectric loss factor (tanδ) at 30°C screen temperature (f = 50 Hz)

Figure 5 presents the results of measurements performed at a constant frequency of 50 Hz and a stable screen temperature of 30°C. It illustrates the variations in parallel equivalent capacitance (C_p) and relative dielectric permittivity (ε_r) in response to changes in voltage. In Equation 1, there exists a fixed relationship between C_p and ε_r. This is why both of these measures are depicted together on the same graph. Within this equation, C_0 signifies the geometric capacity, C_p represents the capacity obtained through measurement, ε_0 indicates the dielectric constant of the cavity, and $\varepsilon_{r\text{-}air}$ refers to the relative dielectric coefficient of the air.

$$\varepsilon_r = \frac{C_p}{C_0} = \frac{C_p \cdot ln\left({}^{r_2}/_{r_1}\right)}{2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_{r_{air}} \cdot l} \tag{1}$$

Equation 2 displays the calculated geometric capacity value for the cable under measurement.

$$C_0 = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_{r_{air}} \cdot l}{ln\left(\frac{r_2}{r_1}\right)} = \frac{2 \cdot \pi \cdot 8{,}854 \cdot 10^{-12} \cdot 1 \cdot 11}{ln\left(\frac{13{,}22}{7{,}52}\right)} = 1084{,}7\ pF \tag{2}$$

As the applied voltage increases, C_p remains approximately constant up to about 6 kV, with a value of 2538.7 pF. When voltage continues to increase up to 12 kV, the maximum increase is around 0.04%. Due to this very small rate of increase, it can be said that cable capacitance and the relative dielectric coefficient of the dielectric material do not change significantly with voltage. The reason for this lack of voltage-related change in the relative dielectric coefficient or cable capacity is the new condition of the cable used for measurements. However, if measurements were conducted on an aged cable, changes related to voltage could be observed in C_p and ε_r.

Figure 6 illustrates the tanδ values measured in response to an increase in voltage (1-12 kV) at a consistent frequency (50 Hz) and temperature (30°C). The tanδ remains approximately constant at 0.039% from 1 kV to 7 kV. However, when the measurement voltage is raised from 8 kV to 12 kV, tanδ increases to 0.043%, indicating an 11.4% rise when the voltage goes from 7 kV to 12 kV. The equations for tanδ in both the series and parallel equivalent circuits indicate that tanδ is not affected by the measurement voltage. As a result, a significant increase in tanδ due to voltage variations is not anticipated.

Nevertheless, it's established that the parameters within the equations for R_p and C_p change with voltage, leading to the observed voltage-related increase. Equation 3 introduces an alternative expression for tanδ.

$$tan\ \delta = \frac{\sum p_k}{\sum Q_c} \tag{3}$$

In this context, tanδ is described as the proportion of all active losses occurring in the dielectric material to the complete reactive power (Q_c) of the dielectric material. According to this definition, tanδ value rises above a specific voltage level due to the appearance of polarization losses alongside the conduction losses in the dielectric material. This scenario can be clarified as follows:

$$p_k = p_c + p_p + p_i \tag{4}$$

Here, p_c represents conduction losses, p_p represents polarization losses, and p_i represents ionization losses caused by partial discharges (Kalenderli et al., 2005). At low voltage levels, the electric field within the dielectric material and, consequently, the associated polarization and ionization losses are relatively small. As a result, tanδ remains less significant and shows minimal change up to 7 kV. However, beyond 7 kV, it becomes evident that the rise in polarization and ionization losses contributes to an increase in the tanδ value due to the overall loss.

3.2 Measurement Results Based On Temperature

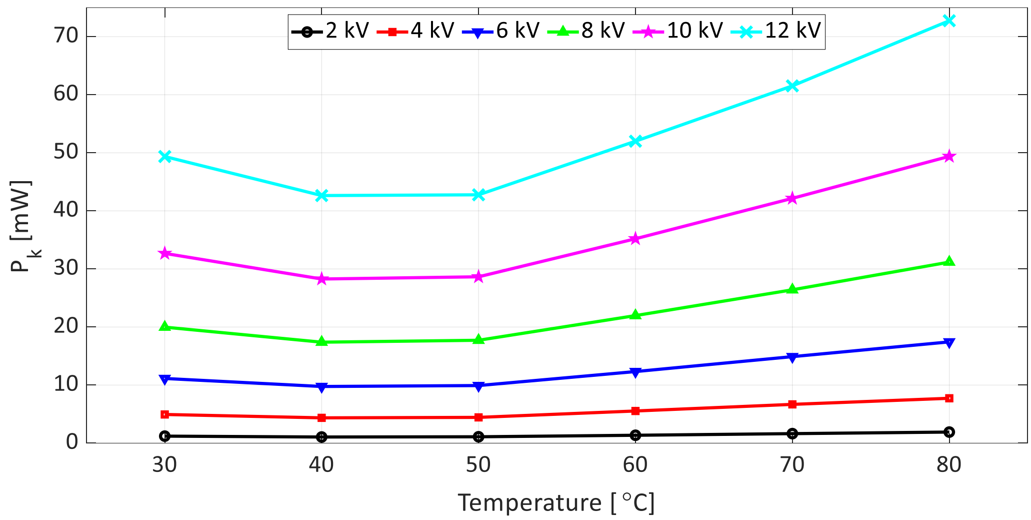

Figure 7. Temperature-dependent change of dielectric loss (p_k) at various voltages (f = 50 Hz)

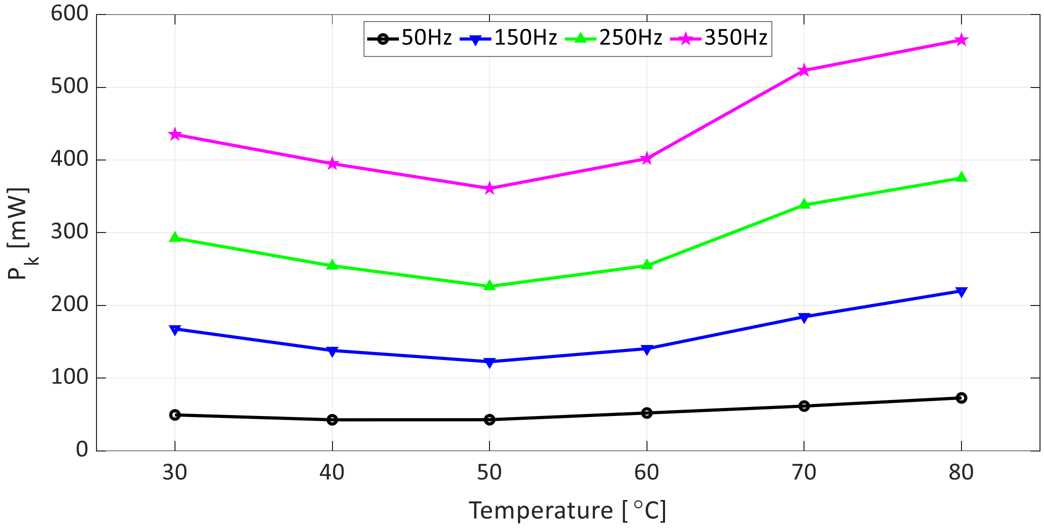

Figure 8. Temperature-dependent variation of dielectric loss (p_k) at at various frequencies (U = 12 kV)

The graph in Figure 7 shows how dielectric loss changes with temperature at a fixed frequency of 50 Hz for various voltage levels. The results indicate that the relationship between dielectric loss and temperature is not straightforward and doesn't follow a linear pattern. When the screen temperature increases from 30°C to 50°C, dielectric loss decreases at all voltage levels. However, as the screen temperature surpasses 50°C, the dielectric loss starts to increase. This change in dielectric loss is influenced by the electric field strength and thermal energy. At room temperature, all dielectric materials have a certain level of molecular thermal energy. This energy causes the molecules in the dielectric material to move thermally to a certain degree. When the temperature of the material rises, the thermal energy of the molecules also increases, leading to more significant thermal motion. The electric field intensity generated when voltage is applied to the dielectric material enhances this molecular movement even further, particularly compared to when the molecules remain orderly due to polarization at lower temperatures. As the voltage amplitude, and consequently the electric field intensity within the dielectric material, increases, it amplifies the dielectric losses, as demonstrated in Figure 7.

In summary, as the temperature of the dielectric material increases, ε_r, and the resistivity values of the dielectric material and semiconductor layers located between the conductor and screen increase. These changes affect the material's equivalent impedance and, therefore, the current value causing the losses. This shift causes losses to decrease up to a certain temperature and then start to increase. The graph in Figure 8 depicts how dielectric loss varies with screen temperature at different frequencies (50 Hz, 150 Hz, 250 Hz, and 350 Hz) while keeping the voltage constant at U_0 (12 kV). Notably, the lowest dielectric loss values for all frequency levels occur when the screen temperature is 50°C.

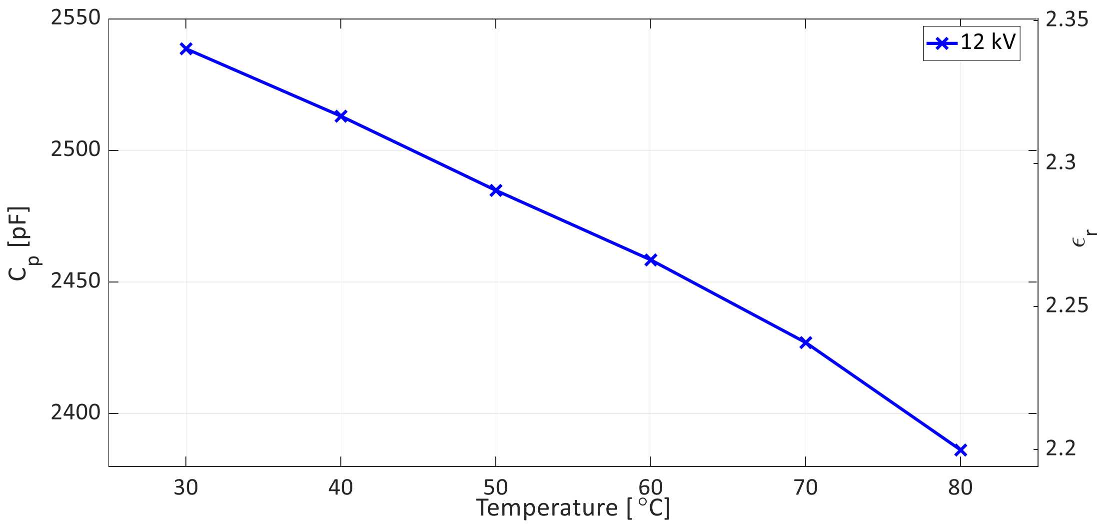

Figure 9. Temperature-dependent change of parallel equivalent capacitance (C_p) and relative dielectric permittivity (ε_r) at 12 kV (f = 50 Hz)

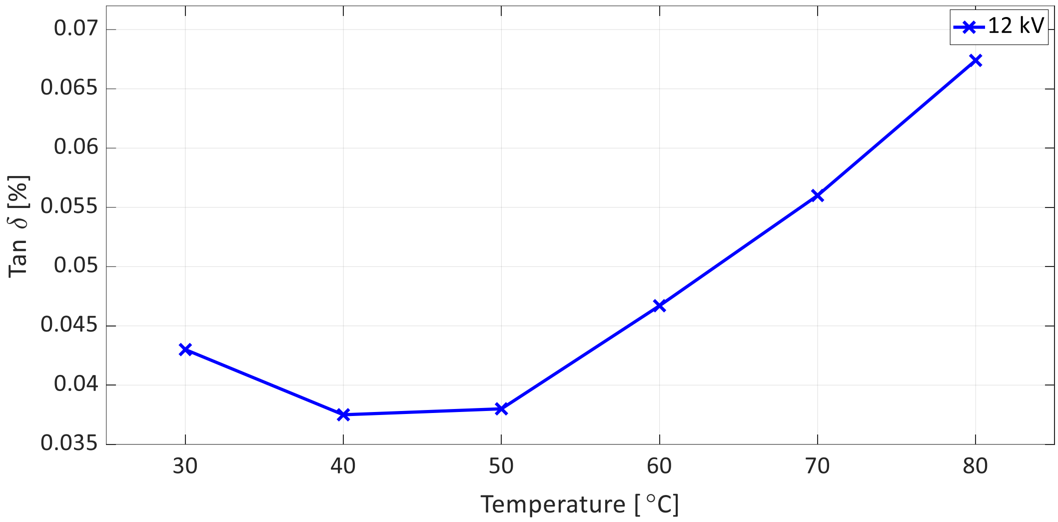

Figure 10. Temperature-dependent variation of dielectric loss factor (tanδ) at 12 kV (f = 50 Hz)

As shown in Figure 9, ε_r decreases as the temperature of the cable screen rises. At 30°C, ε_r is approximately 2.34, but it progressively decreases as the temperature increases. It drops to 2.2 at 80°C. Hence, it is clear that the material's capacitance decreases with higher temperatures, as shown in Figure 9. For instance, the cable's capacitance, which measured 2540 pF at 30°C, decreases by 6.1% to 2385 pF when the temperature is increased to 80°C. This implies that as the cable's temperature rises, its capacitive reactive power decreases.

In Figure 10, the change in tanδ is observed depending on the screen temperature. This is considered at a frequency of 50 Hz and a measurement voltage of 12 kV. The graph in the Figure 10 represents a single case, as they all exhibit very similar behavior under various frequencies and voltages, making the trend more apparent. At 30°C, tanδ is 0.043% and decreases to approximately 0.035% at around 40°C as the temperature rises. It remains relatively constant between 40°C and 50°C. However, beyond 50°C, tanδ of the cable insulation rises quickly.

This change is attributed to the fact that temperature variation has a more substantial impact on active power losses compared to reactive power. Since tanδ quantifies the ratio of active losses occurring within the dielectric material to its capacitive reactive power based on material capacity, it's reasonable to assume that active power losses follow a similar pattern with temperature. In essence, the temperature of the insulation layer significantly affects and dominates active power losses, explaining the resemblance in the patterns of p_k and tanδ concerning temperature.

3.3 Measurement Results Based On Frequency

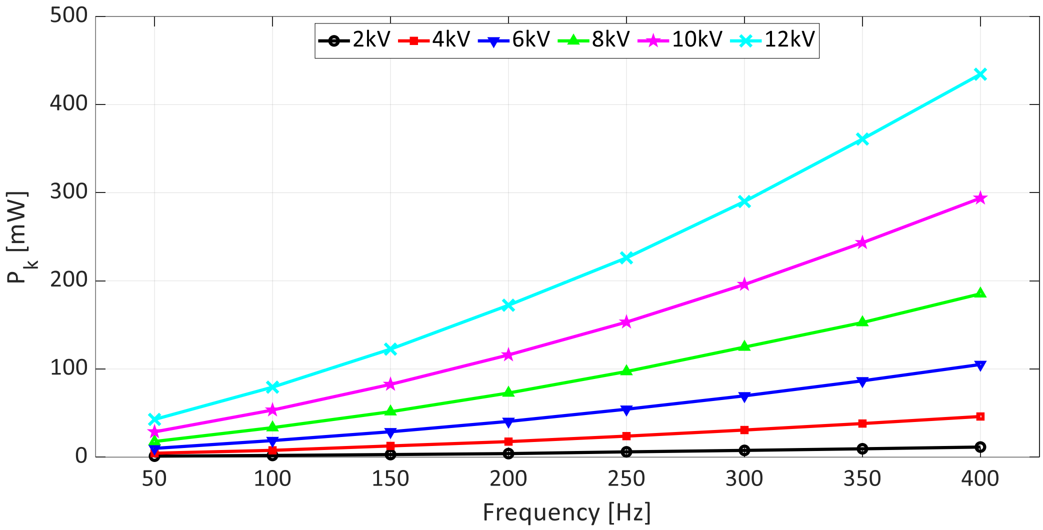

Figure 11. Frequency-dependent change of dielectric loss (p_k) at various voltages (T = 50°C)

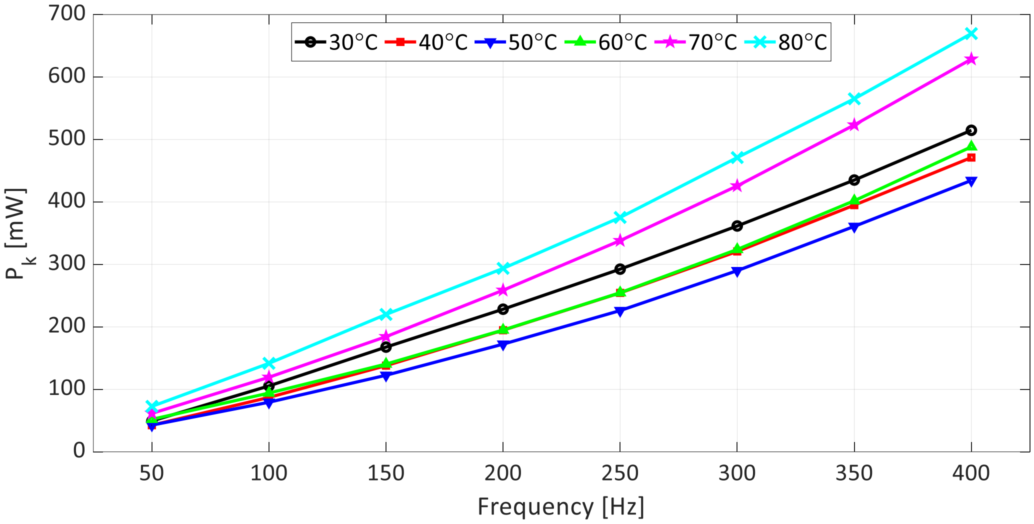

Figure 12. Frequency-dependent variation of dielectric (p_k) at various temperatures (U= 12 kV)

The graph in Figure 11 illustrates how dielectric loss changes with frequency when measurements are conducted at a constant temperature of 50°C with various voltage values. As previously discussed, an increase in voltage results in a quadratic increase in dielectric loss, but this time, with a constant voltage and an increasing frequency, we observe a linear growth in dielectric losses. There are two primary reasons for this nearly linear increase in dielectric losses with rising frequency:

- Decrease in Capacitive Reactance: With increasing frequency, the capacitive reactance of the dielectric material decreases. Consequently, the equivalent impedance of the dielectric material also decreases. As a result, when the frequency increases while maintaining a constant voltage, more current flows through the material, leading to higher dielectric loss values.
- Polarization Losses: At a constant voltage, as the frequency rises, polarization losses within the dielectric material also increase. As frequency increases, the atomic and molecular movements induced by the electric field intensify. However, the predominant factor contributing to this frequency-related increase in losses is conduction.

Figure 12 illustrates how dielectric loss changes with frequency at different screen temperatures. Increasing the frequency from 50 Hz to 400 Hz leads to higher dielectric losses. When measurements are made at various temperature levels, it's seen that dielectric losses increase from 30°C to 50°C. However, there is a decrease when comparing temperatures within this range (for example, the loss at 40°C compared to that at 30°C). Nonetheless, it's observed that losses increase after 50°C. The reason behind this increase in losses as frequency rises lies in the amplified current passing through the conductor - screen. Consequently, this leads to increased conduction losses within the insulator and between the inner and outer semiconductor screens. Additionally, within all these layers, frequency-dependent polarization losses also occur.

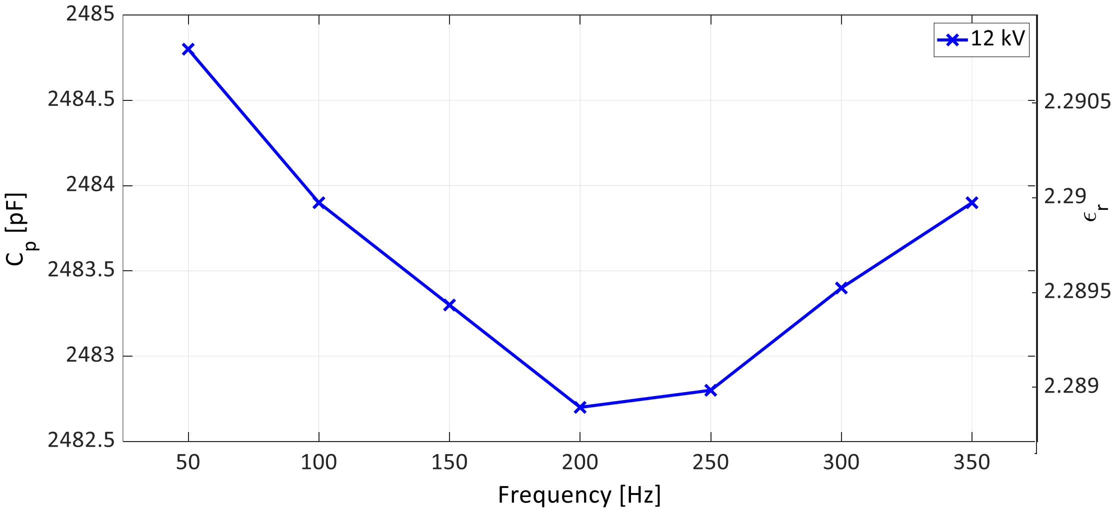

Figure 13. Frequency-dependent change of parallel equivalent capacitance (C_k) and relative dielectric permittivity (ε_r) at 12 kV (T = 50°C)

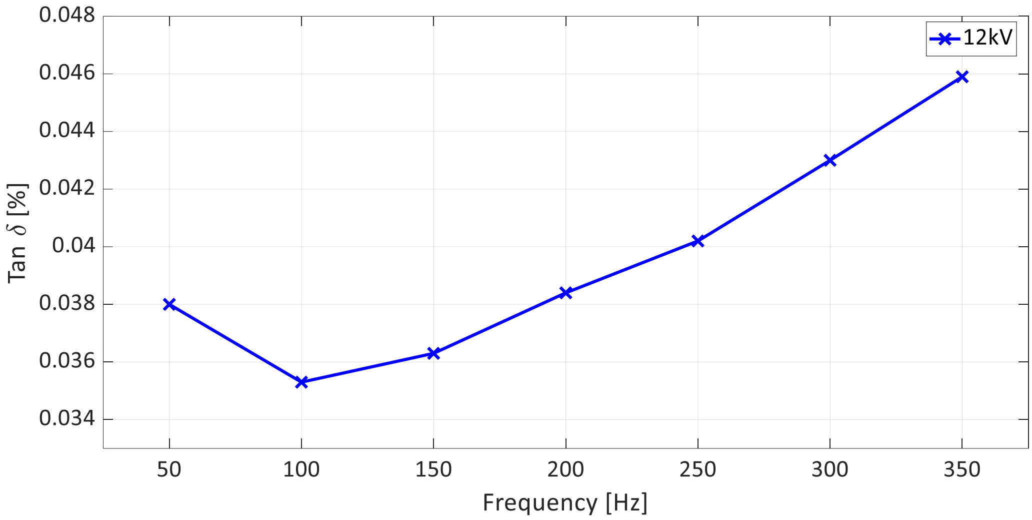

Figure 14. Frequency-dependent variation of dielectric loss factor (tanδ) at 12 kV (T= 50°C)

To investigate the variation in tanδ observed in previous measurements at specific frequencies, the shift in C_p concerning frequency was measured. In Figure 13, C_p and ε_r changes with frequency are demonstrated at U_0 voltage (12 kV) and a screen temperature of 50°C. At 50 Hz, material's capacitance was measured at 2484.8 pF. As the frequency was increased, the cable's capacitance decreased until it reached 200 Hz. At 200 Hz, the cable's capacitance was measured at 2482.7 pF, signifying a 0.9% reduction in cable capacitance when moving from 50 Hz to 200 Hz. However, as the frequency was increased from 200 Hz to 350 Hz, the cable capacitance increased by nearly 0.05%.

The change observed at 200 Hz is ascribed to distinct responses of polarization movements in the dielectric material at different frequencies. The relative dielectric coefficient of the dielectric material varies with shifts in both temperature and frequency. Changes in temperature have a stronger impact compared to changes in frequency, and this similarity becomes more noticeable at higher frequency ranges. When evaluating relative changes within the examined frequency range (50 Hz - 350 Hz), it can be deduced that the effect of varying voltage frequency on C_p and ε_r is limited.

Figure 14 displays the change in tanδ with respect to frequency. Measurements carried out at 12 kV voltage and a screen temperature of 50°C revealed that tanδ decreased from 0.038% to 0.035% as the frequency increased from 50 Hz to 100 Hz. Beyond 100 Hz, tanδ exhibited nearly linear growth up to 400 Hz. When considering the overall shift, it's clear that the tanδ parameter doesn't follow a linear trend as the frequency increases. Existing literature describes two equivalent circuit models (parallel and series) for tanδ. Compared to the parallel circuit, tanδ increases with rising frequency, but when compared to the series circuit, it decreases. The decrease in the tanδ up to a certain frequency, followed by an increase, indicates a different circuit structure corresponding to different frequency values.

4. Conclusion

This study aimed to understand how MV cables, used in distribution networks, behave under different conditions like voltage (ranging from 0.5 kV to 12 kV), frequency (from 50 Hz to 400 Hz), and temperature (between 30°C and 80°C). These conditions mimic what the cables could experience in real-world operation. The research discovered that increasing the applied voltage exponentially raised dielectric losses. This increase wasn't just from conduction losses but also polarization losses, particularly after around 8 kV. Similarly, the study noted an increase in tanδ within the same voltage range, although it stabilized after about 8 kV. This indicated that increasing the voltage within this range didn't affect cable capacity or relative dielectric coefficient for fixed temperature and frequency. The study also showed that variations in voltage harmonics in MV networks affected dielectric parameters, introducing additional losses. Moreover, changing the frequency altered cable capacitance, with a noticeable reduction up to 200 Hz and a slight increase afterward. This change was due to polarization losses and losses in both inner and outer semiconductors. The research found that reactive power of MV cables could differ under various load conditions within the distribution system. This was due to changes in temperature when keeping voltage (12 kV) and frequency (50 Hz) constant. When temperatures increased from 30°C to 80°C, dielectric losses decreased from 30°C to 40°C, then increased. The most optimal working temperature range for minimizing dielectric losses was found to be between 40°C and 50°C. Improving the thermal, electrical, and physical properties of MV cables' semiconductor and dielectric material within this temperature range could further reduce dielectric losses. Overall, the study provided valuable insights into how MV cables perform under different operational conditions, allowing for a comparison between the dielectric parameters of cables in use and newly manufactured ones. This could contribute to a more detailed analysis of MV cables' dielectric lifespan and capacitance. In the future, studies can be conducted on designing online condition monitoring systems where cable dielectric parameters can be observed, and the dielectric performance of the cable can be estimated using artificial intelligence methods.

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Conflict of Interest

No conflict of interest was declared by the authors.

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