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Enhancement of Dielectric Strength for Medium Voltage Cross-Linked Polyethylene (XLPE) Cables

Shreya Dhamake[1], Aparna A. Patil[2]

Assistant Professor[1], Studenet[2]

Department of ECE

Yeshwantrao Chavan College of Engineering (YCCE), Nagpur

Corresponding Author's E-mail: *patilaparna18april@gmail.com*

Abstract

The varieties of polymeric materials used in medium voltage cables, which are considered to be the foundation of the power system, are of importance to energy distribution firms. This study attempted to improve the electrical characteristics of cross-linked polyethylene (XLPE) after adding inorganic fillers such as Silica (SiO2) filler at 10%, 20%, 30%, and 40% concentration percentages. The samples' dielectric strength was evaluated under various heat settings (0, 25, and 100 C0) to imitate various types of environments. Thermal ageing is simulated for one week at various temperatures (70, 100, and 120 C0) to explore the influence of increased temperature stressors on the electric characteristics of XLPE in a thermal drying oven following the addition of Silica filler. Curve fitting is used to select the best relationship between dielectric strength rates for each temperature state and various Silica filler percentages. It was discovered that the maximum value of dielectric strength for XLPE may be produced with a 30% SiO2 filler [max. at 70 Co (30.07kV/mm)]. Polynomial regression using MATLAB code was used to determine the appropriate percentages of SiO2 filler and the greatest dielectric strength value. This regression technique is a kind of linear regression that includes higher order powers of an independent variable (2nd, 3rd, etc.) and defines a link between an explanatory variable and a response variable.

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Keywords: *(XLPE) Cables, dielectric strength, various temperatures, power system, Polyethylene.*

INTRODUCTION

Underground cables are a critical component of any power distribution system. These cables are either installed in ducts or buried in the ground. Unlike overhead lines, air is not included in the insulation; therefore the conductor must be totally insulated. This implies that the cable must be chosen depending on the losses, costs, and environmental conditions that surround [1]. The integrity of cables' polymeric insulation and jacket materials is a crucial component determining their safety and dependability [2].

Degradation of insulating materials may occur during manufacture owing to the heat to which the materials are subjected. Some elements, such as plastic type, production temperature, and the compounds utilised, have an impact on the final product. The output goods should be retained as high quality as feasible by avoiding insulation deterioration as much as possible.

XLPE is a low density polyethylene (LDPE). In the absence of a filler, it is combined with dicumyl peroxide 4-methoxy phenol (3 wt percent) as a cross-linking agent to produce XLPE (ASTMF876-10el). To make XLPE Composites with varying silica ratios (10, 20, 30, and 40% by weight) (SiO2). For electrical tests, all samples are examined in accordance with (IEC 60156).

Polymeric materials used for electrical insulation must not only have acceptable physical qualities, but they must also have adequate electrical properties. 01 which is concerned with the so-called charge trapping event in dielectric and insulating materials [3–4].

Power cable ageing is influenced by a variety of causes, some of which are internal due to the flow of energy and others which are external due to the environment. These issues include current intensity, mechanical wiring systems, water, and thermal ageing. The mechanism of cable ageing is largely carried out by the temperature of the insulating substance. The increase in temperature hastens the chemical reaction of the insulator and hastens the process of insulator breakdown induced by other ageing causes [5–6].

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The surrounding environment, operational circumstances, and the load attached to the cable are all elements that might have an impact on the cable. As a result, the core, insulating layer, and surface will all heat up. The temperature rises as one gets closer to the core. When the current running through the cable exceeds its rated capacity in long-term over-load operation, the temperature of the core rises excessively. Under over-heat temperatures, the ageing of the cable insulation material accelerates; insulation breakdown may occur; hence, the core temperature should be utilised as the ageing temperature of the cable. The cable core temperature is calculated based on the cable's actual operation and the comparable external temperature [7].

To increase stress and minimise material life, the endurance test was established at high ac field by testing transformer (HV transformer 9105-terco) and high temperature by ageing oven (heraeus-6450hanau). Before the test, all samples were conditioned to eliminate any contaminants or humidity. The least squares approach (regression analysis) is used to analyse findings by selecting the polynomial that minimises the sum of squares of these mistakes.

Regression analysis is a statistical technique used to investigate correlations between variables. A regression analysis is a statistical approach used to identify the linear connection between two or more variables. Regression is largely used for forecasting and inferring causal relationships. Regression, in its most basic (bivariate) form, depicts the connection between one independent variable (X) and one dependent variable (Y) (Y). Regression therefore demonstrates how variation in one variable co-occurs with variation in another. One of the goals of the software engineering community is to build usable models that reliably predict development effort [8]. Indeed, putting together a single global model may be quite challenging. Non-linear regressions reduce the space into smaller sections where interactions are more manageable [9].

This study can identify the appropriate curve or line that introduces the preferred fit of collected data points. This curve or line, whether linear, parabolic, or other, is used to illustrate the predicted direction of data. Specialists use a variety of approaches to carry out regression analysis.

The purpose of this research was to investigate the effects and repercussions of

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adding an inorganic filler (silica filler) to XLPE on the electrical performance of cross-linked polyethylene used in medium voltage cables. These effects may be observed by testing the dielectric strength of XLPE at various temperatures and filler weight percentages.

MATERIALS AND METHODS

The preparation of XLPE is affected by several elements such as the XLPE ratio, the kinds and concentrations of filler, and the qualities of the base material and final product. Samples were prepared in the National Research Center's polymers and pigments department's laboratory (NRC). Polymer composite was created by combining various ratios of Silica filler (0, 10, 20, 30 and 40 wt. percent). The samples were prepared at room temperature (25°C) until curing happened. Figure 1 depicts the dielectric strength experimental setup in an HV laboratory (1).

The dielectric strength test was carried out in accordance with ASTMD149 and IEC6024 standards. As illustrated in Fig. 1, the electrodes are two stainless steel cylinders with a diameter of 25 mm at room temperature (2). The voltage was gradually raised at a rate of 1 kV/s until breakdown occurred, which is a measure of the dielectric strengths of the samples. Ten specimens are made and examined for each type of specimen. To evaluate the performance of the samples, the median value of the ten test results is used, and the odd values are excluded.



Figure 1: Dielectric strength experimentation in the HV laboratory

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Figure 2: Two stainless steel electrodes are made up of supporting arrangements and manually actuated gear.



Figure 3: The HV 9103 control desk comes with measurement tools and a trigger device.

The dielectric strength is calculated by dividing the breakdown voltage by the sample thickness. The data is provided in (kV/mm) and was obtained by measuring a circular sample with a thickness of 1 mm and a diameter of 50 mm.

A greater dielectric strength signifies a higher grade of insulator, which this research attempts to maximise. Figure 3 shows the control desk, which comprises measurement tools utilised in our investigations.

RESULTS AND DISCUSSIONS

Temperature-Related Dielectric Strength Measurements

The dielectric strength of an insulating material is the largest amount of electric field intensity that the insulator can withstand internally without losing its insulating qualities until the insulator breaks down. Failure occurs when too much current flows through the material, resulting in fractional destruction. It is scientifically acknowledged that the greater the dielectric strength, the better the insulator's efficiency.

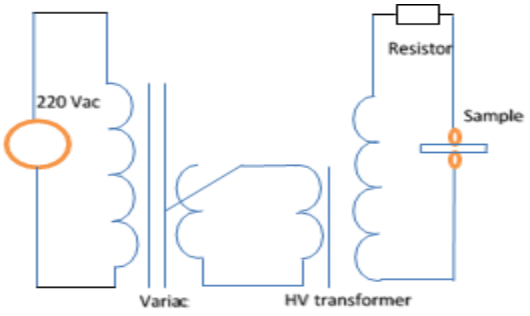


Figure 4: Circuit schematic for dielectric strength testing.

The dielectric strength of XLPE have been studied under several environment conditions, i.e.: 0°C, 25°C (room temperature) and 100 °C with different

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percentages of filler which is (SiO2 filler),Fig (4) shows the circuit used for dielectric strength test.

Addition of SiO2 filler

Average dielectric strength (kV/mm) for XLPE with different SiO2 filler percentages at variant thermal conditions, i.e. 0°C ,25°C (room temperature) and 100 °C shown in table (1) and drawn in figure (5). It can be noted that the dielectric strength of XLPE was improved by adding SiO2 filler. It can be concluded from the results in table (1) that:

When the Sio2 filler was increased from 10% to 30 % the value of dielectric strength increased from 22.9% to 38.8% compared to XLPE sample without adding any filler percentage.

Then after adding more filler (from 30% to 40 %), the value of dielectric strength of XLPE decreased from 38.8% to 26.8% compared to XLPE sample without adding any filler percentage.

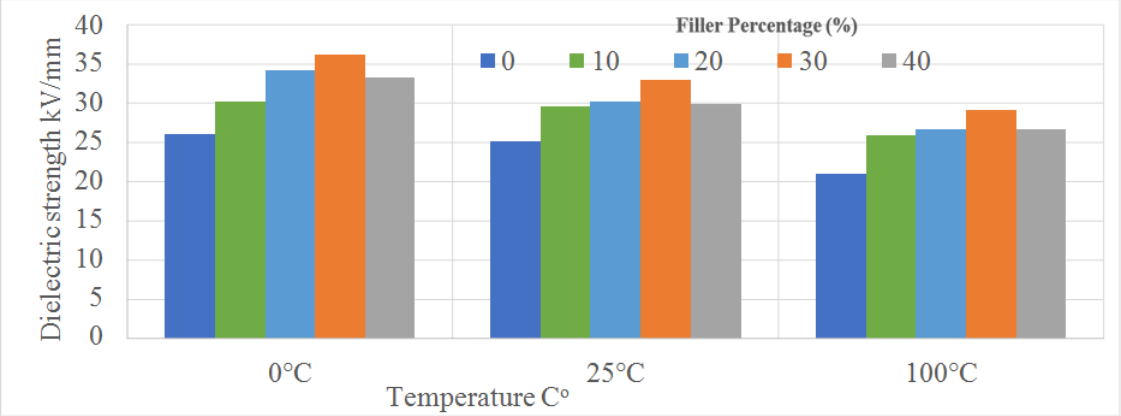


Figure 5: At different temperatures, there is a relationship between dielectric strength (kV/mm) and filler percentages.

Table 1: Dielectric strengths (kV/mm) for XLPE with various SiO_2 filling percentages

SiO2 filler percentages (%)	The mean dielectric strength (kV/mm) at different temperatures.		
	0°C	25°C	100°C
0	26.04	25.16	21.02
10	30.24	29.64	25.83
20	34.15	30.18	26.74
30	36.18	32.98	29.17
40	33.21	29.87	26.66

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Thermal Ageing and Dielectric Strength Measurements

The most often utilised method for the accelerated thermal ageing format is the accelerated thermal ageing oven [10-11]. It primarily employs fast heating in the oven to imitate the ageing state of the cable insulation material in real-world usage and compares and evaluates the characteristic value of life, which is significantly connected to longevity [7]. Because of temperature constraints and intervals, three ageing temperatures were chosen, namely 70 °C, 100 °C and 120°C, where after one week of exposure to these ageing temperatures, the average dielectric strength (kV/mm) of XLPE with varied SiO_2 filler percentages was evaluated; the findings are presented in table (2) and depicted in fig (6).

After each ageing process (168 hrs), samples were placed in the constant room temperature at 25 C°, it observed from results that when SiO_2 filler percentage increased from 10% to 30 % ,the value of dielectric strength increased from 22.9% to 38.8% compared to XLPE sample without adding any filler percentage.

Table 2: After one week, the average dielectric strengths (kV/mm) of samples at various temperatures

SiO2 filler percentages (%)	Average of dielectric strength (kV/mm) at variant temperatures		
	0°C	**25°C**	**100°C**
0	22.81	20.42	19.13
10	26.22	24.85	22.11
20	27.94	23.87	23.16
30	30.07	27.55	25.17
40	28.15	22.01	22.91

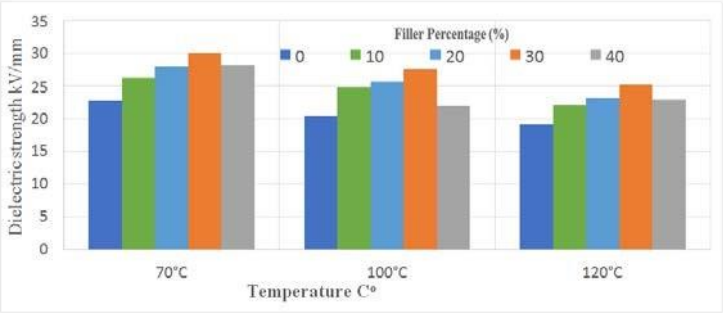


Figure 6: After one week of ageing, the relationship between dielectric strength (kV/mm) and filler percentages was established

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Using the MATLAB tool for curve fitting (polynomial regression analysis), the highest curve fitting for the test results may be expressed by a 3rd degree polynomial equation to minimise errors as much as feasible. It may go into further detail on each scenario of exposing samples to each degree of ageing temperature for one week, as illustrated below:

At 70 ^{O}C Temperature Level

The Effect of filler addition on dielectric strength and the observed error between actual and predicted dielectric strength (kV/mm) after one week ageing 70 ^{O}C are shown in table (3) and drawn in fig (7). The equation of curve fitting results of blends at that case, can be determined as follows:

$$D7700 = -0.0001967P^{33} + 0.0044786P^{22} + 0.269P + 22.9$$

Where D70 parameter is the dielectric strength value (KV/mm) at 70 ^{O}C condition, P is the percentage of concentration of Silica filler in the samples.

$$Error_{70} = Actual\ DS_{70} - Predicted\ DS_{70}$$

Where $Error_{70}$ *is the* observed error between actual and predicted dielectric strength at 70 ^{O}C (DS70) the method of least squares chooses the polynomial that makes the sum of the squares of these errors as small as possible.

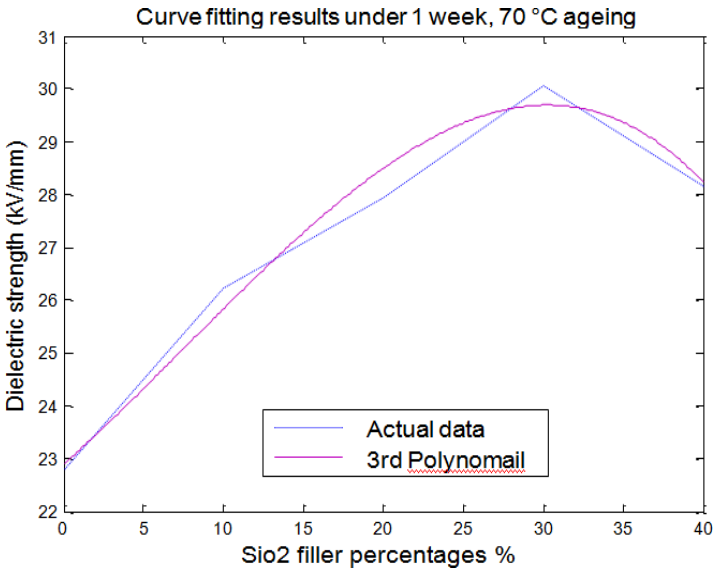


Figure 7: After one week of ageing 70 ^{o}C, the effect of filler addition on dielectric strength.

Table 3: Observed error between actual and predicted dielectric strength at 70^{o}C

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Actual dielectric strength (KV/mm)	Predicted70 dielectric strength (KV/mm)	Error70 value
22.81	22.9	-0.09
26.28	25.84	0.38
27.94	28.49	-0.55
30.07	29.69	0.38
28.15	28.23	-0.08

At 100 ºC Temperature Level

The Effect of filler addition on dielectric strength and the observed error $Error100$ between actual and predicted dielectric strength (DS_{100}) at 100 ºC after one week ageing are shown in table (4) and drawn in fig (8). The equation of curve fitting results of blends at that case, can be determined as follows:

$$D_{10000} = -0.0003175P^{33} + 0.005564P^{22} + 0.3252P + 20.61 \quad (3)$$

$$Error_{100} = Actual\ DS_{100} - Predicted\ DS_{100} \quad (4)$$

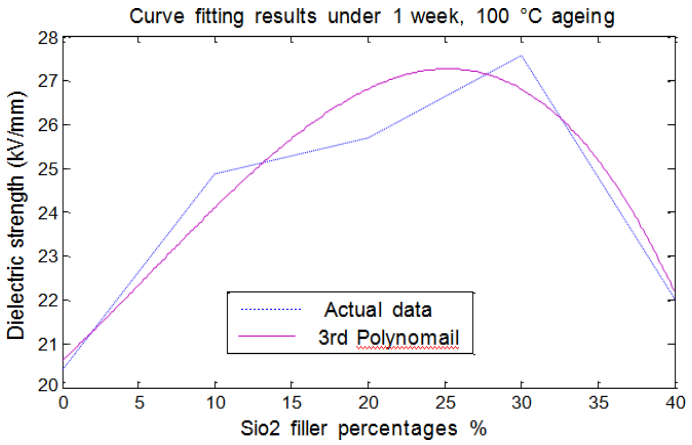


Figure 8: After one week of ageing 100ºC the effect of filler addition on dielectric strength.

Table 4: Observed error between actual and predicted dielectric strength at 100 ºC

$Actual_{100}$ dielectric strength (KV/mm)	$Predicted_{100}$ dielectric strength (KV/mm)	$Error_{100}$ value
20.42	20.61	0.18
24.85	24.1	0.75
25.67	26.79	-1.12
27.55	26.8	0.75
22.01	22.19	-0.18

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At 120 ^{O}C Temperature Level

The Effect of filler addition on dielectric strength and the observed error between actual and predicted dielectric strength (DS100) at 120 ^{O}C after one week ageing are shown in table (5) and drawn in figure (9). The equation of curve fitting results of blends at that case, can be determined as follows:

$$D_{12200} = -0.000195P^{33} + 0.0049P^{22} + 0.2105P + 19.25 \quad (5)$$

$$Error_{120} = Actual\ DS_{120} - Predicted\ DS_{120} \quad (6)$$



Figure 9: Effect of filler addition on dielectric strength after one-week ageing at 120 ^{O}C.

Table 5: Observed error between actual and predicted dielectric strength at 120 ^{o}C

Actual120 dielectric strength	Predicted120 dielectric strength (KV/mm)	Error120 value
19.13	19.25	-0.12
22.11	21.65	0.46
23.16	23.85	-0.69
25.17	24.71	0.46
22.91	23.03	-0.12

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It was discovered in the prior three situations that raising the SiO_2 filler % steadily raised dielectric strengths until a certain value was reached, at which point it was lowered. This is due to the saturation that occurred in the XLPE lattice and the increased addition of SiO_2 filler to XLPE rendered the composites brittle, resulting in a loss in dielectric strength, as well as the growing flow of leakage current, which raises the possibility of break down.

CONCLUSIONS AND RECOMMENDATIONS

According to the findings of this study, the appropriate addition of SiO_2 filler resulted in some improvement in the electrical characteristics of XLPE, where the dielectric strength of XLPE was enhanced. Without thermal ageing, the greatest dielectric strength for XLPE may be reached with a 30% SiO_2 filler percentage [max. at 0 Co (36.18kV/mm)]. After exposing samples to thermal stress for one week (168 hours), the greatest value of dielectric strength for XLPE can be reached with a 30% SiO2 filler percentage [max. at 70 Co(30.07kV/mm)]. Suitable percentages of SiO2 filler must be added to XLPE, with more filler leading to a decrease in XLPE dielectric strength. The decrease in XLPE dielectric strength can be explained by exposing the samples to different high temperatures for an extended period of time, which causes the physical structure of the samples to change and become more rigid than before, where colour begins to change and composite bonds begin to break. Finally, it suggests that SiO_2 filler be utilised in the use of XLPE subterranean cables used in power companies for medium voltage cable (11 kV up to 66 kV).

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