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Combined Effects of Insulation Thickness and Wire Curvature Radius on Maximum Electric Field Intensity for Domestic Wires

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ABSTRACT

The electric field intensity is influenced by several factors, including the thickness of the dielectric material and the magnitude of the applied voltage. In scenarios involving curved wires or cables, the radius of curvature plays a significant role in determining the electric field intensity. To minimize the need for conducting numerous experiments or simulations to ascertain the maximum electric field intensity under varying conditions, a mathematical model can be employed. In the present study, the geometric configuration of the PVC curved wires was modelled using Finite Element Analysis (FEA) software (COMSOL Multiphysics). The simulation involved varying the insulation thickness between 0.6 mm and 1.0 mm, and the wire curvature radius from 0.4 mm up to 0.7 mm. The study reveals that a multi-linear regression model effectively predicts maximum electric field intensity based on insulation thickness and wire curvature radius, achieving a prediction error of only 1% to 3%. This analytical approach allows for the assessment of electric field intensity without the need for computer simulations or physical measurements for each variation in insulation thickness and curvature during domestic wire design.

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1.0 Introduction

The electric field intensity within insulated conductors is a crucial aspect of electrical engineering, particularly when considering the performance and reliability of insulation systems. Various studies have examined how different parameters affect the distribution of electric fields in the insulating materials that encase conductors. Noteworthy research contributions include those by Lachini et al. (2010), Salem et al. (2019), and Uydur et al. (2018). While these investigations offer significant insights, many have concentrated on the effects of defects in electrical power components on electric field distribution. For example, Lachini et al. (2010) conducted a study that explored the electric field distribution in cables influenced by moisture and air voids. Their aim was to evaluate how humidity and air cavities impact the electric field intensity within cable insulation systems, utilising the Finite Element Method (FEM) for their analysis. Their findings revealed that the presence of air cavities can lead to localised increases in electric field intensity, which may result in breakdowns within the insulator due to potential water tree phenomena triggered by humidity.

There are numerous other studies that explored the effects of insulation defects, including research conducted by Nekahi et al. (2015), Ghiasi et al. (2021), Syakur et al. (2008), Musa et al. (2021), Andrei et al. (2014), Zhang et al. (2022), Nadolny (2022), and Illias et al. (2013). The results from most of these investigations reveal a significant correlation between insulation defects and electric field distribution. Specifically, these defects cause an uneven distribution of the electric field within the insulating material, leading to certain areas experiencing markedly higher electric field intensity than others.

A research study by Salem et al. (2019) investigated the impact of insulator geometrical profiles on electric field distribution under polluted conditions, considering scenarios both with and without water droplets. The study specifically analysed four different profiles of 11 kV composite insulators. To conduct their analysis, the researchers utilised COMSOL Multiphysics, software based on Finite Element Analysis, which facilitated comprehensive modelling of both standard and optimised designs of insulators. The results indicated that optimally designed insulators experienced lower maximum electric field stresses compared to those with conventional designs when exposed to polluted and wet environments. The findings from this study emphasise the necessity for enhanced design strategies to ensure better functionality and durability of electrical insulators when faced with adverse conditions.

Other studies have explored the impact of geometric parameters on electric field intensity. One notable research project conducted by Ma et al. (2018) established a theoretical model that integrated experimental test results to examine how insulation thickness influences the breakdown strength of cross-linked polyethylene (XLPE) insulation. The findings indicated that the breakdown field strength increases as the sample thickness rises, specifically within a range of 50 µm to 100 µm. Additionally, another investigation by Ma et al. (2019) focused on the curvature effects on electric field stress in high voltage differentials, particularly in configurations where an electrical conductor is encased in dielectric material. This study analysed how the radius of curvature at the junctions between dielectrics and electrical conductors affects electric field stress. The results showed that the geometry in which the conductor has a shorter curvature radius will experience higher electric field intensity in the insulation region near the curvature corners compared to the rest of the regions.

The study by Kiiza (2024) investigated how the curvature radius on the Polyvinyl Chloride (PVC) wire used in domestic installation affects the electric field distribution. In that study, the researcher developed a mathematical model equation that relates the maximum electric field intensity and the curvature radius. The researcher found that the geometry with a shorter curvature radius tends to have high values of electric field intensity as compared to the geometry with a larger curved radius. Additionally, the findings indicated that the power equation can describe effectively the relationship between maximum electric field intensity and curvature radius, provided that the insulation thickness remains constant.

A comprehensive review of the current literature has indicated a notable deficiency in empirical or theoretical mathematical model equations that can accurately determine the maximum electric field intensity for power lines, including those used in domestic installations. This gap is particularly evident when considering the combined effects of multiple parameters, such as the curvature radius of the wire and the thickness of insulation. Most of the surveyed literature investigated the electric field intensity on the cables or domestic wires by considering possible defects which can occur within the cables or wires. On the other hand, the studies on the effect of geometric configuration focused only on one defect at a time. Therefore, this research seeks to fill this gap by developing a mathematical model equation capable of calculating the maximum electric field intensity while taking into account both the curvature radius of the wire and the insulation thickness.

The results of the simulation were derived using COMSOL Multiphysics, a software based on Finite Element Analysis that facilitates comprehensive modelling and analysis of complex physical phenomena. It is anticipated that the generalised mathematical equations can be employed to optimise the design and installation processes for power cable insulation. This approach could minimise the need for conducting simulations or real-time measurements when assessing whether the expected electric field intensity aligns with the defined design or installation criteria.

2.0 Materials and Methods

2.1 Adding the Geometry in the Model

The specifications of the PVC wire used in domestic installations are provided in International Electrotechnical Commission IEC 60364-1 (IEC, 2005) regarding Electrical Installations of Buildings. This standard outlines general requirements for electrical installations in buildings. According to this standard and as also detailed in Kiiza (2024), the recommended wire size may range from 1.5 mm^2 to 6 mm^2 depending on the types of loads to be supplied by the specific wire, which gives the conductor radius from 0.7 mm up to 1.4 mm. On the other hand, for nominal voltages not exceeding 400 V, the typical minimum insulation thickness for PVC insulated wires ranges from approximately 0.6 mm to 1 mm.

This study employed standard insulation thicknesses ranging from 0.6 mm to 1 mm in the simulation of electric field intensity. The wire curves in practical scenarios may be introduced arbitrarily. However, it is important to select a curvature radius that is not excessively small, as such conditions could introduce sharp points that would significantly disrupt the patterns of electric field distribution.

In situations where the radius of curvature significantly exceeds the thickness of the insulation, achieving complete curvature on both the conductor and insulation surfaces may not be possible. For example, this study demonstrated that it was feasible to attain curvature on both the conductor and insulator with an insulation thickness (t) of 0.6 mm and a curvature radius (r) of 0.7 mm; however, this was not achievable with t = 0.6 mm and r = 0.8 mm, as shown in the zoomed sections of Fig. 1. Therefore, this analysis indicates that for the geometry examined in this study, the wire curvature radius should not surpass 0.7 mm to conduct simulations that consider a minimum thickness of 0.6 mm. This implies that the developed model should only be used to predict the maximum electric field intensity when a curvature radius of at least 0.7 mm is desirable.

The geometry was modelled in COMSOL Multiphysics using a conductor radius of 14 mm, which is ten times larger than the actual size. This approach was taken to mitigate challenges related to meshing and to reduce the computational time that can be prolonged by small particle sizes. The selection of a larger conductor size for simulation purposes, compared to the actual conductor size, does not impact the results because the electric field intensity inside the conductor is zero (Kalluri, 2013).

2.2 Dielectric Material Properties and Boundary Conditions

The electric field intensity can be accurately determined by solving Poisson's equation, as presented in Equation (1), where; ε_0 represents the permittivity of free space or air, while ε_r denotes the relative permittivity of a material in relation to free space or air. Additionally, ρ_v signifies the volume charge density measured in coulombs per cubic meter (C/m³). The operator ∇ is known as the vector operator.

Equation (1) is integrated within the COMSOL Multiphysics software platform. To effectively utilize this equation, it is essential to assign the relative permittivity values of the dielectric materials involved, along with specifying the electric potential values at their respective boundaries. As previously mentioned, this study focuses on polyvinyl chloride (PVC) wire, which has a relative permittivity that typically ranges from 3 to 4 (Haynes, 2014).

$$\nabla \bullet (\varepsilon_0 \varepsilon_r \mathbf{E}) = \rho_v \qquad (1)$$

For the purposes of this analysis, an average relative permittivity value of 3.5 was adopted to represent the material properties of PVC.

In terms of boundary conditions for the simulation, the surface of the conductor was assigned an electrical potential of 230 V. Conversely, an electric potential of 0 V was designated for the outer surface of the insulation surrounding the conductor.

The details of COMSOL Multiphysics software can be found in COMSOL. (2011) and description of the geometry is provided in detail in Kiiza (2024).

2.3 Geometry Meshing

The procedure for determining the appropriate mesh element size was detailed in a previous study (Kiiza, 2024). For the geometries considered in this study of which one of them is presented in Fig 2 for insulation thickness of 0.8 mm at curvature radius of 0.4 mm and 0.7 mm, the finer mesh element size was determined as the appropriate mesh element size.

2.4 Validation of the Model

The results from the simulation regarding electric potential and electric field intensity for a straight wire, which were intended to validate a model, were comprehensively discussed in the author's earlier publication (Kiiza, 2024). In that paper, the simulated electric field intensity of a straight conductor encased in PVC insulation material was compared against values obtained from the mathematical expression outlined in Equation (2). In this equation, E represents the electric field intensity, V indicates the potential difference, and d denotes the thickness of the insulation that separates areas of high and low potential. The results by Kiiza (2024) demonstrated a perfect correlation between the simulated and calculated values, confirming that the accuracy of the COMSOL Multiphysics in determining the electric field intensity was 100%.

$$E = \frac{V}{d} \qquad (2)$$

The previously published results in (Kiiza, 2024) focused on the relationship between maximum electric field intensity and the curvature radius of a wire.

In the current study, this analysis has been broadened to examine how both the wire curvature radius and insulation thickness simultaneously affect the maximum electric field intensity.

Figure 1

A Zoomed Portion of the Geometry for Typical Wire Used in Domestic Installation Showing Conductor and Electrical Insulation with Insulation Thickness of 0.6 mm at Curvature Radius of: (A) 0.7 mm, (B) 0.8 mm

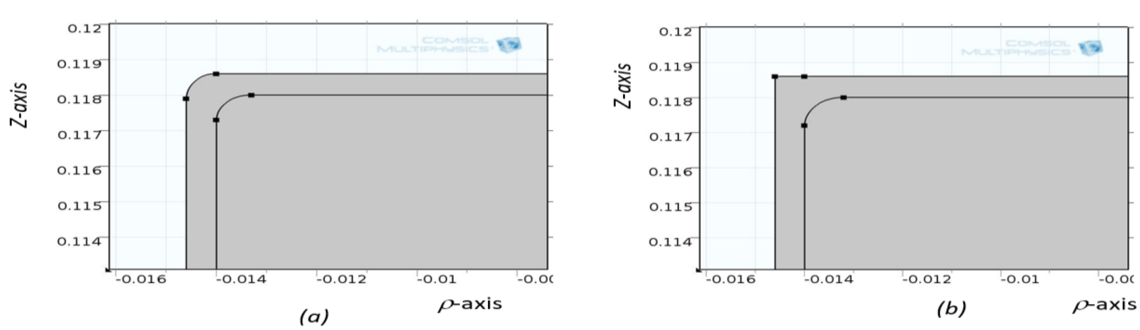
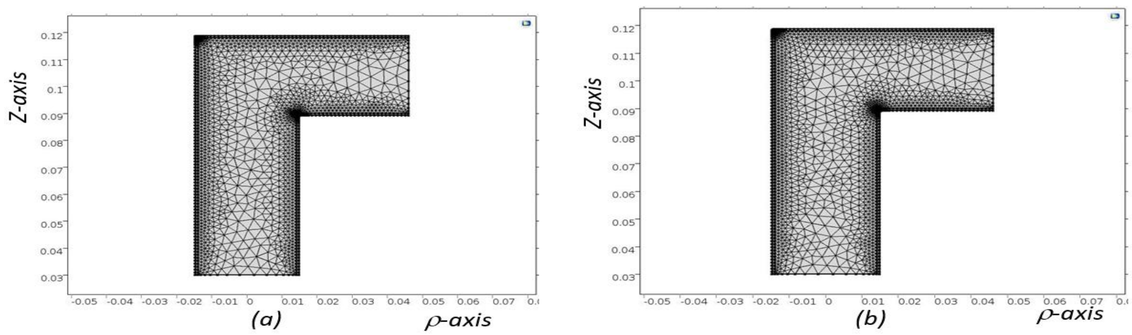


Figure 2
A Geometry for Insulation Thickness of 0.8 mm at Curvature Radius of: (A) 0.4 mm and (B) 0.7 mm after Meshing with a Finer Mesh Element Size with Distances along the Axes Measured in Metres (m)



3.0 Results and Discussion

This section details the simulation results for electric field intensity simulated under stationary conditions, taking into account the combined effects of insulation thickness and the radius of wire curvature. Additionally, it includes a mathematical model equation designed to predict the maximum electric field intensity based on a specified insulation thickness and wire curvature radius.

3.1. Surface Electric Field Intensity as Influenced by Combined Effects of Insulation Thickness and Curvature Radius

The samples surface plots for Electric Field Intensity are presented in Fig 3 and Fig 4. Fig 3 shows the results of electric field intensity at a fixed insulation thickness of 0.8 mm but at the two distinct curvature radii of 0.4 mm and 0.7 mm. On the other hand, Fig 4 shows the electric field intensity at the fixed wire curvature radius of 0.5 mm but at the two distinct insulation thicknesses of 0.6 mm and 1 mm. The results of the simulated maximum electric field intensity for other cases of curvature radii and insulation thicknesses including those from Fig 3 and Fig 4, are summarized in Tab 1.

The results from Fig 3 shows that fixing the insulation thickness at 0.8 mm while varying the wire curvature radius from 0.4 mm to 0.7 mm, reduced the maximum electric field intensity by approximately 18%. On the other hand, fixing the wire curvature radius 0.5 mm but varying the insulation thickness from 0.6 mm to 1.0 mm, as shown in Fig 4 reduced the maximum electric field intensity by approximately 28%.

The results from Fig 3 and Fig 4, and also from Tab 1 clearly indicate that both wire curvature radii and insulation thicknesses affect the magnitudes of electric field intensity in electrical insulation. In the next section, the empirical equation has been developed to investigate how both wire curvature and insulation thickness affect the maximum electric field intensity inside the insulation.

Figure 3
Electric Field Intensity at a Fixed Insulation Thickness of 0.8 mm, while Varying Curvature Radius: (A) 0.4 mm and (B) 0.7 mm, with Distances along the Axes Measured in Metres (m)

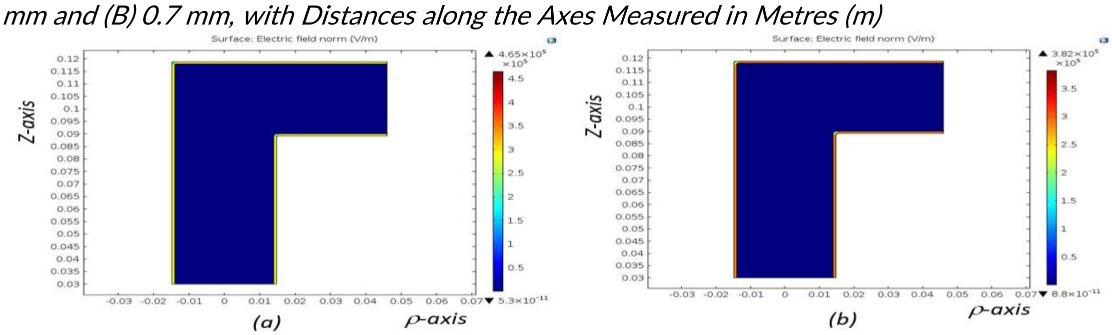


Figure 4

Electric Field Intensity at a Fixed Wire Curvature Radius of 0.5 mm, while Varying Insulation Thicknesses of (A) 0.6 mm and (B)1 mm, with Distances along the Axes Measured in Metres (m)

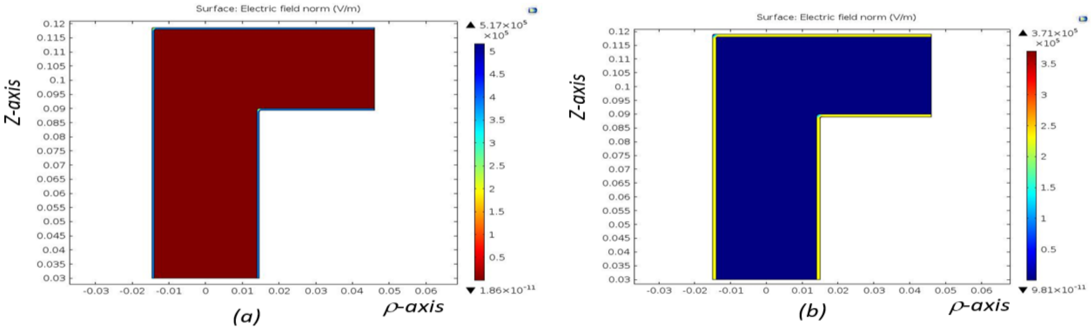


Table 1

Simulated Maximum Electric Field Intensity [V/M] and Corresponding Wire Curvature Radii and Insulation Thicknesses in [mm]

r [mm]	*t* [mm]	E_{max} [V/m] *10^4
0.4	0.6	55.7
0.5	0.6	51.7
0.6	0.6	49.3
0.7	0.6	47.4
0.4	0.7	50.5
0.5	0.7	46.8
0.6	0.7	44.1
0.7	0.7	42.2
0.4	0.8	46.5
0.5	0.8	42.8
0.6	0.8	40.2
0.7	0.8	38.2
0.4	0.9	43
0.5	0.9	39.7
0.6	0.9	37.2
0.7	0.9	35.3
0.4	1	40.2
0.5	1	37.1
0.6	1	34.8
0.7	1	32.9

3.2. Multi-Linear Regression for Establishment of the Mathematical Model Equation Relating Maximum Electric Field Intensity, Wire Curvature Radius and Insulation Thickness

The data in Tab 1 were entered into an Excel spreadsheet for regression analysis, which produced results that are presented in the summary output found in Tab 2.

From the findings detailed in Tab 2, a multi-linear equation presented in Equation (3) can be derived:

$$E_{max}(r,t) = (86.642 - 26.44r - 36.65t)10^4 \text{ V/m} \quad (3)$$

In this equation, *r* represents the wire curvature radius measured in millimetres (mm), *t* denotes the insulation thickness also in millimetres (mm), and Emax signifies the maximum electric field intensity expressed in volts per metre (V/m). Additionally, as indicated in Tab 2, the coefficient of determination, denoted as R Square (R^2), serves as a metric for assessing how effectively the multi-linear regression equation aligns with the actual data. The value of R^2 is calculated to be 0.9801. This high value suggests that the multi-linear regression equation provides an excellent fit for the data, as an R^2 value close to 1 indicates a strong correlation between the model and observed values, while a value closer to 0 would imply a poor fit.

3.3. Validation of Multi-Linear Regression Equation Relating Maximum Electric Field Intensity, Wire Curvature Radius and Insulation Thickness

The validity of the multi-linear regression equation was assessed by calculating the maximum electric field intensity for insulation thicknesses that were not included in the development of the mathematical model. The findings are summarized in Tab 3.

The analysis comparing the simulated maximum electric field intensity (E_{max}) with the predicted values derived from a multi-linear regression model reveals that the predictions are highly accurate. Specifically, for pairs of insulation thickness (*t*) and curvature radius (*r*) not utilized during the development of the regression model, the prediction error was observed to range from 1% to 3%. This level of accuracy suggests that the multi-linear regression equation in Equation (3) is effective in estimating E_{max} within the specified geometric dimensions. This indicates that when simulations or actual measurements are not performed to determine the maximum electric field intensity for a specific insulation thickness and wire curvature radius, the value calculated using the mathematical model in Equation (3) will differ from the true value by approximately 1% to 3%.

Table 2
Summary Output of the Regression Analysis for Data in Tab 1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99
R Square	0.9801
Adjusted R Square	0.9778
Standard Error	0.9215
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	712.057	356.0287	419.3042	3.42E-15
Residual	17	14.4346	0.849094		
Total	19	726.492			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	86.642	1.55834	55.59907	1.13E-20	83.3542	89.9298	83.3542	89.9298
X Variable 1	-26.44	1.84293	-14.3468	6.26E-11	-30.3282	-22.5518	-30.3282	-22.5518
X Variable 2	-36.65	1.45696	-25.1551	6.85E-15	-39.7239	-33.5761	-39.7239	-33.5761

Table 3
Comparison between Simulated and Predicted E_{max} under Different Wire Curvature Radius (R) and Insulation Thickness (T) Values for Testing the Validity of the Multi-Linear Regression

r [mm]	*t* [mm]	Simulated E_{max} [V/m] $*10^4$	Predicted E_{max} by Equation (3) $*10^4$	Prediction Percentage Error
0.45	0.7	48.5	49.1	1
0.55	0.8	41.4	42.8	3
0.65	0.8	33.8	32.8	3

4.0 Conclusion

This paper presents the findings regarding the influence of wire curvature and insulation thickness on the distribution of electric fields within domestic PVC wires. The study utilised finite element-based software, COMSOL Multiphysics, to model the geometry of the wires accurately. The simulation results were visualised using scatter plots, which were subsequently curve-fitted to derive an equation that best represents the data. This approach allowed for a detailed analysis of how varying parameters affect electric field intensity.

The study found that both the radius of wire curvature and the thickness of insulation significantly influence the maximum electric field intensity. However, increasing the insulation thickness while maintaining the same wire curvature radius resulted in a decrease in maximum electric field intensity. In addition, it was found that multi-linear regression analysis demonstrated a high level of accuracy in determining how both the radius of wire curvature and insulation thickness influence the maximum electric field intensity.

Generally, mathematical equations for predicting electric field intensity across varying insulation thicknesses and wire curvature radii will offer significant advantages. These equations streamline the design and installation processes of power cable insulation, reducing the reliance on simulations or real-time measurements when assessing whether the expected electric field intensity aligns with the defined design during cable manufacturing or electrical installations.

5.0 Conflicting Interests

The author declares no conflict of interest.

6.0 References

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