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Original Article

Electric Field Intensity Assessment on Curved Wires for Domestic Installations

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ABSTRACT

The increasing complexity of domestic electrical installations necessitates a thorough understanding of electric field intensity, particularly when dealing with curved wires. This paper presents the results on the assessment of the electric field intensity in curved wire configurations, which are commonly encountered in residential settings due to architectural constraints. This study employs both theoretical and simulation approaches with the help of the Finite Element Based Software (COMSOL Multiphysics). The theoretical and simulations were used for a case of straight wire to allow validation of the model through comparing simulation results with the theoretically computed electric field intensity using mathematical formula. Later on, the COMSOL Multiphysics were used to compute electric field intensity under various curvature radii. The results of maximum electric field intensity against curvature radii were then plotted as scatter in excel and then fitted by the equation from the trendline option. The results show that the curvature of wires significantly influences electric field distribution. The electric field intensity was observed to be much higher for a case of small curvature radius as compared to larger curvature radius. For example, for the type of the geometry presented in this paper to represent the PVC wire used in domestic buildings' electrical installations, the maximum electric field intensity for curvature radius of 0.025 mm was observed to be about 7 times for a case when the curvature radius was 10 mm. In additional, the power equation was found to model well the relationship between the maximum electric field intensity and curvature radius of the geometry presented in this paper.

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INTRODUCTION

Proper electrical installation is essential for extending the lifespan of both the electrical system and the connected equipment (Bayliss and Hardy, 2012). Additionally, it plays a critical role in ensuring the safety of personnel and equipment. In many countries, there exists a regulatory body tasked with ensuring that electrical installations are regulated to ensure quality to all consumers. This is particularly important for low-income, rural, and disadvantaged populations who may otherwise face barriers to accessing these critical services in a required quality. Particularly, in the United Republic of Tanzania, the institution responsible for promoting the availability of regulated energy and water utility services is the Energy and Water Utilities Regulatory Authority (EWURA). The body is tasked with ensuring that all electrical installation activities are conducted safely and in accordance with established standards. It is mandatory for any individual or entity wishing to conduct electrical installation work to obtain a license from EWURA.

This requirement aims to ensure that only qualified personnel perform electrical installations, thereby safeguarding public safety and promoting compliance with technical standards. The licensing process serves several critical functions that include safety assurance, quality control and accountability. Licensed electricians are expected to have undergone training and possess knowledge about safe practices in electrical installations. This reduces the risk of accidents caused by improper installations. In addition, by regulating who can perform electrical work, it helps to maintain a standard of quality across all installations. This includes adherence to national and international codes. On the other hand, licensed electricians can be held accountable for their work, which provides a mechanism for addressing any issues that arise from faulty installations.

Curved wires are often employed in residential settings due to space constraints or structure of the building sections; however, their unique geometrical properties can significantly influence the distribution of electric field (Salem, 2019). In most of the cases, during electrical installations requiring curving of wires, the wire is usually curved at any curvature radius determined arbitrarily. These necessities the study on the effect of curvature radii on parameters that may affect the performance of electrical installations. One of the parameters that may affect the performance of electrical installations is concentrated electric fields in the wire insulation.

The assessment of electric field intensity in curved wires is a critical area of study that intersects electrical engineering and safety standards (Poljak, Doric & Birkic, 2021; Clinch, Healy & King, 2001). Curved wires exhibit unique characteristics compared to straight wires due to the influence of geometry on electric fields distribution. According to Ma, Jones, Mille, & Kozaczek (2019), the radius of curvature of a wire affects its electric field distribution, which can lead to concentration of electric field at some points inside the insulation. Several methodologies have been developed for assessing electric field intensity in curved wires. For example, Finite Element Analysis (FEA) has emerged as a prominent technique due to its ability to simulate complex geometries and material properties accurately. Research by Illias et al. (2013); Cristina & Feliziani (1989); and Musa et al. (2021) highlight how FEA can be utilized to model partial discharge pulses, compute multiconductor cable parameters, and simulate electric fields distribution in a three-core XLPE cable with multiple cavities, respectively. Specifically, in the study by Musa et al. (2021) it was observed that the electric fields concentrated more in the cavities of the XLPE cable than on the rest part of the insulation.

Through the surveyed literature, it has been observed that little has been done in modelling the real wire configurations used in domestic installations by investigating the effect of curvature radius on the maximum electric field intensity in the typical insulation type, i.e. Polyvinyl Chloride (PVC) wire that is used in domestic installations. The present study was organized into two main cases. The first case compared the electric field distribution in the insulation for electrical wire of a small curvature radius (2.5 mm) with that of larger curvature radius (10 mm). The second case simulated the domestic wire model under various curvature radii that later helped to establish mathematical model equation that can be used to predict the maximum electric field intensity for any other curvature radius. The study utilized the Finite Element Based Software (COMSOL Multiphysics, Version 4.2). The detailed presentation of the features of COMSOL Multiphysics can be found in its manual (COMSOL, 2011). The model was first validated by considering a uniform PVC wire geometry in which the magnitude of electric field intensity obtained through simulation was compared with the result obtained through the mathematical formula.

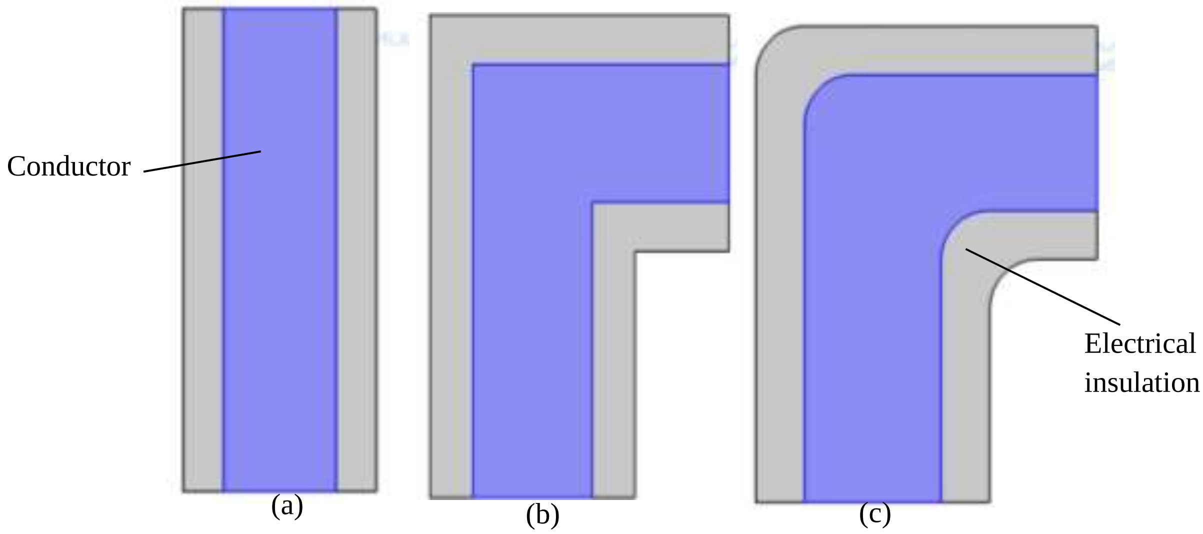
RESEARCH METHODOLOGY

In this section, the set-up of the configuration used to model the domestic wire is described in details. The method used to validate the results is also presented. In addition, the procedures of modelling the domestic wires in FEM software (COMSOL Multiphysics) are presented.

Geometry of the Domestic Wire

The geometry of the insulation body surrounding the cylindrical conductor is shown in Figure 1. Such configurations have been used to mimic the domestic wires. The Finite Element Method based software, COMSOL Multipysics of version 4.2, has been used in analysing electric field distribution in the insulation. With COMSOL Multiphysics software, it is possible to simulate various problems by considering some combination of studies such as *a.c./d.c.*, acoustics, fluid flow, heat transfer, optics, plasma, and mathematics. These studies are referred to in COMSOL Multiphysics as modules. The electric field intensity in the insulation body is computed using Electrostatics interface under a.c./d.c. module. The magnitudes of electric field intensity in the insulation body are influenced by the electric potential distributions in the dielectrics as $\mathbf{E} = -\nabla V$, where **E** is electric field intensity.

Figure 1: *A geometry for typical wire used in domestic installation showing conductor and electrical insulation: (a) uniform wire, (b) curved wire with small curvature radius (2.5 mm), and (c) curved wire with larger curvature radius (10 mm).*



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There are a number of steps to be followed when modelling electrical components in COMSOL Multiphysics. These include adding the geometry in the model, drawing the geometry, adding equations, defining dielectric material properties, adding excitation voltage and initial conditions to the model, geometry meshing, and finally simulation to see the results.

Adding the Geometry in the Model

The 2D that has been arrived after omitting the ϕ-axis has been used in this study. This is due to the reason that the electric fields are not rotational and therefore total electric field intensity combines the components from only the two axes, i.e. from the radial and axial axes. The horizontal axis in this case represents the ρ-components and the vertical represents the *z*-components.

The International Electrotechnical Commission (IEC) has established various standards that dictate the requirements for electrical installations, including those related to wire insulation. The most relevant standard for low-voltage wiring, IEC 60364-1 (IEC, 2005), outlines general requirements for electrical installations for buildings. The International Electrotechnical Commission (IEC) provides guidelines that help to determine the appropriate wire sizes based on their intended use and the current they will carry. As examples, the minimum recommended wire size for lighting circuits where the lower current loads are expected is 1.5 mm^2 and for general-purpose sockets, especially in areas like living rooms or bedrooms, a wire size of 2.5 mm^2 is typically used. On the other hand, appliances such as washing machines and dryers require much power and therefore the larger wire size of around 4 mm^2 is required. Some cases may necessitate even larger wires, for example high-power appliances like ovens and air conditioning units may require a minimum size of 6 mm^2. In additional, the standard specifies the recommended insulation thicknesses.

For a nominal voltage not exceeding 400 V, the typical minimum insulation thickness for PVC insulated wires is around 0.6 mm to 1 mm. For a case of XLPE insulated wires, the thickness may range from approximately 0.8 mm to 1.5 mm depending on specific applications and environmental factors. In this study, a Polyvinyl Chloride (PVC) material property was used. However, the dimensions were scaled up by a factor of 10 to avoid difficulties that arise in meshing as well as longer computational time associated with tiny geometries. Therefore, the geometry was implemented in COMSOL Multiphysics with a thickness of 10 mm and conductor size of 14 mm radius. The geometries under these conditions are shown in Figure 2. The dimension in Figure 2 is in the SI unit of metres. Therefore, the value of 0.014 that has been mentioned earlier, represents the radius of the conductor.

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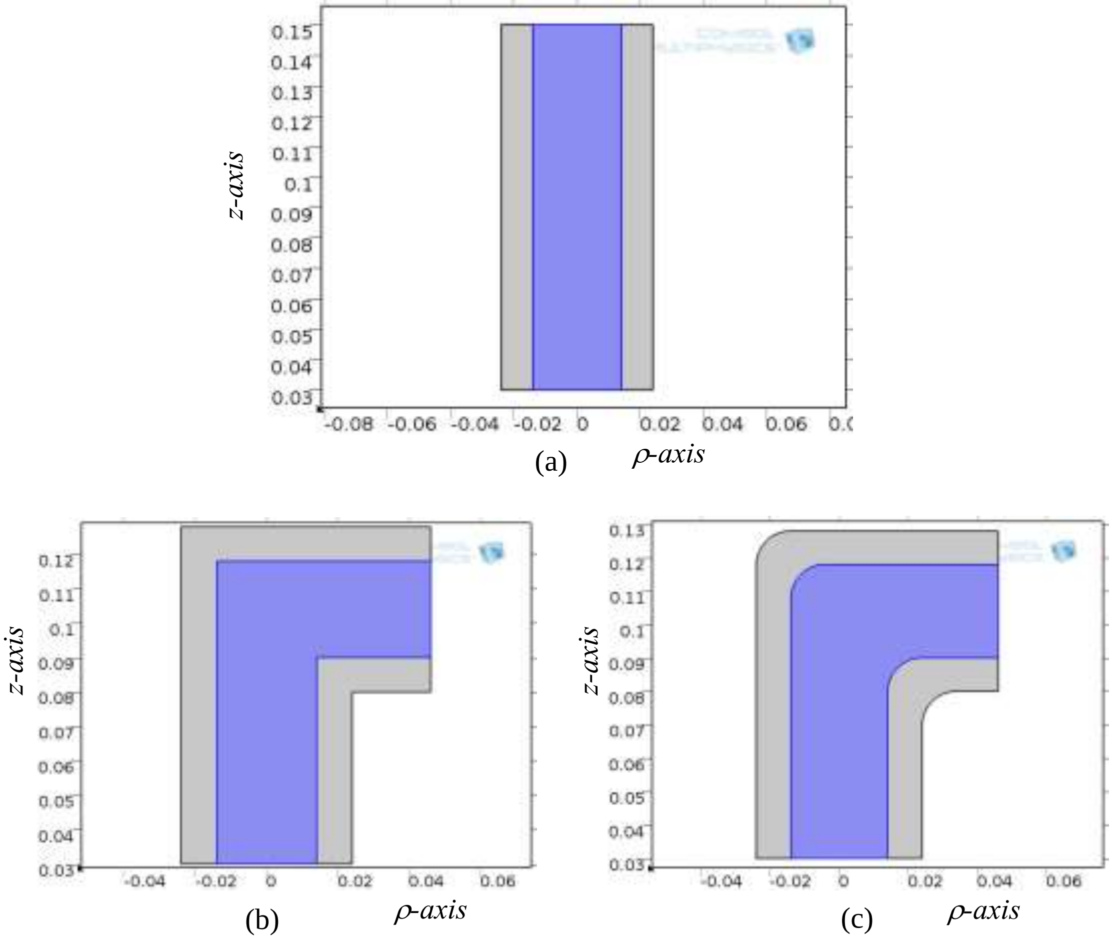
Figure 2: The model of domestic wire (single core) in COMSOL Multiphysics window with scaled up dimensions, conductor radius is 14 mm or 0.014 m and the insulation thickness is 10 mm or 0.01: *(a) uniform wire, (b) curved wire with smaller curvature radius (2.5 mm), and (c) curved wire with larger curvature radius (10 mm)*



Governing Equations

The electric field intensity, **E** in the insulation can be obtained through solving equations (2) and (3).

$$\mathbf{E} = -\nabla V \quad (2)$$

$$\nabla \bullet (\varepsilon_0 \varepsilon_r \mathbf{E}) = \rho_v \quad (3)$$

In equation (2), V is an electric potential and in equation (3), ε_0 is the permittivity of free space or air, ε_r is a relative permittivity of a material with respect to the free space or air, and ρ_v is the volume charge density (C/m^3). The symbol ∇ is the vector operator. These equations are built in COMSOL Multiphysics under AC/DC electrostatics application mode, and they are solved numerically using the techniques of solving the differential equations.

Assigning Dielectric Material Properties and Boundary Conditions

Equation 3 that is commonly referred to as Poisson equation shows that in order to study electric field distribution, the relative permittivity of the dielectric materials will have to be defined. The relative permittivity, also known as the dielectric constant, of PVC (polyvinyl chloride) insulation is typically in the range of 3 to 4 (Haynes, 2014). In this study the average value, i.e. 3.5 was used do represent material property of PVC. Regarding the boundary conditions, the surface of the conductor was set to be at an electrical potential of 230 V and the 0 electric potential was set on the outer surface of the insulation.

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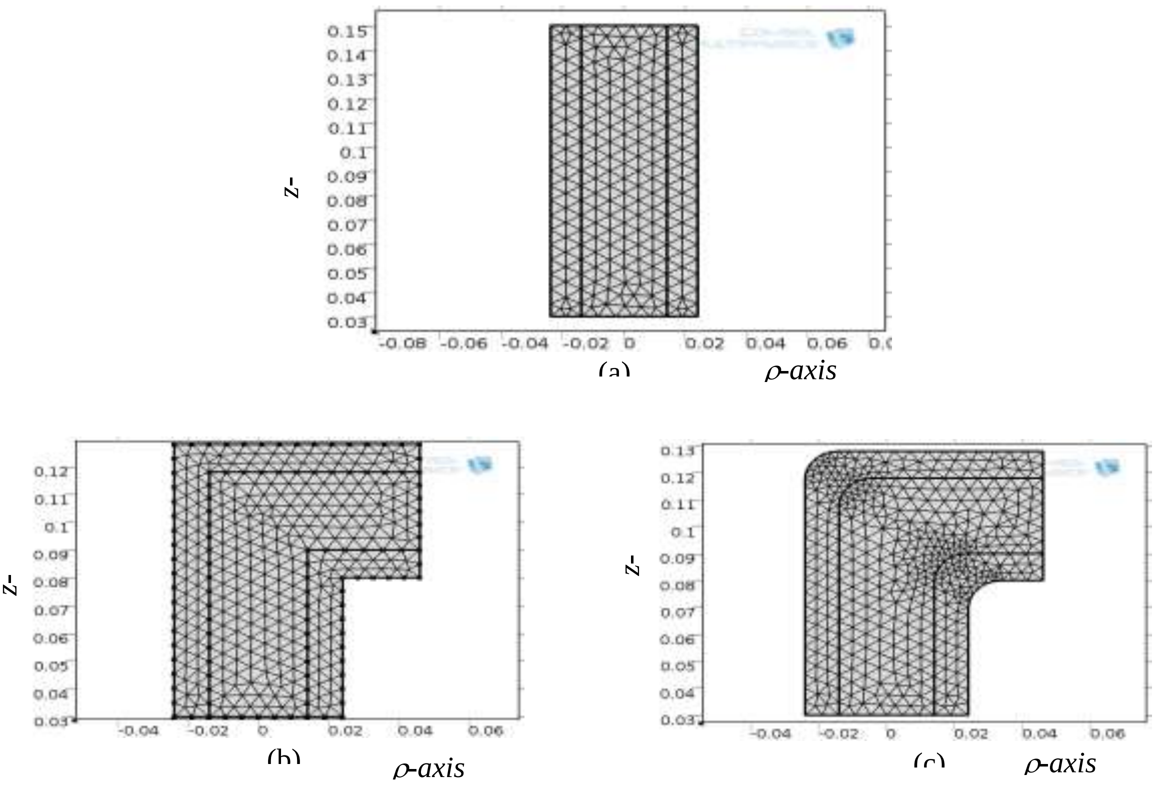
Geometry Meshing

Solving differential equations presented in Equation (2) and Equation (3) requires discretization in space. The same can be done in COMSOL Multiphysics using meshing built-in application by choosing element type and size. The best way of choosing appropriate meshing element size is to start with the larger elements and then reduce their sizes step by step, while computing for solution. The trial has to continue until when no difference is observed between the solutions of the two closer mesh element sizes. For the geometry shown in Figure 3, the *finer mesh element size* was used as the obtained solution under this mesh element size was the same as the solution obtained by considering the larger immediate mesh element size, which is referred to as *fine mesh element size*.

RESULTS AND DISCUSSION

The electric field distribution may be studied as stationary, time-dependent or frequency-dependent. The type of study depends on the intended investigations but governs the shape of the voltage waveform to be assigned when defining the boundary conditions. For the results presented in this section, the choice was stationary study and therefore the voltage and material properties were defined as constant function. The model was first validated by comparing simulated electric field intensity for straight wire (Figure 3a) with the value calculated using mathematical expression in Equation (4).

Figure 3: *The meshed geometries: (a) uniform wire, (b) curved wire with smaller curvature radius (2.5 mm), and (c) curved wire with larger curvature radius (10 mm)*



Model Validation

The simulation results for electric potential and electric field intensity for straight wire with a purpose of validating a model is shown in Figure 4. From Figure 4, it can be observed that the electric potential is according to the set values, i.e. from 0 V to 230 V, which indicates that the model was giving out the accurate results. In addition, it can be observed that the maximum electric field intensity was 2.3×10^4 V/m. This value was compared with the value that was obtained by using the mathematical expression in equation (4),

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$$E = \frac{V}{d} \quad (4)$$

where E is electric field intensity, V is the potential difference and d is the insulation thickness, i.e. the distance between the high potential and low potential. As stated earlier in Section 3.2 and Section 3.4, the potential difference V is 230 V and the insulation thickness was set to 10 mm. Substituting these values gives $E = \frac{230\ V}{10 \times 10^{-3}\ m}$, which is equal to 2.3×10^4 V/m. This is exactly equal to the maximum electric field intensity obtained through simulation as shown in Figure 4. This indicates that the degree of accuracy of the developed model is 100%.

Simulation Results on Effect of Radius of Curvature on Electric Field Distribution

The simulation results of the two curvature conditions, wire curved with small radius (2.5 mm) and another case with larger radius (10 mm) are presented in Figures 5 and 6 where Figure 5 is for the electric potential and Figure 6 is for electric field intensity. The model was validated in Section 4.1 by considering a uniform straight wire. In this case, from Figure 5, it can still be observed that the electric potential distribution is as expected as the values are ranging from 0 V to 230 V, which are the values that were assigned to the boundaries. For a case of electric field intensity as shown in Figure 6, configuration of curves may likely affect the magnitudes of electric field intensity. As it can be observed, the geometry with smaller curvature radius tends to have high values of electric field intensity as compared to the geometry with larger curved radius.

Figure 4: *Simulation results for a case of uniform wire: (a) electric potential and (b) electric field intensity*

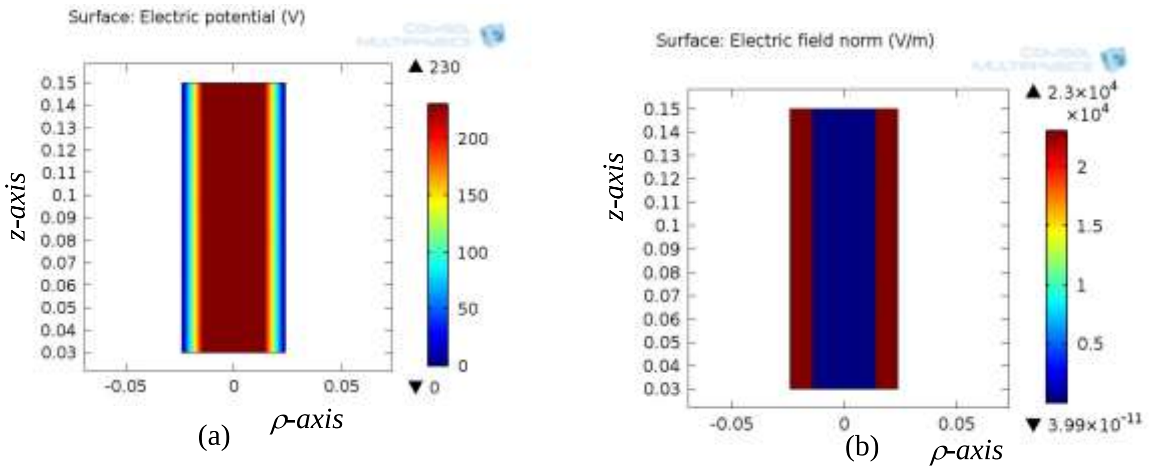

Figure 5: *The surface electric potential: (a) geometry curved with smaller radius (2.5 mm) (b) geometry curved with larger radius (10 mm)*

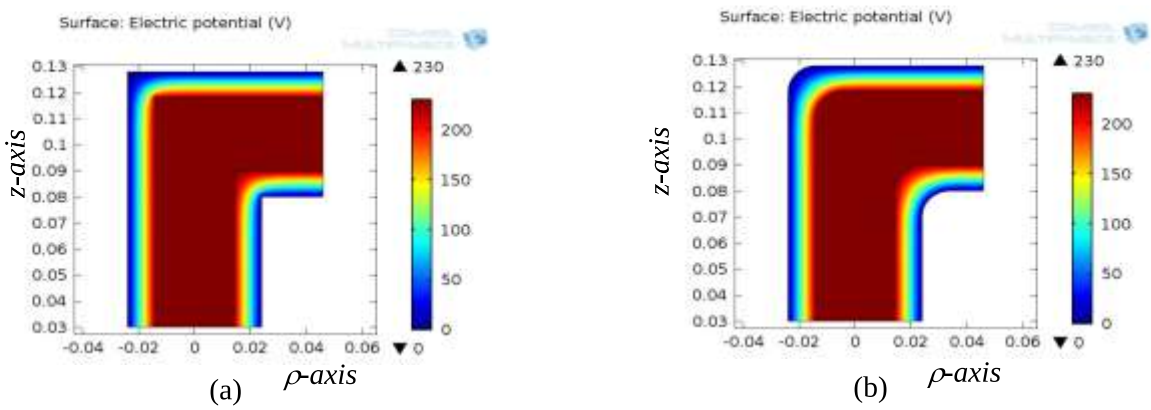

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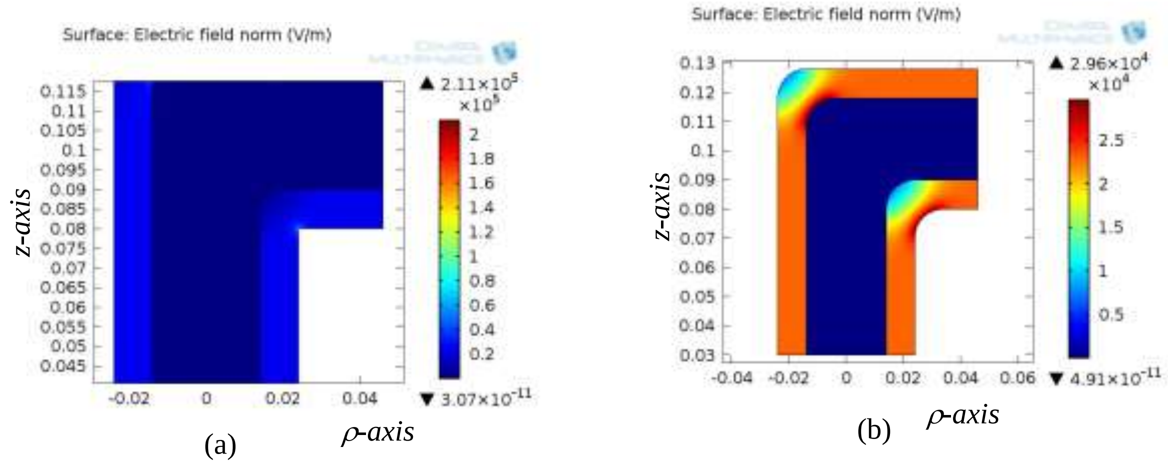
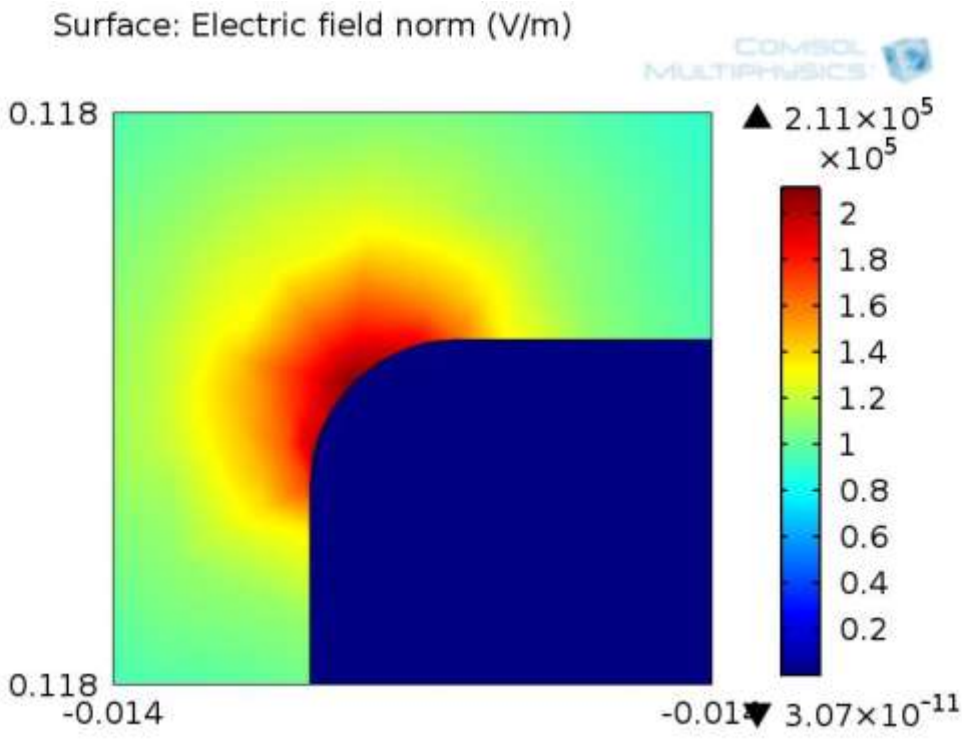
Figure 6: *The surface electric field intensity: (a) geometry curved with smaller radius (2.5 mm) (b) geometry curved with larger radius (10 mm)*



The simulation results in Figure 6 clearly indicates that the maximum electric field intensity for a case of a geometry with smaller curved radius is more than 7 times the value for the case when the curvature radius is large. The maximum electric field intensity appears in the insulation regions near the curved edge. Figure 6 (a) was zoomed out in order to see clearly the electric field intensity near the curved edges. The results are presented in Figure 7.

Figure 7: *The portion of the geometry of Figure 6 (a) showing the surface electric field distribution for the insulation region nearby the curved edge*



The concentrated electric field intensity on solid insulation, e.g. PVC (Polyvinyl Chloride) insulation, in localized areas may compromise the performance of the insulation. One of the primary effects of concentrated electric field intensity in PVC insulation is the initiation of partial discharge (PD) when the electric field strength exceeds the local dielectric strength of the

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material, leading to localized breakdown within voids or imperfections in the insulation (Syakur et al., 2008). In the PVC, this can happen at interfaces or within microvoids that may be present due to manufacturing defects or aging processes. The presence of PD can lead to significant degradation over time.

Mathematic Modelling for Prediction of the Magnitude of Electric Field Intensity at Various Curvature Radii

The geometry in Figure 3 was simulated at various curvature radii, from 2.5 mm to 12 mm. The results are presented in Table 1. In order to obtain an equation that best fits the data of curvature radius against maximum electric field intensity, the data were inserted in excel sheet. Through trials, the power option from Trendline was found to fit well the data with R^2 of 0.9995. The results of the scatter plot and the trendline fit by power option are presented in Figure 8. The variables in the equation generated by the data fit technique were written using the physical quantities from Table 1 in which *y* can be replaced with the maximum electric field intensity (E_{max}) and *x* with the curvature radius (r) as shown in Equation (4). The mathematic model equation was developed for curvature radii from 0.025 mm to 9 mm. The curvature radii from 10 mm to 12 mm were not used in the development of the mathematical model equation as they were reserved for validation of the model.

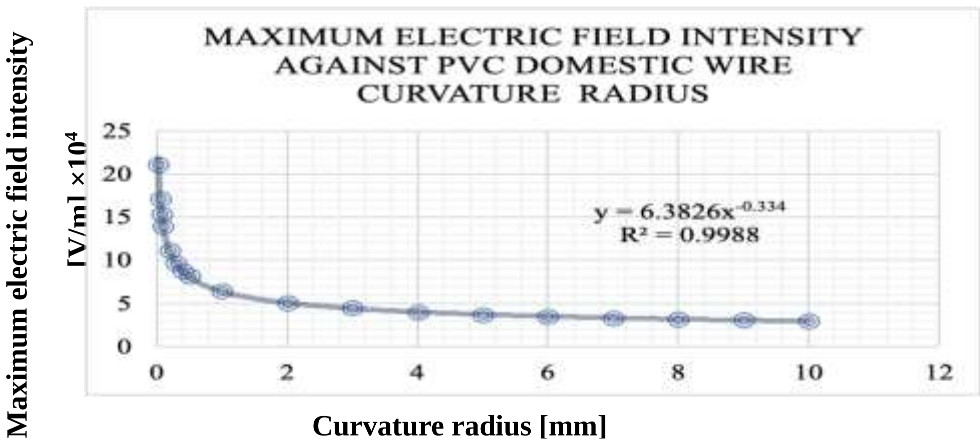
$$E_{max} = 6.3826r^{-0.334} \quad (4)$$

Table 1: Results of curvature radii with their corresponding maximum electric field intensity obtained by simulating the geometry in Figure 3 at various curvature radii

Curvature radius [mm]	0.025	0.05	0.075	0.1	0.2	0.3	0.4	0.5	1
Maximum Electric Field Intensity [V/m] *10^4	21.1	17.1	15.3	13.9	11.1	9.67	8.79	8.17	6.48

Curvature radius [mm]	2	3	4	5	6	7	8	9	10	11	12
Maximum Electric Field Intensity [V/m] *10^4	5.11	4.44	4.02	3.71	3.48	3.28	3.14	3.03	2.96	2.88	2.82

Figure 8: Scatter plot of maximum electric field intensity against curvature radius with a curve fitting for determination of the mathematical equation relating maximum electric field intensity with the curvature radius



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Mathematic Model Equation Validation

The curvature radii from Table 1 that were not used in mathematic model development were used in the validation. These values are 10 mm, 11 mm and 12 mm. The maximum electric field intensity corresponding to these curvature radii obtained through computer simulation with the help of Finite Element Based Software COMSOL Multiphysics have already been presented earlier in Table 1. In Table 2, the same results have been presented again together with the results that have been computed using the mathematical model in Equation (4). In addition, the prediction error in percentage comparing the developed mathematical model equation and the simulation results using the COMSOL Multiphysics are also presented in the same table, i.e. Table 2. From Table 2, it can be clearly observed that the power equation can present well the relationship between the curvature radii and the maximum electric field intensity as the prediction error is quite low, i.e. not exceeding 1.4%.

Table 2: **Validation for mathematical model equation**

Curvature radius [mm]	10	11	12
Maximum electric field intensity [V/m]*10^4 obtained by simulation	2.96	2.88	2.82
Predicted results of maximum electric field intensity [V/m]*10^4 obtained using mathematical expression, i.e. Equation 4.	2.96	2.87	2.78
Prediction error in %	0	0.7%	1.4%

CONCLUSION

This paper presented the results on the effect of wire curving on the distribution of electric fields in domestic wires, specifically PVC wire. The geometry was implemented in the Finite Element Based Software (COMSOL Multiphysics). The simulation results were plotted by scatterplot and then curve-fitted to obtain the equation that best fits the data. The results show that;

- The geometry with smaller curvature radius tends to have high values of electric field intensity as compared to the geometry with larger curved radius, e.g. in the results presented in this paper, the maximum electric field intensity for curvature radius of 0.025 mm was more than 7 times than that obtained for curvature radius of 10 mm; and

- The power equation can predict well the maximum electric field intensity at a given curvature radius as the comparison between the results obtained through simulation and through the power equation had the error of not more than 1.4%.

  The concentrated electric field intensity on solid insulation, e.g. PVC (Polyvinyl Chloride) insulation, in localized areas may initiate partial discharge (PD) when the electric field strength exceeds the local dielectric strength of the material.

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