Jurnal Kejuruteraan 37(7) 2025: 3601-3612
https://doi.org/10.17576/jkukm-2025-37(7)-36

Simulation of Electric Field Distribution in XLPE Cable Containing Alumina Nanoparticles

Muhammad Akmal Marican Abu Bakar Marican[a], Nazatul Shiema Moh Nazar[a*], Noor Fadzilah Mohamed Sharif[a], Mohamad Kamarol Mohd Jamil[b], Suresh Thanakodi[c] & Noor Amalina Ramli[a]

[a]*Department of Electrical and Electronics Engineering, Faculty of Engineering, Universiti Pertahanan Nasional Malaysia*

[b]*School of Electrical and Electronics Engineering, Universiti Sains Malaysia.*

[c]*Department of Science and Maritime Technology, Faculty of Science and Defence Technology, Universiti Pertahanan Nasional Malaysia*

[*]*Corresponding author: nazatul.shima@upnm.edu.my*

Received 30 March 2025, Received in revised form 15 July 2025
Accepted 10 August 2025, Available online 30 October 2025

ABSTRACT

This paper includes a comprehensive investigation into the electric stress behaviour of crosslinked polyethylene (XLPE) cables containing alumina nanoparticles. XLPE is commonly utilised in high-voltage applications because of its excellent dielectric characteristics, mechanical strength, and heat resistance. However, there are two main factors contribute to the critical issues that lead to dielectric breakdown because the XLPE insulation may age over time and high voltage applications create significant electrical stress within the insulator of XLPE cable. Therefore, this research studies electric field distribution in XLPE and XLPE containing alumina nanoparticles. Alumina was chosen in this research due to its high thermal conductivity to efficiently transfer heat and high resistant to corrosion, acids and bases. By adding the alumina nanoparticles in XLPE it will enhance the performance of the cable. This research also studies the various shapes of alumina nanoparticles (sphere, rod and triangle) with three different cases (3 layers, 5 layers and 7 layers) of alumina nanoparticles in XLPE cable. The research includes modeling XLPE and XLPE containing alumina nanoparticles with different shapes through three cases, followed by simulation and analysis by using COMSOL Multiphysics software. The outcome of this research, XLPE containing sphere alumina nanoparticles gives better results with the increment of 58% (2.37×10^7 V/m) compared to pure XLPE (1.50×10^7 V/m), increment about 8.44% from Case 1 (2.37×10^7 V/m) to Case 2 (2.57×10^7 V/m) and decrement about −2.33% from Case 2 (2.57×10^7 V/m) to Case 3 (2.51×10^7 V/m). to enhance the performance of cable in terms of higher electric field intensity around nanoparticles while reducing the electric field distribution and it will contribute to the higher breakdown strength.

Keywords: XLPE; COMSOL; high voltage; shapes; breakdown strength

INTRODUCTION

Cross-linked polyethylene (XLPE) cables are critical components of modern electrical power systems, and their reliable operation is of paramount importance for the stable distribution of electricity (Liu et al. 2017; Pallon et al. 2016). However, dielectric breakdown is a primary cause of insulation failure, in which an accelerated and fatal increase in current flow comes from the insulating material's capability to deal with the high electric field (Lee et al. 2023; Zhu et al. 2020). The XLPE insulation may age with time, resulting in the formation of voids or other problems (Patel et al. n.d.). Furthermore, high voltage applications create significant electrical stress on the XLPE insulation, which could increase the occurrence of breakdown. These two factors might be the critical issues that may contribute to the dielectric breakdown in XLPE cables used in high-voltage applications.

Therefore, to solve these problems, the demand for increased power transmission and low intensity electric field distribution capabilities has led to the development of high-voltage cables containing nanoparticles as insulating materials. These nanoparticles are expected to enhance the cable's insulation and mechanical performance by lowering the intensity of electric field distribution and reducing electric stress (Jayakrishnan et al. 2016). Nonetheless, there is a lack of comprehensive research on the effects of nanoparticles on electric fields within high-voltage cables.

The findings of this research will provide valuable insights into the feasibility and effectiveness of incorporating nanoparticles into high-voltage cable insulation materials (Balachandran Amrita Vishwa Vidyapeetham 2017; Kavitha et al. n.d.; Elsayed et al. 2020; Hu et al. 2020, Alsharif et al. n.d.; Kadim et al. 2021). This research highlighted the impact of nanoparticle addition on the dielectric characteristics of insulating materials and their potential to improve cable electrical performance by reducing the tendency of breakdown. Furthermore, it will contribute to the understanding of electric stress in such cables and help improve their design, performance, and safety in power transmission and distribution applications. In this research, a simulation will be carried out using pure XLPE cable and XLPE cable containing alumina nanoparticles but with different shapes and various concentrations to analyse the electric field distribution.

METHODOLOGY

Figure 1 shows the research workflow, which begins with a study of the electric field distribution through a literature review. After exploring COMSOL software as the platform to model the cross-sectional area of the insulator of XLPE cable to show the layer of insulator inside the cable. Next, designing the various shapes from one type of nanoparticles that will be mixed with the insulator before simulation was done to see how the nanoparticles affected the electric field distribution when the simulation is running. Finally, the process will be repeated with different shapes and concentrations of nanoparticles to make a comparison and analysis among those results on how the parameters affected the electric field distribution within an insulator's cable.

PARAMETER OF MODELING SETUP

A versatile simulation program that can be used for modeling and analysing a variety of physical phenomena, including electromagnetic, is called COMSOL Multiphysics. COMSOL may be quite helpful for creating insulators for monitoring the dispersion of electric fields by modeling the insulator's shape and structure. The powerful geometry modeling capabilities in COMSOL enable the design of precise and comprehensive 2D models of insulators, including complicated geometries and complex forms. It also makes it possible to give certain model components varied material qualities, such as conductivity and permittivity (Jiang et al. 2015).

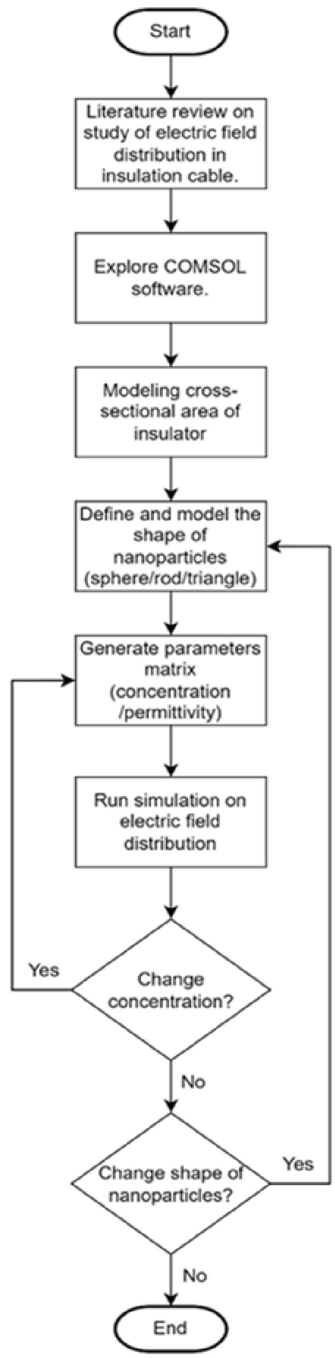

FIGURE 1. Research flowchart

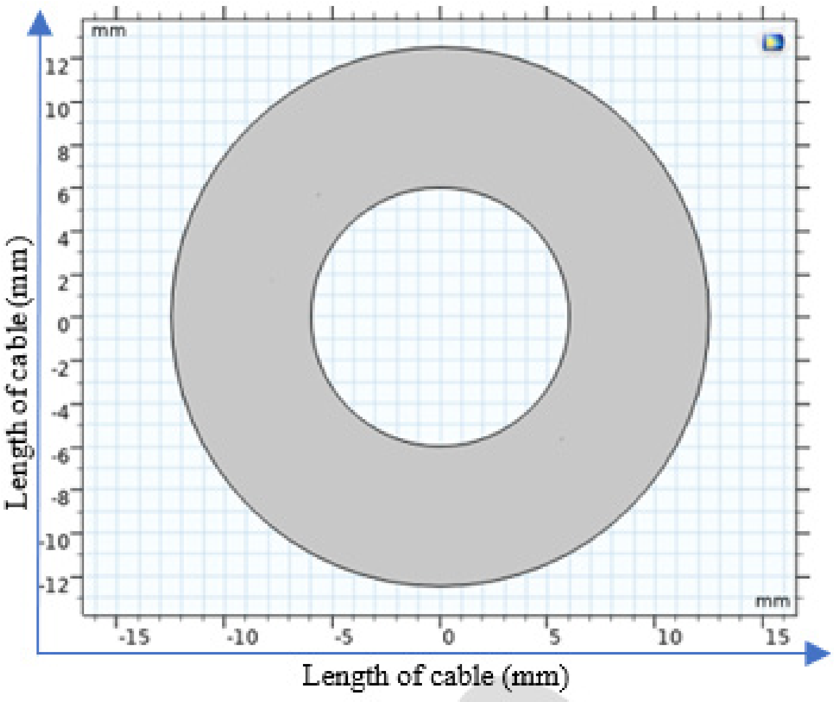

FIGURE 2. Cross sectional area of XLPE cable

XLPE CABLE

Geometry of the XLPE cable was constructed in 2D by referring to the parameters in Table 1. The cross-sectional design of the power cable consists of two domains where the inner domain represents the conductor of the cable with injected voltage of 66kV and the outer domain is the insulator using XLPE as the material while attached to the ground. Figure 2 shows the raw two-dimensional design of an XLPE cable. Table 2 shows the material properties of XLPE for the insulation system.

TABLE 1. Geometry of XLPE cable

Parameter	Value (mm)
Radius of conductor	6.0
Thickness of insulator	6.5

TABLE 2. The material properties of XLPE

Properties	Value
Electrical conductivity	3×10^{-16} S/m
Relative permittivity	2.4
Density	930 kg/m^3

ALUMINUM OXIDE (ALUMINA) NANOPARTICLES

In this research, alumina nanoparticles were infused with XLPE to improve the performance of the cable itself by increasing and reducing the amount of electric field intensity accordingly. The tendency of a cable to breakdown affected by the electric field distribution within the insulator of a cable. Three shapes of alumina were chosen (sphere, rod and triangle) to differentiate the stress patterns of electric field within XLPE cable insulation system. All the parameters of each shape were recorded in Table 3 and Figure 3 (a), (b) and (c) show the geometry of alumina nanoparticle of each shapes respectively.

TABLE 3. Area of alumina nanoparticles.

Parameter	Value (mm^2)
Sphere	
Rod	$\approx 3.142 \times 10^{-10}$
Triangle	

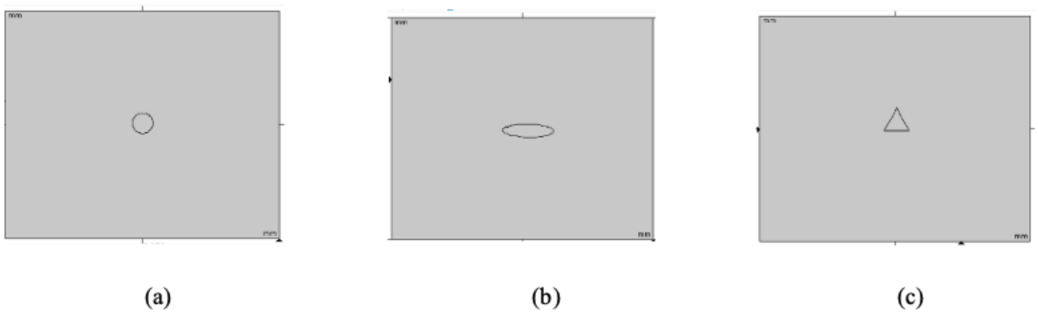

FIGURE 3. Geometry of (a) sphere (b) rod (c) triangle

CASE STUDY

The data of this simulation will be measured among all the variables mentioned in Table 4. In the beginning of this research, the simulation will run on the pure XLPE to observe the distribution of electric field within the insulator of pure XLPE since no presence of any nanoparticles being mixed with the insulator. After the result was obtained, the simulation continued with different shapes of alumina nanoparticles by varying case study of nanoparticles within the insulator through three different case studies and each case study consists of three, five and seven layers of alumina nanoparticles respectively. The variation of case studies will be used to compare which variables will produce the lowest intensity of electric field distribution as shown in Figures 4 (a), (b) and (c). These three figures illustrate how the alumina nanoparticles in spherical shape will occupy the area within insulator with influenced by various concentrations. The blue domain represents the alumina nanoparticles according to the percentage of concentration to the ratio of the total area of insulator. This process will analyse which shape and specific concentration has the optimum characteristics to improve the performance of XLPE cable by reducing the tendency of dielectric breakdown.

TABLE 4. Case study of XLPE and XLPE containing alumina nanoparticles

Material		Case Study		
		1	2	3
		Layers of alumina-nano		
Pure XLPE			-	
Shapes of alumina nanoparticles	Sphere	3	5	7
	Rod			
	Triangle			

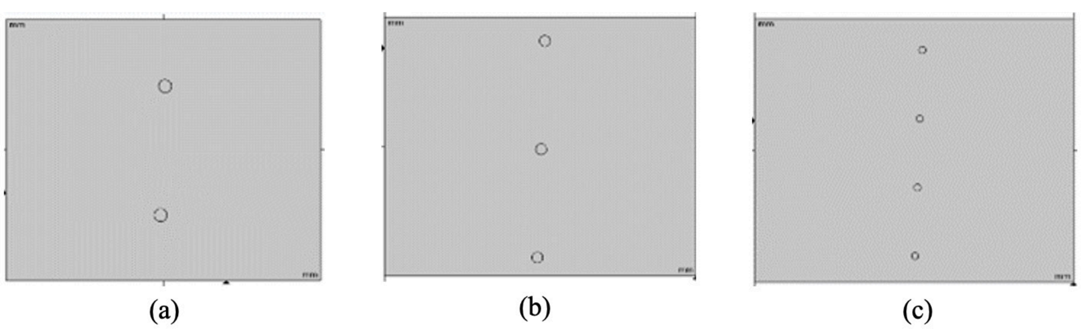

FIGURE 4. Layers of alumina nanoparticles (a) 3 (b) 5 (c) 7

DEFINE BOUNDARIES

To run the simulation on electric field distribution of XLPE cable, every domain and boundary must be defined by selecting the correct region and inserting the required value. Figure 5 and 6 show the boundary defined for the grounding and injected voltage of the cable.

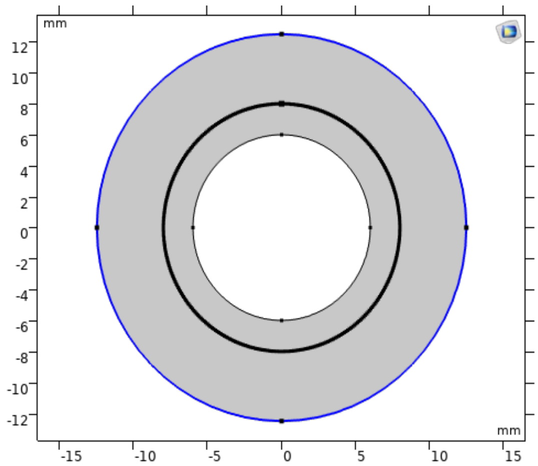

FIGURE 5. The outer boundaxry as the ground

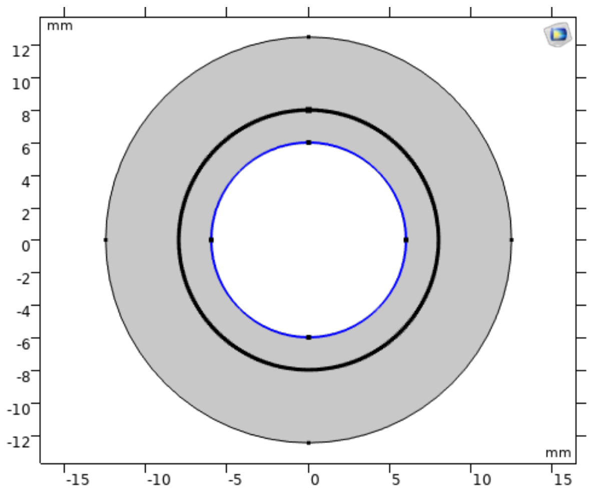

FIGURE 6. The inner boundary as the ground

MESHING

Meshing is useful for correctly expressing the shape and features of a complicated simulation domain. This is especially crucial for ensuring that the boundary conditions and material interfaces are correctly represented. Furthermore, mesh quality and density have a direct impact on the accuracy of simulation findings. A finer mesh (smaller elements) can capture more subtleties and variations in the electric field distribution, providing more accurate results. Figure 7 shows the physics-controlled mesh using finer element size to compute the electric field distribution of XLPE cable.

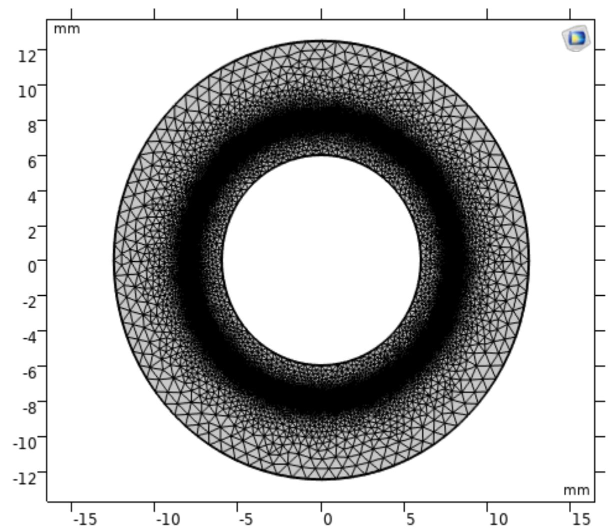

FIGURE 7. The meshing process in simulation on electric field distribution

RESULT AND DISCUSSION

To analyse the electric field distribution, a straight line passing through the alumina nanoparticles within the insulator to tabulate the data of the maximum electric field intensity from various shapes and concentrations. The length of the straight line cutting through the nanoparticles is 0.9mm and fixed for every concentration with same angle and coordinates of the plotted line. insulator to tabulate the data of the maximum electric field intensity from various shapes and concentrations. The length of the straight line cutting through the nanoparticles

PURE XLPE

Figure 8 shows the stress patterns for the electric field distribution within the insulator of only pure material of XLPE. The highest electric field intensity was recorded at the inner boundary which is the conductor of the cable with value of 1.5E-7 V/m. Figure 9 displays the close up of the electric field distribution within the cable of pure XLPE.

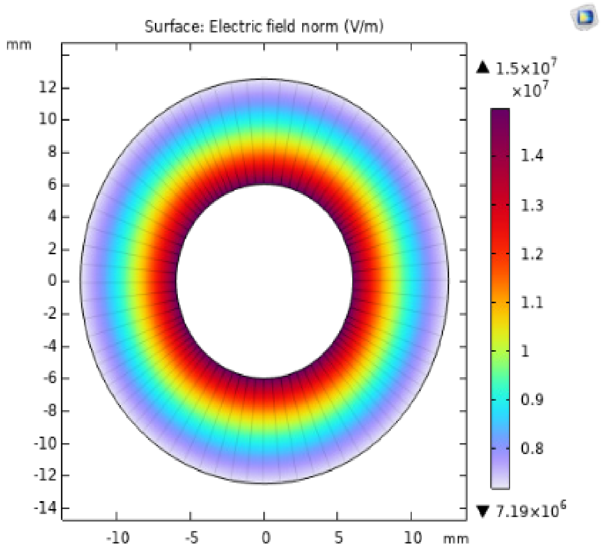

FIGURE 8. Stress patterns for pure XLPE cable

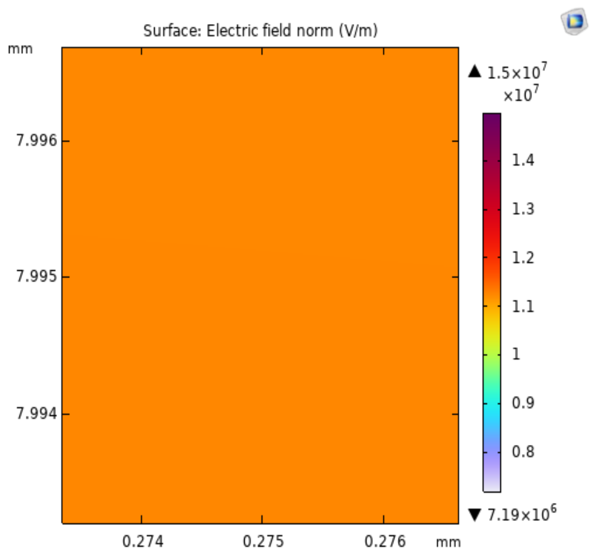

FIGURE 9. Electric field of pure XLPE along a straight line

CASE STUDY 1 (3 LAYERS)

The first case is varying the concentrations of alumina nanoparticles within the insulator with 3 layers surrounding the cable with total amount of 538 domain of alumina nanoparticles. Figure 10 (a), (b) and (c) show the stress patterns of electric field distribution of Case 1 condition consists of 3 layers alumina nanoparticles from various shapes surrounding the XLPE cable.

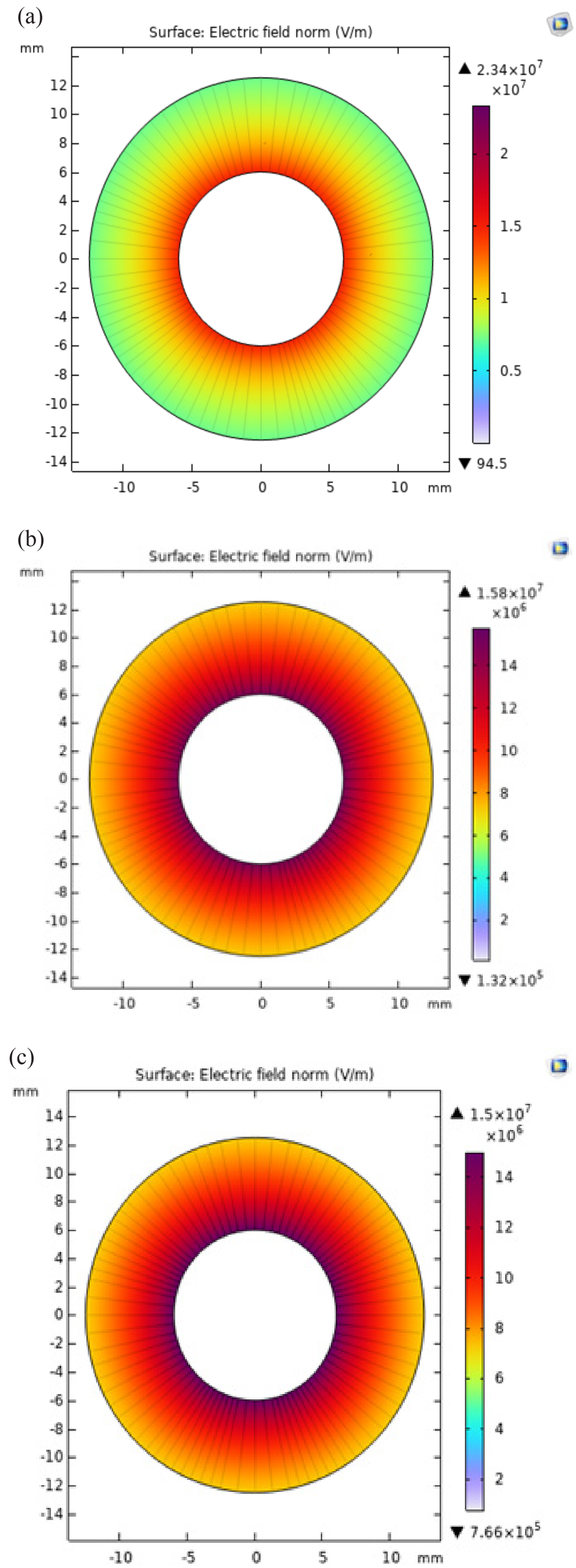

FIGURE 10. XLPE cable with different shapes of alumina nanoparticle for Case 1(a) sphere (b) rod (c) triangle

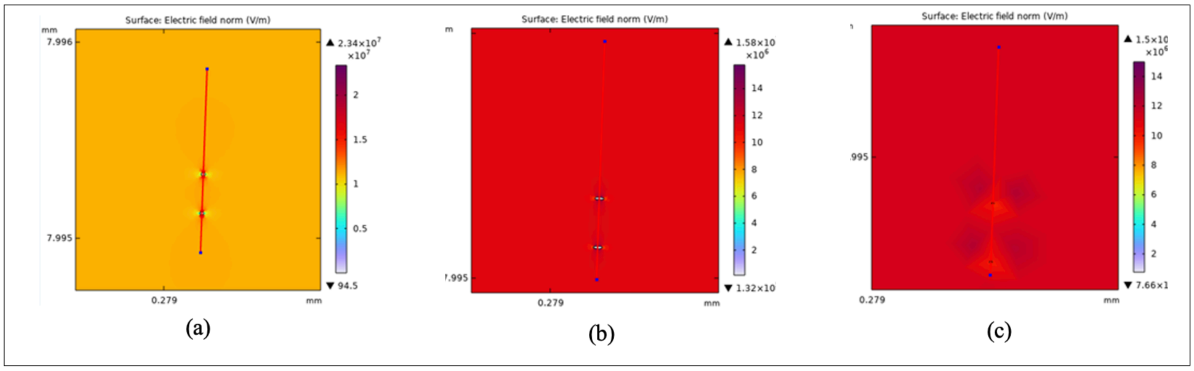

FIGURE 11. Electric field of XLPE containing 3 layers with different shapes alumina nanoparticles along a straight line (a) sphere (b) rod (c) triangle

Figure 11 (a), (b) and (c) show the straight line plotted through two alumina nanoparticles for each shape to compute the maximum electric field intensity around the alumina nanoparticles. Figure 12 (a), (b) and (c) show the electric field intensity along a straight line. For Case 1, three layers of alumina nanoparticles of sphere shape recorded the highest electric field intensity compared to rod and triangle shape. Triangular-shaped alumina nanoparticles produced the least amount of electric field intensity in the condition of Case 1 simulation.

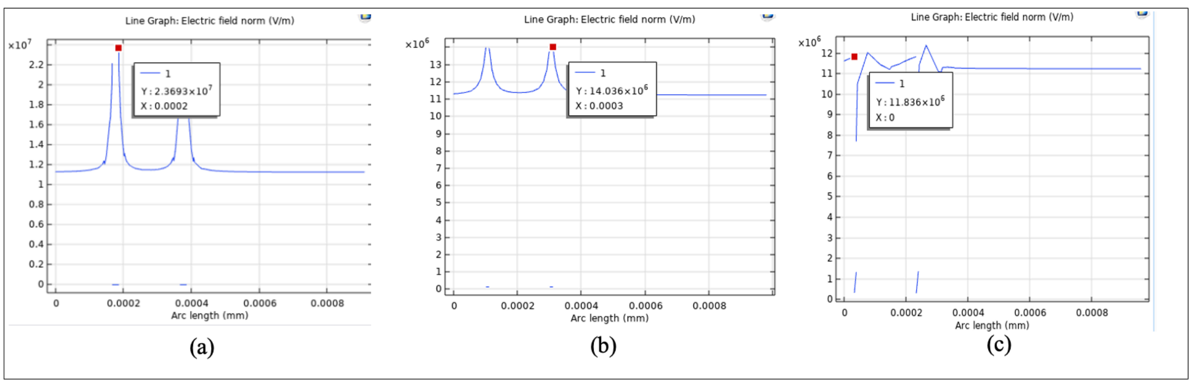

FIGURE 12. Graph of electric field recorded along a straight line in Case 1 for different shapes of alumina nanoparticle (a) sphere (b) rod (c) triangle

CASE STUDY 2 (5 LAYERS)

The second case is varying the concentrations of alumina nanoparticles within the insulator with 5 layers surrounding the cable with total amount of 897 domain of alumina nanoparticles. Figure 13 (a), (b) and (c) show the stress patterns of electric field distribution of Case 2 condition consists of 5 layers alumina nanoparticles from various shapes surrounding the XLPE cable.

Figure 14 (a), (b) and (c) show the straight line plotted through three alumina nanoparticles for each shape to compute the maximum electric field intensity around the alumina nanoparticles. Figure 15 (a), (b) and (c) show the electric field intensity along a straight line. For Case 2, the trend of the three shapes remains the same as Case 1. Five layers of alumina nanoparticles of sphere shape recorded the highest electric field intensity compared to rod and triangle shape. The rod-shaped alumina nanoparticles remain constant from Case 1. Triangular-shaped alumina nanoparticles produced the least amount of electric field intensity in condition of Case 1 simulation.

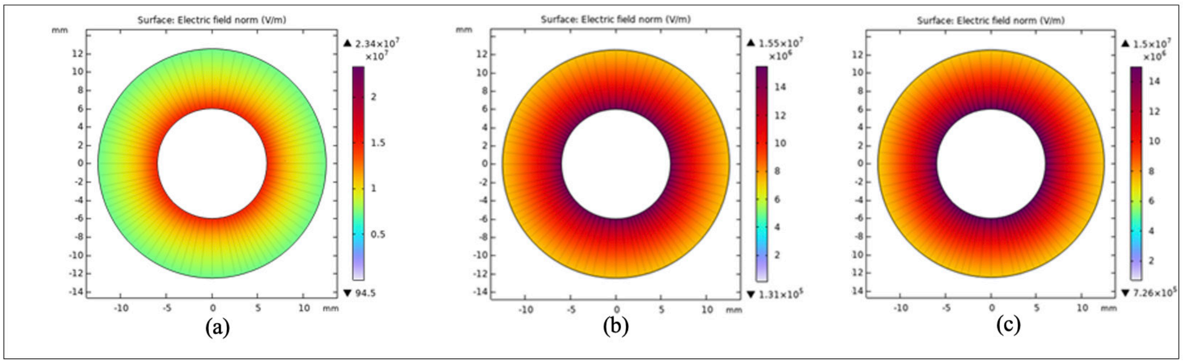

FIGURE 13. XLPE cable with different shapes of alumina nanoparticle for Case 2 (a) sphere (b) rod (c) triangle

Figure 14 (a), (b) and (c) show the straight line plotted through three alumina nanoparticles for each shape to compute the maximum electric field intensity around the alumina nanoparticles. Figure 15 (a), (b) and (c) show the electric field intensity along a straight line. For Case 2, the trend of the three shapes remains the same as Case 1. Five layers of alumina nanoparticles of sphere shape recorded the highest electric field intensity compared to rod and triangle shape. The rod-shaped alumina nanoparticles remain constant from Case 1. Triangular-shaped alumina nanoparticles produced the least amount of electric field intensity in condition of Case 1 simulation.

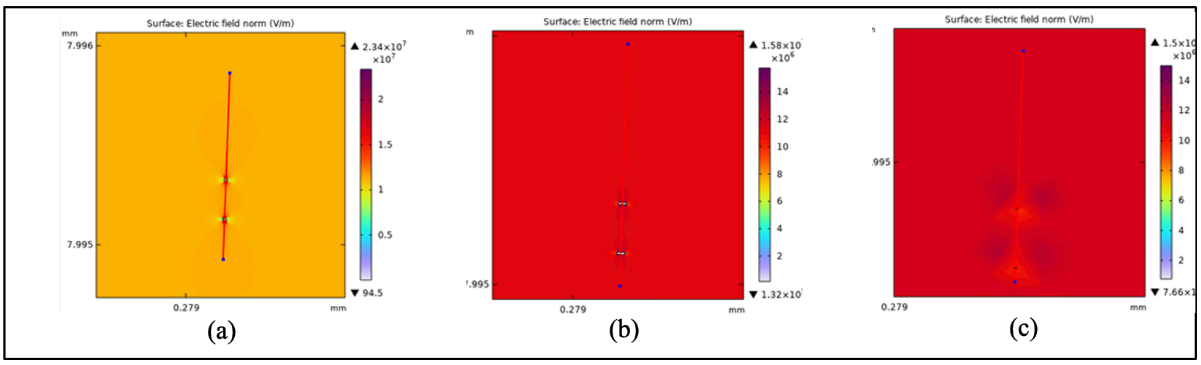

FIGURE 14. Electric field of XLPE containing 5 layers with different shapes alumina nanoparticles along a straight line (a) sphere (b) rod (c) triangle

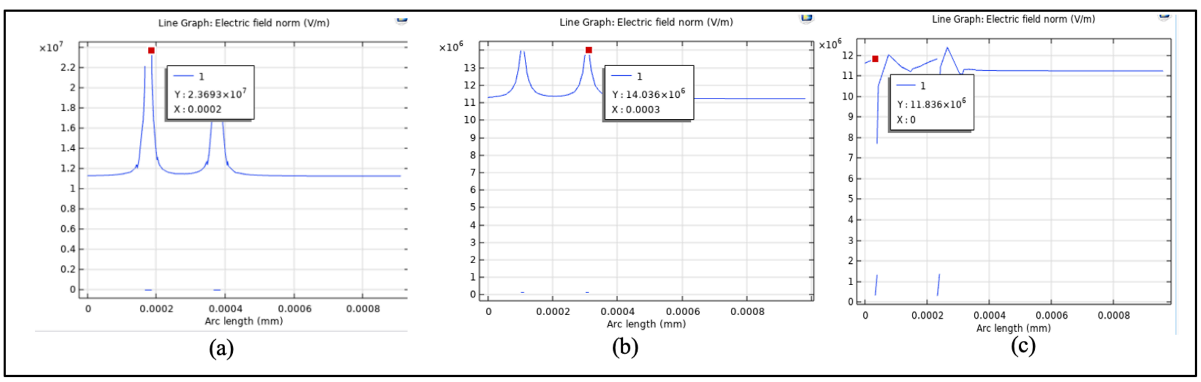

FIGURE 15. Graph of electric field recorded along a straight line in Case 2 for different shapes of alumina nanoparticle

(a) sphere (b) rod (c) triangle

CASE STUDY 3 (7 LAYERS)

The third case is varying the concentrations of alumina nanoparticles within the insulator with 7 layers surrounding the cable with total amount of 1256 domain of alumina nanoparticles. Figure 16 (a), (b) and (c) show the stress patterns of electric field distribution of Case 2 condition consisting of 5 layers alumina nanoparticles from various shapes surrounding the XLPE cable.

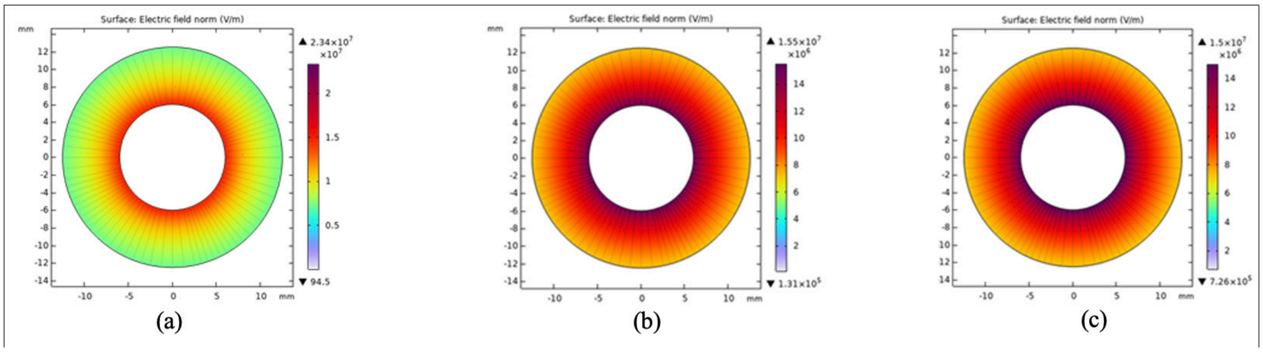

FIGURE 16. XLPE cable with different shapes of alumina nanoparticle for Case 3 (a) sphere (b) rod (c) triangle

Figure 17 (a), (b) and (c) show the straight line plotted through three alumina nanoparticles for each shape to compute the maximum electric field intensity around the alumina nanoparticles. Figure 18 (a), (b) and (c) show the electric field intensity along a straight line. Seven layers of alumina nanoparticles of sphere shape maintain as the highest electric field intensity compared to rod and triangular shape, but triangle shape became higher than rod-shaped alumina nanoparticles.

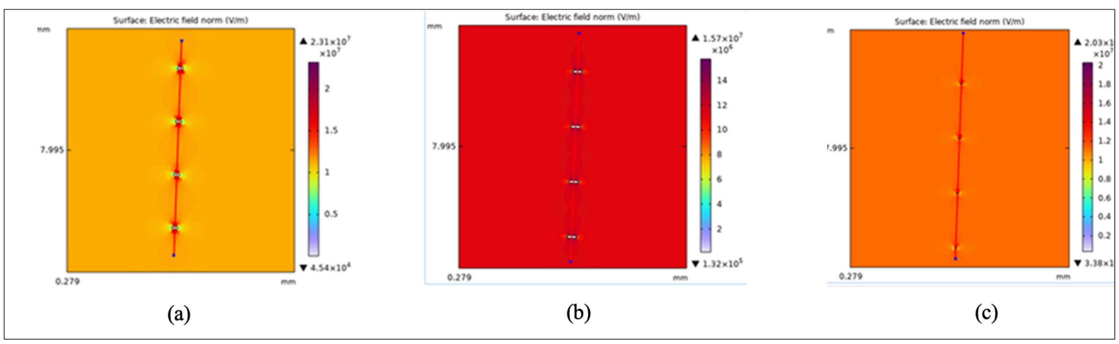

FIGURE 17. Electric field of XLPE containing 7 layers with different shapes alumina nanoparticles along a straight line (a) sphere (b) rod (c) triangle

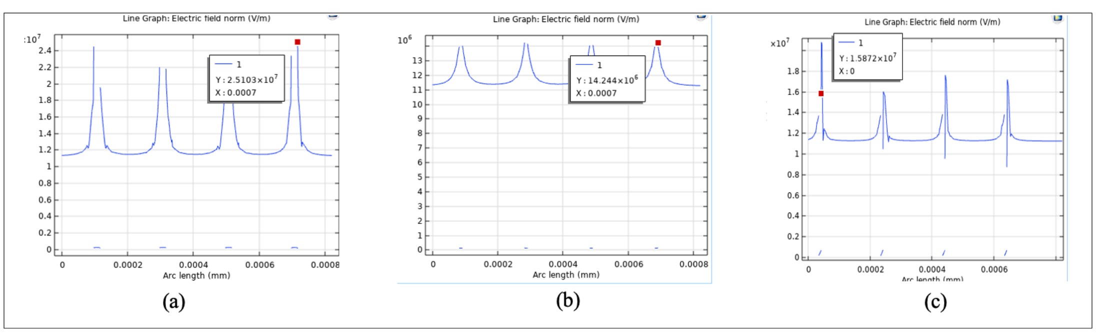

FIGURE 18. Graph of electric field recorded along a straight line in Case 3 for different shapes of alumina nanoparticle (a) sphere (b) rod (c) triangle

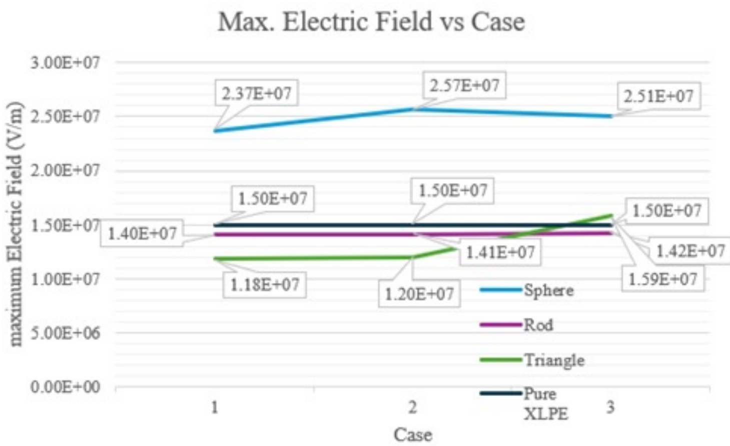

FIGURE 19. Results on overall simulation.

Table 5 shows all the data of maximum electric field intensity produced by pure material XLPE and XLPE containing three different shapes with three various case studies. Figure 19 shows the trend of each shape of alumina nanoparticles through three cases with three different concentrations including pure XLPE cable. For pure XLPE cable, there are no changes in the maximum electric field across all three cases which is 1.50×10^{7}V/m because no alumina nanoparticles were added in the insulation material. For XLPE cable containing spherical-shaped alumina nanoparticles, there is increment of 58% (2.37×10^{7}V/m) compared to pure XLPE (1.50×10^{7}V/m). There is an increment of 8.44% from Case 1 (2.37×10^{7}V/m) to Case 2 (2.57×10^{7}V/m) and a decrement of −2.33% from Case 2 (2.57×10^{7}V/m) to Case 3 (2.51×10^{7}V/m). Spherical nanoparticles initially increase the electric field however, further addition leads to a minor decrease, possibly due to amount of alumina nanoparticles. For XLPE cable containing rod-shaped alumina nanoparticles, there is decrement of -6.67% (1.40×10^{7}V/m) compared to pure XLPE (1.50×10^{7}V/m). The electric field intensity increases about 0.71% from Case 1 (1.40×10^{7}V/m) to Case 2 (1.41×10^{7}V/m) and another increment same value of 0.71% from Case 2 (1.41×10^{7}V/m) to Case 3 (1.42×10^{7}V/m). The electric field shows a small and consistent increase with the addition of more layers of rod-shaped alumina nanoparticles through cases. For XLPE cable containing triangular-shaped alumina nanoparticles, there is decrement of 21.33% (1.18×10^{7}V/m) compared to pure XLPE (1.50×10^{7}V/m). There is a small increase from Case 1 (1.18×10^{7}V/m) to Case 2 (1.20×10^{7}V/m) about 1.69%, followed by a significant increase from Case 2 (1.20×10^{7}V/m) to Case 3 (1.59×10^{7}V/m) about 32.50%.

TABLE 5. Electric field around nanoparticles for different shapes and various case studies.

Shapes of nanofiller	Electric Field (V/m) / (Case)		
	1	2	3
Pure XLPE	1.50E+07	1.50E+07	1.50E+07
Sphere	2.37E+07	2.57E+07	2.51E+07
Rod	1.40E+07	1.41E+07	1.42E+07
Triangle	1.18E+07	1.20E+07	1.59E+07

From this simulation, the permittivity may play the main role of affecting the electric field distribution but since only one material was used in this research, the permittivity will not be the important variables (Alsharif et al. n.d.). There are two theories explaining the relationship between the electric field intensity and the tendency for the cable to breakdown. The first theory explains that as the electric field intensity increases, the tendency for the cable to breakdown increases and it is only applicable for the pure XLPE cable since there are no additives in the material (Alsharif et al. n.d.). The second theory is only valid if there are addition of nanoparticles within the insulator which explains the higher electric field intensity surrounding the nanoparticles, and the lower tendency for the cable to breakdown (Fouad et al. 2021; Thabet & Fouad, 2021). This phenomenon happens when the increasing number of alumina nanoparticles in XLPE cable, it may also increase the electric field intensity of the cable. Figure 19 shows the comparison and trend of the shapes and layers of alumina nanoparticles that affected the electric field distribution inside the cable. Throughout the simulation of electric field distribution with three different cases on pure XLPE and XLPE containing alumina nanoparticles of sphere, rod and triangle shapes, the electric field intensity around the nanoparticles will affect the breakdown strength of the cable by reducing the electric field distribution of the cable. As for the pure XLPE cable, the maximum electric field intensity was recorded near the conductor of the cable because there is no presence of any nanoparticles within the insulator. By adding spherical shaped alumina nanoparticles into the insulation system, the electric field intensity around the nanoparticles appears to be higher than the conductor of the cable. Due to high electric field intensity around the nanoparticles, the treeing branch from the source of high voltage will move around the nanoparticles and will reduce the tendency for the cable to breakdown by prolonging the breakdown rate (Thabet & Fouad, 2021). Furthermore, rod-shaped alumina nanoparticles in XLPE cable seems not to cooperate with the distribution of the electric field even though the concentration increased from three layers to seven layers. In addition, sharp edges from the triangular-shaped alumina nanoparticles produced lowest electric field intensity but with an appropriate concentration of alumina nanoparticles, the electric field intensity increases for the simulation in Case 3 (Thabet & Fouad 2021).

CONCLUSION

This research reports on the effect of nanoparticle's shape and its concentrations on tuning the electric field intensity. Modeling and analysis through three different cases with various concentrations revealed that higher concentration of nanoparticles resulted in increased electric field intensity. Furthermore, the increased electric field intensity degraded the electric field distribution resulting in decreasing its breakdown strength. Moreover, the shape's geometry also affected the distribution of electric field inside XLPE cable. In conclusion, by conducting simulation on the electric field with addition of alumina nanoparticles from various shapes, the lower the electric field intensity will lead to higher breakdown strength. Spherical-shaped alumina nanoparticles in XLPE produced the highest electric field intensity and lowest breakdown strength which is the ideal innovation for future development of XLPE cables containing alumina nanoparticles.

Through the simulation on electric field distribution of pure XLPE and three different shapes of alumina nanoparticles through three different cases, electric field intensity of XLPE without addition of alumina nanoparticles are higher than rod and triangle shapes of alumina nanoparticles through Case 1 and 2, but in Case 3, electric field intensity of XLPE cable containing triangular-shaped alumina nanoparticles becomes higher than XLPE and XLPE containing rod alumina nanoparticles. However, XLPE cable containing spherical-shaped alumina nanoparticles recorded the highest electric field intensity among two other shapes and pure XLPE through all cases. By comparing pure XLPE cable with XLPE cable containing spherical alumina nanoparticles, there is increment of 58% from 1.50×10^7V/m to 2.37×10^7V/m. This research can conclude that among pure XLPE and XLPE cable containing three different shapes of alumina nanoparticle, sphere alumina nanoparticles produce the best electric field distribution to reduce the tendency for the cable to breakdown due to higher electric field intensity around alumina nanoparticle and lower electric field distribution from injected voltage that produces higher breakdown strength.

As for the recommendation, this research may contribute ideas to other researchers who are doing experimental research in this field. Further study can be done to obtain more appropriate results in determining and understanding the best distribution of electric field within the XLPE cable insulation. In future work, the variable of the concentration, types and sizes of nanoparticles also may be changed to obtain more accurate results on how the nanoparticles will influence the electric stress with its presence. Furthermore, the shape also can be changed if the existing shape has experienced any difficulties during the simulation process to obtain the expected result on electric field distribution.

ACKNOWLEDGEMENT

This paper did not receive any external fundings.

DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Alsharif, M., Wallace, P., Hepburn, D. and Zhou, C. 2012. FEM modeling of electric field and potential distributions of MV XLPE cables containing void defect, *Excerpt from the Proceedings of the COMSOL Conference*, 1 : pp. 1–4, 2012.

Balachandran Amrita Vishwa Vidyapeetham, M. 2017. Modeling of electric field distribution in epoxy nanocomposites using Finite Element Method. *Journal of Electrical Engineering* 15(3): 1-6.

Elsayed, A. E., Said, A. R., Nawar, A. G., Abd-Allah, M. A., & Kamel, S. 2020. High voltage cross-linked polyethylene insulator characteristics improvement using functionalized ZnO nanoparticles. *Egyptian Journal of Chemistry* 63(12): 4929–4939.

Fouad, M., Thabet, A., Ahmed, A.-M., & Elnodi, A. 2021. High performance of power cables using nanocomposites insulation materials. *Indonesian Journal of Electrical Engineering and Informatic*s (IJEEI) 9(1): 8-21.

Jayakrishnan, A., Kavitha, D., Arthi, A., Nagarajan, N., & Balachandran, M. 2016. Simulation of electric field distribution in nanodielectrics based on XLPE. *Materials Today: Proceedings* 3: 2381–2386

Jiang, J. G., Duan, H. W., He, T. H., & Li, B. 2015. Electric field simulation and experimentation of needle-plate type electrospinning machine. *Journal of Computational and Theoretical Nanoscience* 12(9): 2016–2022.

Kadim, E. J., Noorden, Z. A., Adzis, Z., & Azis, N. 2021. Nanoparticles application in high voltage insulation systems. *IEEE Transactions on Dielectrics and Electrical Insulation* 28(4): 1380–1399.

Kavitha, D., Nambiar, T. N. P., Sindhu, T. K., & Balachandran, M. 2015. Modeling of electric field distribution in epoxy nanocomposites using finite element method. *J. Electr. Eng.* 15(3): pp. 7–7.

Lee, J. I., Jeong, W. H., Dinh, M. C., Yu, I. K., & Park, M. 2023. Comparative analysis of XLPE and thermoplastic insulation-based HVDC power cables. *Energies* 16(1).

Liu, D., Hoang, A. T., Pourrahimi, A. M., Pallon, L. K. H., Nilsson, F., Gubanski, S. M., Olsson, R. T., Hedenqvist, M. S., & Gedde, U. W. 2017. Influence of nanoparticle surface coating on electrical conductivity of LDPE/Al2O3 nanocomposites for HVDC cable insulations. IEEE *Transactions on Dielectrics and Electrical Insulation* 24(3): 1396–1404.

Pallon, L. K. H., Hoang, A. T., Pourrahimi, A. M., Hedenqvist, M. S., Nilsson, F., Gubanski, S., Gedde, U. W., & Olsson, R. T. 2016. The impact of MgO nanoparticle interface in ultra-insulating polyethylene nanocomposites for high voltage DC cables. *Journal of Materials Chemistry A* 4(22): 8590–8601.

Thabet, A., & Fouad, M. 2021. Assessment of dielectric strength and partial discharges patterns in nanocomposites insulation of single-core power cables. *Journal of Advanced Dielectrics* 11(4): 1-10.

Zhu, M. X., Li, J. C., Song, H. G., & Chen, J. M. 2020. A phase field model for the propagation of electrical tree in nanocomposites. *IEEE Transactions on Dielectrics and Electrical Insulation* 27(2): 336–342.