Electric Field Computation and Optimization for A 400 kV Y-shaped Composite Cross-arm

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***Abstract*—A new proposed Y-shaped composite pylon has a potential to become the next new generation 2x400kV overhead line transmission tower. However, according to previous work, the electric field magnitudes inside the hollow cross-arm tube exceeds the onset electric field strength of corona, which does not meet the requirements of insulation. In this paper, an electrostatic field model is established by using finite element method analysis. Aiming to previous existing issues, we propose using low density polyethylene (LDPE) as filling material to fill the cross-arm. Meanwhile, the clamps structure is redesigned. Then, the electric field distribution results along the surface of the cross-arm and around the clamps are presented. Furthermore, through the shape optimization, the electric field distribution of clamps and sheds meets the design criteria. Finally, taking advantages of the insulation margin, the conductor enclosure is removed and the height of the clamp is decreased. The final clamp structure meets the insulation requirement.**

Keywords—composite pylon, electric field, optimization, uni-body cross-arm, Finite Element Method

I. INTRODUCTION

Recently, the development of comprehensive performance of insulating material has progressed the interest for the composite towers in transmission system [1]. One novel design of a composite pylon uses a Y-shaped structure and an integrated cross-arm as Fig. 1 (a) shows. The pylon mast is made of steel, and a bare grounding conductor goes down through the Fiber-Reinforced Plastic (FRP) cross-arm tube and connects with the pylon body. This pylon has lower height and lower shielding failure rate when compared with a lattice tower at the same voltage level [2]. Meanwhile, the application of the composite pylon can reduce both the line corridor areas and the use of steel, making it a good alternative to the traditional transmission towers [3].

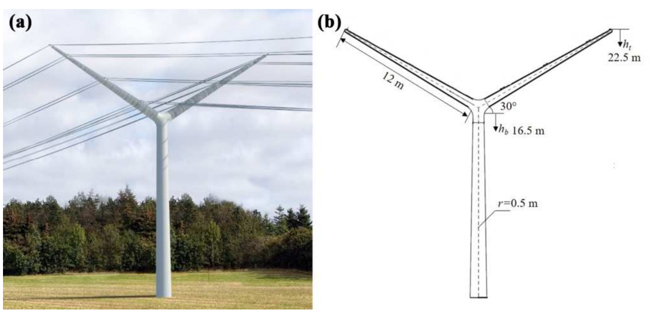

Fig. 1 (a) The concept map of the Y-shaped composite pylon. (b) The structure parameters of the composite pylon.

Insulation performance is a factor of concern in the process of transmission tower design. Insulating performance is related to the safe and reliable operation of transmission lines. Under long-term operation condition, the local electric field distortion can cause corona activities, which accelerates the insulating material ageing and degeneration, leading to mechanical and insulation failure [4]. Research work shows that the higher local field strength is also the inducement of dry flashover [1]. Thus, improving the electric field distribution is of great significance in the design of the transmission insulation.

However, to date, there are just a few scientific works on the electric field and potential distribution on the composite pylon. Reference [3] investigated the electric field distribution of uniform and non-uniform shed profiles on the cross-arm according to the guidelines of IEC 60815-3 [5]. The results showed that there was no obvious significant difference between the performances of both shed profiles. Afterwards, a systematic research had been conducted in terms of the electric field strength on this uni-body composite cross-arm [1]. The work suggested that plastic conductor clamps combined with metallic conductor enclosures were prefer solutions to improve the degree of electric field distortion based on the Finite Element Method (FEM) simulation analysis. However, there are two critical problems with respect to this cross-arm. One is the electric field strength in the air between the conductor and clamp exceeding 10 kV/mm, which is far beyond the inception electric field strength of the corona. This issue is solved by installation of a conductor enclosure to increase the equivalent diameter of the conductor. The other is the ground downlead inside the hollow cross-arm exposed to a maximum electric field (E-field) magnitude of 3.08 kV/mm. This is still a pending problem that restricts this composite pylon promotion [1].

Here, we propose that using LDPE as filling material to suppress the electric field distortion inside the cross-arm. Additionally, the configuration of the conductor clamps is redesigned, and the gap between the conductor and the clamp is filled with semiconductor material. Based on the configuration of the uni-body cross-arm referenced by [1], the 2D composite pylon models are built and FEM analysis is used to simulate the electric field distribution. The ceramic parts are considered and the clamp height is adjusted to make

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the electric field magnitude of the cross-arm meet the electrical requirements.

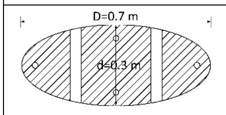
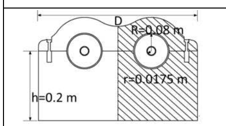
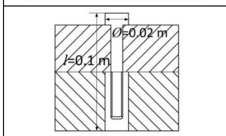
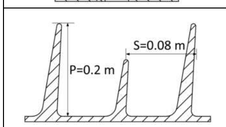
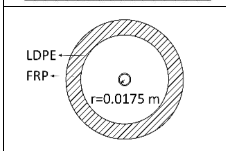
II. Electric Field Computation

A. Configuration of the pylon

The pylon adopts a novel uni-body cross-arm with the inclination angle of 30°, and the parameters of the pylon are illustrated in Fig. 1 (b). The length of the cross-arm is 12 m. The integration of insulators in the form of uni-body cross-arm replaces the hanging insulator strings used for traditional lattice towers. The clamps are mounted on the cross-arms, and the Aluminum Conductor Steel-Reinforced (ACSR) conductors are a duplex bundle. According to EN 50341-1 [6] and CIGRE TB.72 [7], the air clearances between phase conductors and upper phase conductor to shield wire on the uni-body cross-arm should be 3.68 m and 2.8 m, respectively [8]. Two copper conductors with radii of 17.5 mm inside the two cross-arms are connected with the steel pylon body to provide the ground potential to the shield wires and the path to ground to the lightning current.

In the initial design of the clamps, the configuration inside the clamps exhibits a trumpet shape (Fig. 2). In this paper, the trumpet-shaped fixed conductor design is disregarded, and the gap between conductor and clamp is filled with semiconductor material. The sketch of the component shape, material properties and the simulation parameters are shown in Table I. All models in our research, the filling materials are always considered, and variables include bolt material, conductor enclosure, and height of the clamps and the conductors.

TABLE I. Component Parameters

Sketch	Components		
	Material	*Permittivity*	*Resistivity*
	Clamp[a]: PVC	2.9	-
	Semi-conductor layer	-	0.5
	Conductor: ACSR	-	2.82×10^{-8}
	Enclosure: steel	-	2.48×10^{-7}
	Bolt: steel/Al_2O_3	-	2.48×10^{-7}
	Sheds: silicone rubber	3.7	-
	Cross-arm: FRP	2.64	-
	Filling material: LDPE	2.2	-
	Downlead: copper	-	1.67×10^{-8}

B. FEM model

When the simulation object has rotationally symmetrical geometries, 2D FEM model is widely adopted due to its time saving characteristic and limited errors compared with 3D model. In this paper, 2D composite pylon models with front and lateral view are built. The air area and far-field boundaries are same circles with radii of 50 m. In the process of mesh, extra fine mesh mode is employed. The Electric Currents

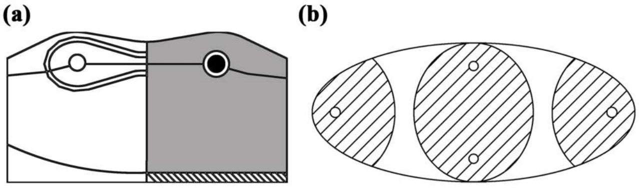


Fig. 2 (a) The front view of the original configuration of the conductor clamp. (b) The top view of the cross-section of the clamp.

interface and Frequency Domain study are used. The stranded conductors as well as conductor enclosures are applied voltage of 400/√3×√2 kV. The phase angle difference of three phase conductors is ±120°.

III. Results and Discussion

A. Critical Electric field requirements for the cross-arm

In a long-term operation of transmission tower, the electric field distortion along and inside the cross-arm can cause local overheating or even partial discharge, which is detrimental to the organic component insulating properties. The Y-shaped novel pylon is expected to have a lifetime of 40~50 years. Thus, the strict restriction on the electric field magnitudes along and inside the uni-body cross-arm should be specified. According to previous work form [1], Electric Power Research Institute (EPRI) [9] and IEEE taskforce on Electric Fields and Composite Insulators [10], the critical electric field criteria are listed below. It should be noted that there are two criteria on the metallic end fittings and grading devices: 1.8 kV/mm from reference [5] and 2.4 kV/mm from reference [8]. Here, the stricter criteria are recommended in our research.

1) The electric field magnitude on the surface and 0.5 mm above the surface of sheath and sheds-0.45 kV/mm.

2) Surrounding the metallic end fittings and grading devices-1.8 kV/mm.

3) The electric field inside the Fiber Reinforced Plastic and the weather-shed material -3 kV/mm.

4) The point at the organic material such as shed housing and unenergised metal such as mental bolt -0.35 kV/mm.

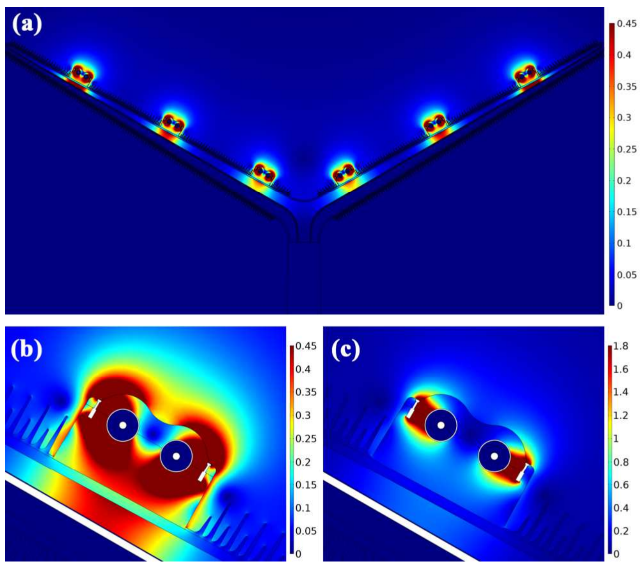


Fig. 3 (a) E-field cloud chart on the cross-arm with metal bolts. The zoomed chart based on (b) the criteria 1) and (c) the criteria 2).

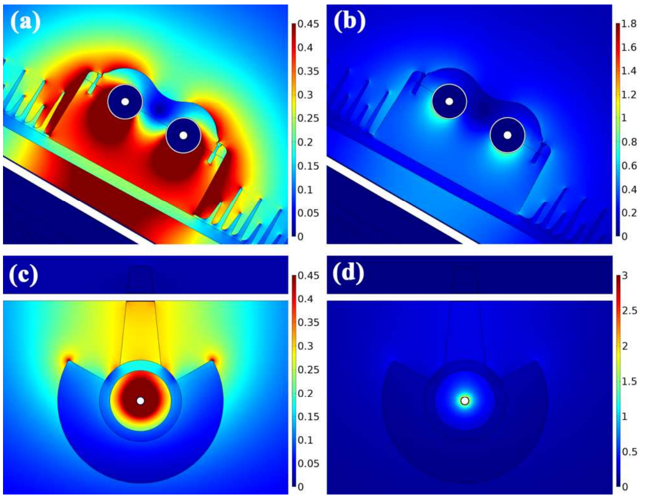


Fig. 4 E-field cloud chart on front view of clamps with the Al_2O_3 bolts based on (a) the criteria 1) and (b) the criteria 2). E-field cloud chart on the lateral view of clamp and the cross-arm based on (c) the criteria 1) and (d) the criteria 3).

B. Metallic Bolts and Enclosure Considered

In the initial model, the height of the conductors are 0.3 m. Two steel bolts are mounted at both sides of the conductor. The Fig. 3 (a) shows the plots of E-field distribution of the whole cross-arm. It can be clearly seen that the E-field magnitude inside the cross-arm below the upper clamps is the highest compared with the areas below the middle and lower clamps. If the worst case that region around upper phase clamp meets the E-field criteria, the other places would satisfy the electrical requirements. Thus, only the upper clamps are considered. Figure 3 (b)-(c) shows the contour plots with the maximum color bar range of 0.45 kV/mm criteria 1) and 1.8 kV/mm criteria 2). The areas in the chart where the field strength exceeds the maximum value are displayed in dark red. We found that the E-field magnitudes on the surface of the shed and the ground downlead as well as on the path at 0.5 mm above the shed surface meet the critical E-field criteria. However, the E-field strength between the conductor enclosure and the metal bolts is much higher than 1.8 kV/mm, which suggests that the presence of the filling material has little effect on decreasing the E-field around the clamps.

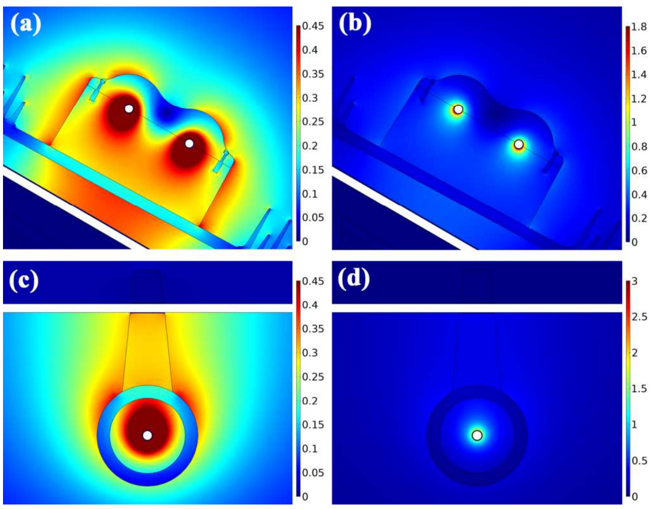


Fig. 5 E-field cloud chart on the front view of clamps without the enclosures based on (a) the criteria 1) and (b) the criteria 2). E-field cloud chart on lateral view of clamp and the cross-arm based on (c) the criteria 1) and (d) the criteria 3).

C. Al_2O_3 bolts

In order to relieve the electric field strength between the enclosure and metal bolts. The porcelain Al_2O_3 bolts that have same structural specifications as steel bolts are used as alternatives to fix the clamps. In this design, there is no metallic components and grading parts on the cross-arm so that the criteria 4) is no longer considered. The E-field distribution around the clamps is shown in Fig. 4. The figures show the E-field distribution around the enclosure has been largely decreased and meets the criteria 2). Meanwhile, the lateral chart shown in Fig. 4 (d) indicates that the filling material leads to an electric field lower than 3 kV/mm, which means the previous issue of having the local E-field magnitudes within the hollow cross-arm higher than the air breakdown strength is solved by using filling material. Metal bolts in the previous case can play a shielding role to protect the sheds from being exposed to the strong field. However, the steel bolts substituted by ceramic bolts causes the extension of the high intensity E-field, and the E-field magnitudes on the surface of the shed and the clamps exceed the 0.45 kV/mm.

D. Remove the enclosure and sheds around the clamps

The function of the enclosure is to extend the equivalent radius of the conductor and to decrease the E-field magnitude on the conductor surface. However, it causes the extension of the dark red areas on the both sides of clamps. Therefore, we attempt to decrease the conductor enclosure radius to minimize the high intensity of the E-field extension. Meanwhile, the sheds around the clamps are trimmed to avoid sharp parts near the clamps. When the conductor enclosure is removed, the E-field chart is shown in Fig. 5. It can be clearly seen that the E-field distribution becomes more uniform, and high intensity E-field is restrained inside the clamps. This moment the E-field strength on the surface of sheds and clamps is lower than 0.45 kV/mm. The detailed data are shown in Fig. 6 including the E-field strength on the path along creepage distances on sheds and clamps, internal path

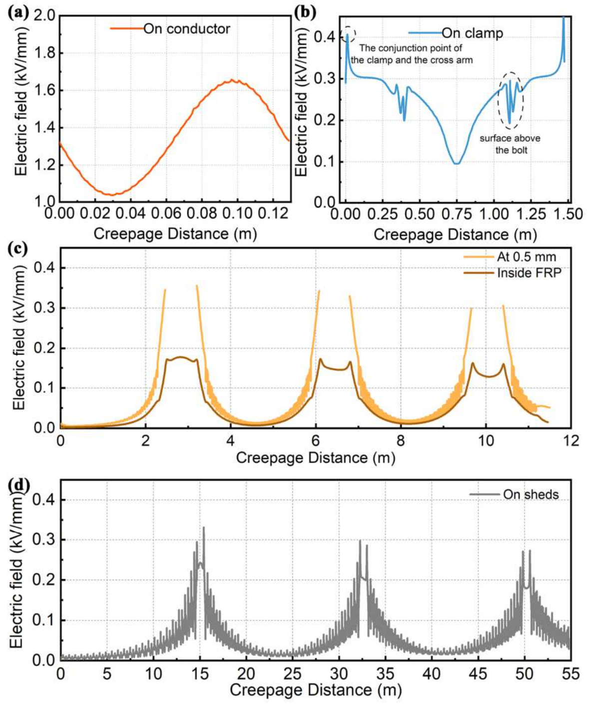


Fig. 6 E-field magnitudes (a) on the path around the conductor, (b) on the surface of clamps, (c) on the path 0.5 mm above and below the cross-arm surface, and (d) on the surface of sheds.

inside the cross-arm, and the external path at 0.5 mm above the surface of sheath. Although the elimination of the enclosure increases the E-field around the conductors to a certain extent, but the all concerned regions are still meet the requirements.

E. Decrease the height of the clamps

Although the revised clamps can meet the electric criteria, we believe there is still room for optimization due to the insulation margin between the simulation results and criteria. First, the joint seam between clamp and cross-arm is filleted to smooth the surface of the clamp. Then, the height of the clamp is decreased. Decreasing the distance between the clamps and the downlead can cause the increase of the E-field magnitude around the metal parts. However, the lower clamp height has three benefits: (1) Low height of the conductor can decrease the moment of force on the clamps when the conductor lines swing. It can decrease the mechanical requirement and benefit the production of the composite cross-arm. (2) When the height of the clamps and conductors is low, the flashover voltages will increase because there is lower probability that the arc bypasses the sheds to discharge. (3) Low height of the clamps can minimize the visual impact on the appearance of the pylon. Here, the height of the conductors from cross-arm is adjusted to 0.2 m. E-field cloud charts are shown in Fig. 7. The E-field strength inside the clamps and cross-arm is higher than the case before the clamp optimization. The detailed data are shown in Fig. 8. We found that the E-field magnitude on the surface of the conductor is near the critical requirements, but the E-field magnitudes on the surface of the shed and inside of the cross-arm are lower than the criteria 1) and 3). It should be noted that the after fillet on the seam of the clamp and cross-arm, the E-field magnitude on the corner of the clamps is decreased and lower than the previous case. Thus, we conclude that the revised clamps with the height of the conductor of 0.2 m is a feasible design after a trade-off on the multi-factor considering.

IV. Conclusion

In this paper, the electrostatic analysis of a Y-shaped composite pylon was investigated. To simplify the computational procedure, 2D models are built to evaluate the E-field magnitudes on the areas of interest. The configuration of the conductor clamps is redesigned and LDPE is used as filling material to curb the high intensity E-field inside the

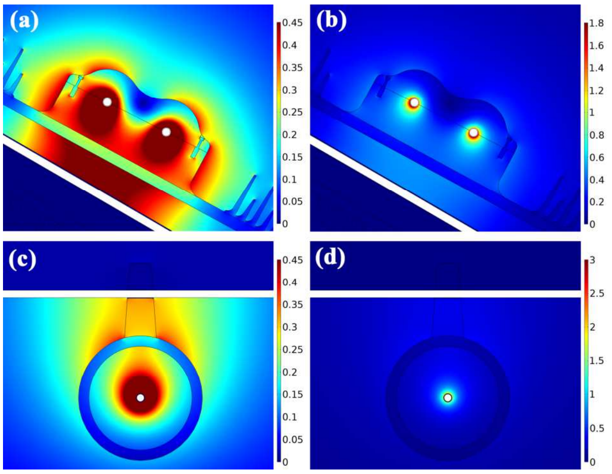


Fig. 7 E-field cloud chart after optimization on the front view of clamps without the enclosures based on (a) the criteria 1) and (b) the criteria 2). E-field cloud chart on lateral view of clamps based on (c) the criteria 1) and (d) the criteria 3).

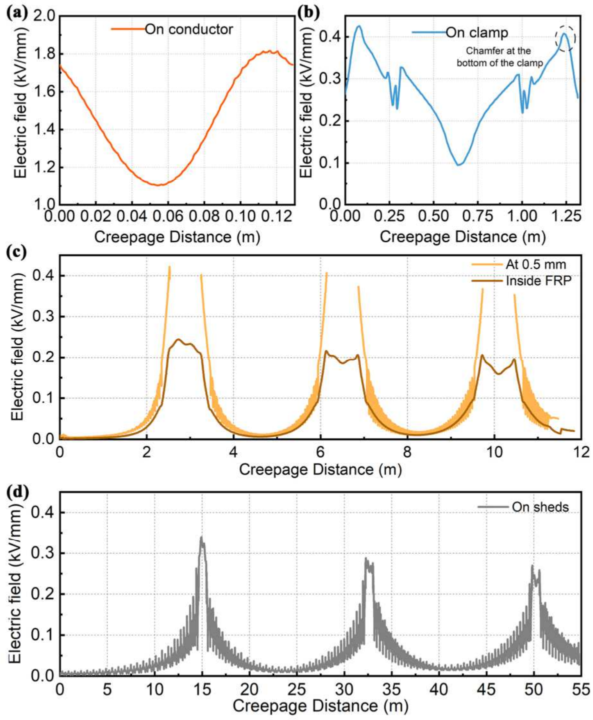


Fig. 8 E-field magnitude after optimization (a) on the path around the conductor, (b) on the surface of the clamp, (c) on the path 0.5 mm above and below the cross-arm surface, and (d) on the surface of sheds.

cross-arm. Based on the simulation results, we further optimize the material selection and the shape of the clamps. Finally, we found removing the enclosure combined with adjusting the conductor height from the cross-arm of 0.2 m is a balanced scheme to meet the E-field, production and appearance requirements.

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