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The Influence of a Curved on Copper-type Down Conductor

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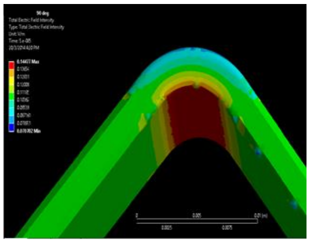
Graphical abstract



Abstract

The objective of this paper is to investigate the influence of curved copper conductor angle under current transient and voltage using numerical analysis approach. A thorough evaluation for copper down-conductor attainable in lightning protection system with a recommended cross-sectional area of conductor based on the standards under different numerous angles will be examined. The results in terms of field values were reviewed and considered in resemblance with the critical breakdown value of air. Although the comparison is by no means rigorous, it may shed some light on how the geometrical modelling and the physical parameters weighted in the computational modelling and how further refinement could be synthesized. In the end, a realistic approach for the optimal angle of down-conductor contributed to the installation design of a down-conductor in confined area is set and establish.

Keywords: Lightning protection system; down-conductor

■1.0 INTRODUCTION

Nowadays, the installation of down-conductor on protected structure is following to the shape of building just to meet the installation aesthetical requirements. Hence, the exposed-type of down-conductor was bended to certain degrees during the installation process based on the structure itself. Lightning Protection System (LPS) is different for various types of structure, for instance tall buildings, power substation and telecommunications and etc., specifically depending on the level of protection (LPL). However, they are similar for common structures, for instance a house or small buildings. Furthermore, concerning the isolated structure such as oil tanks, solar PV, an isolated protection mechanism is then needed [1]. The general principle of LPS is that the type and location of the LPS should be carefully considered at an early stage of its design, in order to minimise costs, especially for the electrical conductive parts of the structure [1]. An LPS is categorized into four different levels of protection, i.e. Level I, II, III, and IV [1]. Level I refers to the highest level of protection down to Level IV as the lowest level of protection. These levels of protection are also recognized in different classifications, i.e. Class I, II, III, and IV, as described by MS IEC 61643-1 [2]. These four classes are characterized as a set of construction rule, based on corresponding Lightning Protection Levels (LPL) [3], where each level has fixed maximum and minimum lightning current parameters. These maximum and minimum parameter values of lightning current are essential for designing lightning protection components. For instance, the current capability of SPDs, separation distance against dangerous sparking, and derivation of the rolling sphere radius (for positioning of the air-termination system), thus classifying the lightning protection zone. Recently, the theory to calculate the design current based on return period is extensively and progressively being employed in order to determine the LPL [4].

Lightning Protection Zone (LPZ) defines the position of the lightning electromagnetic environment [3] according to the concept of structure measurements, thus forming basic protection of electrical systems within buildings and structures against surges from Lightning Electro Magnetic Pulses (LEMP). A standard LPZ separates the building or structure to be protected, into internal lightning protection zones, according to the LEMP threat level. Consequently, the areas with different LEMP risks can be amended based on the immunity of the electrical system, and a suitable LPZ is achieved, according to the number, type, and sensitivity, of electronic systems. This LPZ can range from small local to large integral zones, such as a whole building [5]. The LPZ defined in MS IEC 62305-4 is based on the type of lightning threat [6], and required that internal zones be defined against the immunity of the protected electrical systems. Equipotential bonding for all metal components and utility (service) lines entering a structure or building should pass either through the boundary that is formed by the shielding measures of each internal zone, or directly through appropriate SPDs [2].

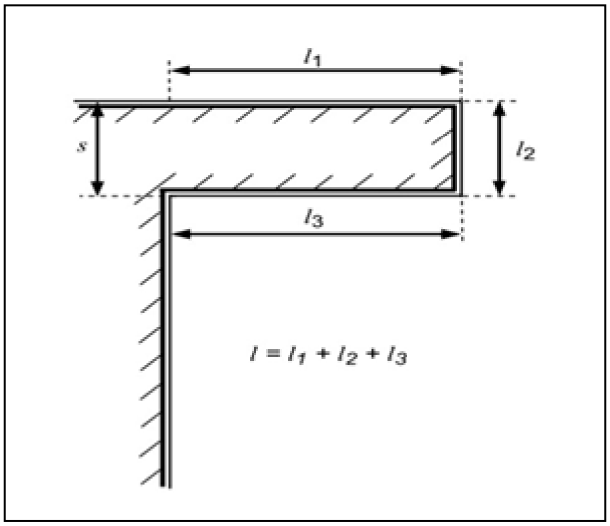


Figure 1 Loop of down-conductor based on MS IEC 62305

2.0 STANDARD RECOMMENDATION

2.1 Installation of Down-conductor

MS IEC 62305-3 recommendation on down-conductor installation criteria specified that it should has several of aligned current pathway which has least possible length that connected to the same earthing system of the structure [7]. Particularly, for the common structure it must more than two down conductors with a safety distance in between and feasibly placed at unprotected corner [7]. Moreover, a straight and vertical down-conductor is advisable in order to provide the minimum distance between the air termination to the earth for lightning current [7]. In other words, the maximum angle allowed and acceptably utilized is 90 degrees, which is vertically aligned with the structure [7]. Figure 1 illustrates the detail construction of down-conductor based on this standard [7]. If this configuration of straight and vertical down-conductor is being used, then the loops configuration is best being evaded as this will probable produce sparks due to increase loop inductance [8]. However, if this loops configuration cannot be avoided, the separation distance, s between the gap must be larger than the total loop, I [7]. Equation (1) is used to calculate the occurrence of sparks due to voltage difference where h is the height of the down-conductor above the ground, with earth resistance of R_{gr} and L_h is the per unit inductance of down-conductor. Referring to the equation, the inductance rises linearly as the height of down-conductor is greater. If the voltage across the point of protected system at certain height h exceeds the certain breakdown voltage, side flashes will definitely happen [8].

$$V(t) = R_{gr} I(t) + L_h h \frac{dI(t)}{dt} \qquad (1)$$

2.2 Material and Dimension of Down-conductor

Various materials were globally used in manufacturing the down-conductor system such as copper, aluminium, stainless steel, galvanized iron and lead in current industries. Those materials are highly conductive with purity of almost 99%. This is to ensure, a successful conduction of the current during lightning strike to a protected structure. Shape-type of down-conductor used can varies from solid tape or round to stranded type. The minimum dimension proposed by MS IEC 62305-3 is 50mm^2 but does not applicable to all shapes and materials being used [7]. For instance, if the copper solid tape been utilized, the recommended minimum cross-sectional area is 50mm^2 [7]. A careful selection of material being used in down-conductor must been made based on the environmental circumstances. It means that for the sulphates-concentrated environment, either copper or aluminium type is suggested due to its good resistivity [7]. However, aluminium is incompatible when used in earthing or embedded in concrete except in open air, but this is not applicable for copper material which is appropriately used for all those stated location of placement and environment condition [7]. As such, copper-type is being chosen in this study.

2.2 Overview of Previous Studies

Previous work done by Hu and Inaba [9] on thick copper wires with diameter 1 mm-2 mm and bent at 90 degree is remarkable. They found that the wire was misshaped into opposite direction then broke as aresult of the magnetic force and the skin effect. In contrast, for the thin copper wire with diameter of 0.3 mm and 0.6 mm, the thermal failure (ohmic heating) was primarily responsible.

Additionally, Hu, Inaba and Kindersberger [10] stated that the curved angle have some influence on the breaking impulse current peak values; which where the value of the electromagnetic force that is distributed along the curve correspondence to the shapes of the wires. Whilst, Liu, Morita, Iwao and Inaba [11] concluded the relationship between temperature and angle of wire which is the temperature deviation increased with the increased of current ratio, while the curved angle and curved radius is decreased. Clearly, the temperature of horizontal curved conductor is higher than a straight conductor.

3.0 NUMERICAL ANALYSIS

3.1 Modelling of Down-conductor

The present work focuses on simulating the bending effect at certain angles on copper material down-conductor type. About 1m of the copper solid tape was used and bended to 90 and 120 degrees. For comparison, the zero degree or straight copper tape was used as reference. The subjects were tested with lightning current of 10/350µs waveshape as proposed by MS IEC 62305-1 which is relevantly accepted for all different level of LPL in LPS [3]. A numerical method analysis applied in current study is simulated by Ansys modelling program which is based on the Maxwell equation. The current impulse of 200kA was applied in this case for each angle of copper tape, as recommended by the MS IEC for LPL 1 [3]. The purpose of the first part of this modeling is to investigate the effect of current on the copper itself.

3.1 Modelling of Inner-Part of Bend Down-conductor

The next part of the modelling is to examine the inner part itself with a distance between a concrete in term of electric field only. Figure 2 illustrates the schematic diagram of an inner-part curved angle modelling. In this case, a copper tape with angle of 90 and 120 degrees with 40 cm separation distance between a concrete wall is demonstrated. This separation distance of 40 cm is calculated for 10 m length of single down-conductor for LPS III and IV which 0.25/100 us wave shapes is being considered [7]. The copper tape was randomly tested at 100 kV voltage with a lightning frequency ranging from 750 MHz to 1.5 GHz [12]. Furthermore, for worst case scenario, the concrete wall is assumed to have a higher conductivity which equal to zero potential.

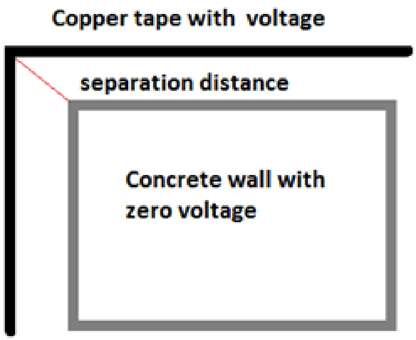


Figure 2 A schematic diagram for an inner-part case

3.1 Modelling of Outer-part of Down-conductor

As continuity, the next objective of current study is to investigate the effect of the electric field towards the outer corner or area of the bended tape as schematically modelled in Figure 3. This model has similar dimension of the bended copper bar in previous section. The bar is to parallel a copper rod with 1 cm in diameter which is located approximately 5 cm away from the outer part of copper bar. The tested parameter is randomly selected to be at 50 kV voltage, and set of frequency ranging from 750 MHz ~ 1.5 GHz.

In this paper, the electric field profile based on voltage analysis of copper bars at different angles and distances will be considered. The results will be compared with the critical breakdown value of electric field in the air and later the optimum value of bar angles will be evaluated. These evaluated angles then will be compared with a standard value which the results will be discussed in detailed.

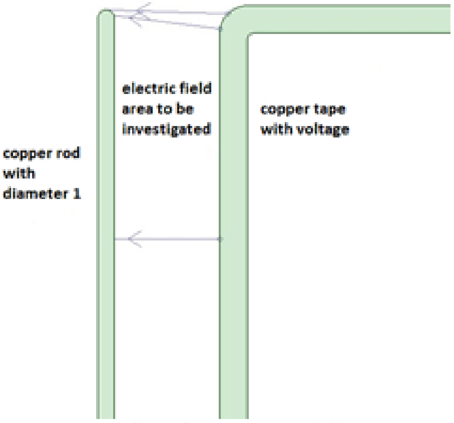


Figure 3 Outline of outer-part modeling

■4.0 RESULT AND DISCUSSION

For the first modelling part of the down-conductor, the result is depicted in Figure 4. This figure shows the analysis was conducted such that the electric field intensity for the 90 degree angle after being injected with peak current of 200 kA on the cross sectional area. The recorded concentration of electric field is at its maximum value at the inner side of bending area. In Figure 5, the electric field intensity for the 120 degree indicated that the concentration of electric field is higher than straight copper tape as in Figure 6. Among others, the electric field for the zero degree angle or straight tape is uniformly distributed. The result shows that at the bent area of copper, the inner part has more significant impact on the electric field compared to the outer part.

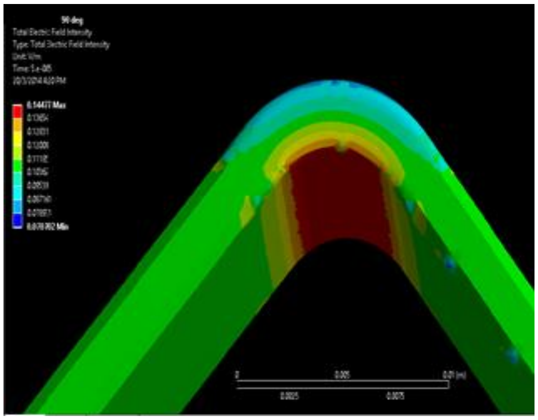


Figure 4 Electric field intensity at 90 degree

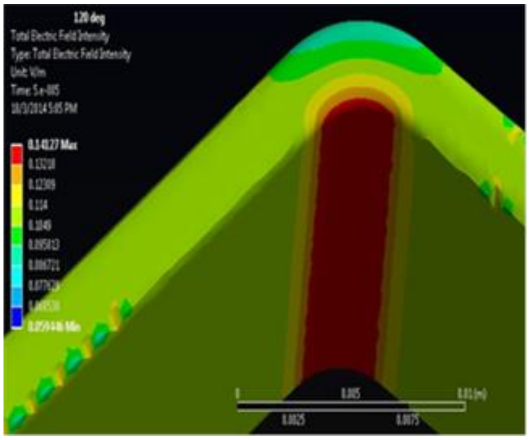


Figure 5 Electric field intensity of 120 degree

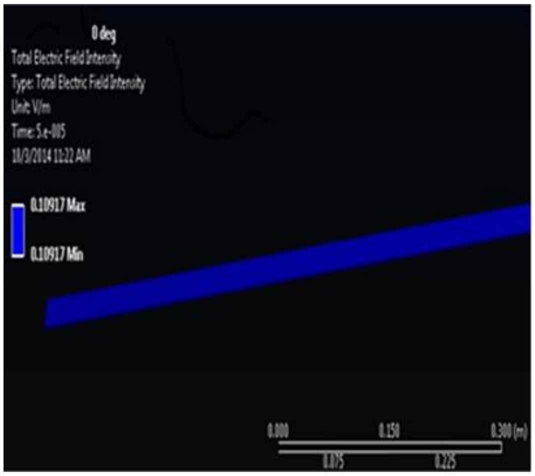


Figure 6 Electric field at straight copper

To check the validity of this statement, the next simulation on the inner-part is applied; therefore the result is indicated in Figure 7 which is for the 90 degree case. It is found that the electric field intensity is higher near the edge of concrete wall. Whilst, Figure 8 describes the schematic diagram of electric field measurement applied in this modelling based on the voltage analysis. From Figure 8, five points of the electric field difference (ΔE) are quantified. The calculated electric field along the Line 1 is at a distance of 40 cm between vertex (bent) of copper and the edge of concrete wall. The separation distance between Line 2 and 3 with Line 1 is 2 cm, when measured from the root attached at the concrete wall whilst Line 4 and Line 5 are measured to be 8 cm away from Line 1 under the same condition.

For the 120 degrees, the overall view of the electric field distribution is illustrated in Figure 9. In Figure 9, the distribution of electric field is quite relatively near to the edge of concrete wall. A more detailed result of electric field difference, ΔE for both 90 and 120 degrees are depicted in Figure 10 and 11. The critical breakdown voltage of air, 30 kV/m is taken into consideration for this study. Based on Figure 10, the highest electric field difference point occurred at Line 1, which exceeds the critical value of air for 10 cm.

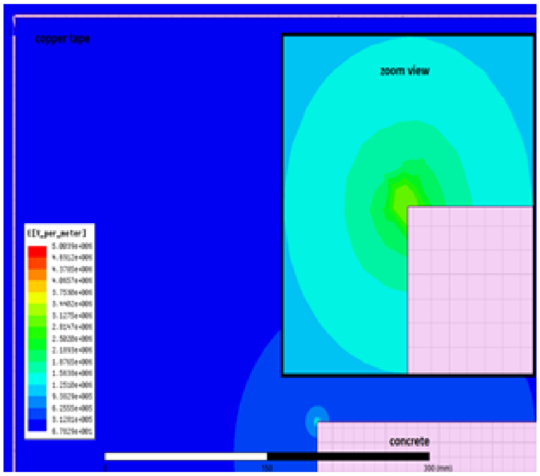


Figure 7 An inner-part of 90 degree angle with 40 cm separation distance

Therefore, the highest critical breakdown value for 90 degree inner-part is notable between area of bent copper and the concrete. Hence at Line 2 and Line 3, the ΔE does not surpass the critical value of air in absentees of the arching. This behaviour was followed at Line 4 and 5, which the ΔE are much lesser than the ΔE value at Line 2 and Line 3. Overall, no arching was presented at Lines 2, 3, 4, and 5 excluding Line 1 area.

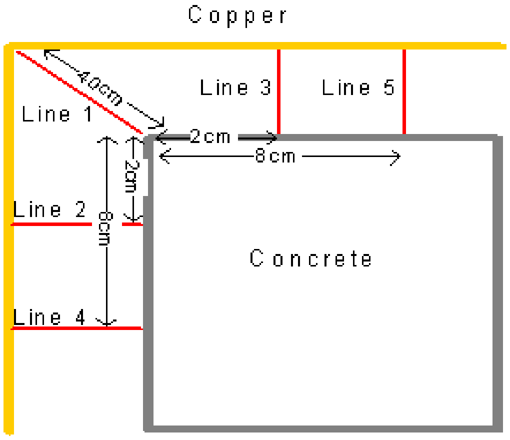


Figure 8 A schemetic diagram of electric field measurement

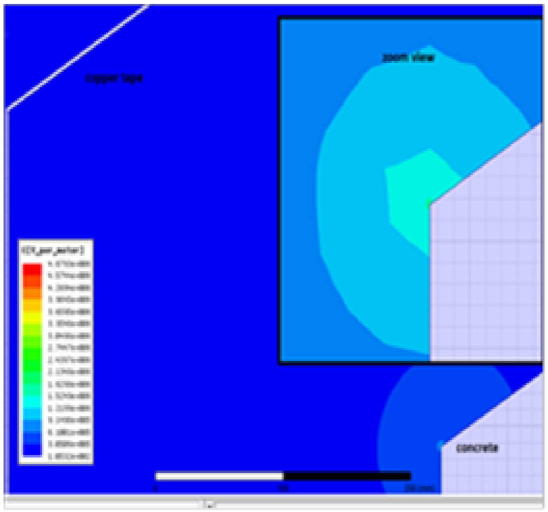
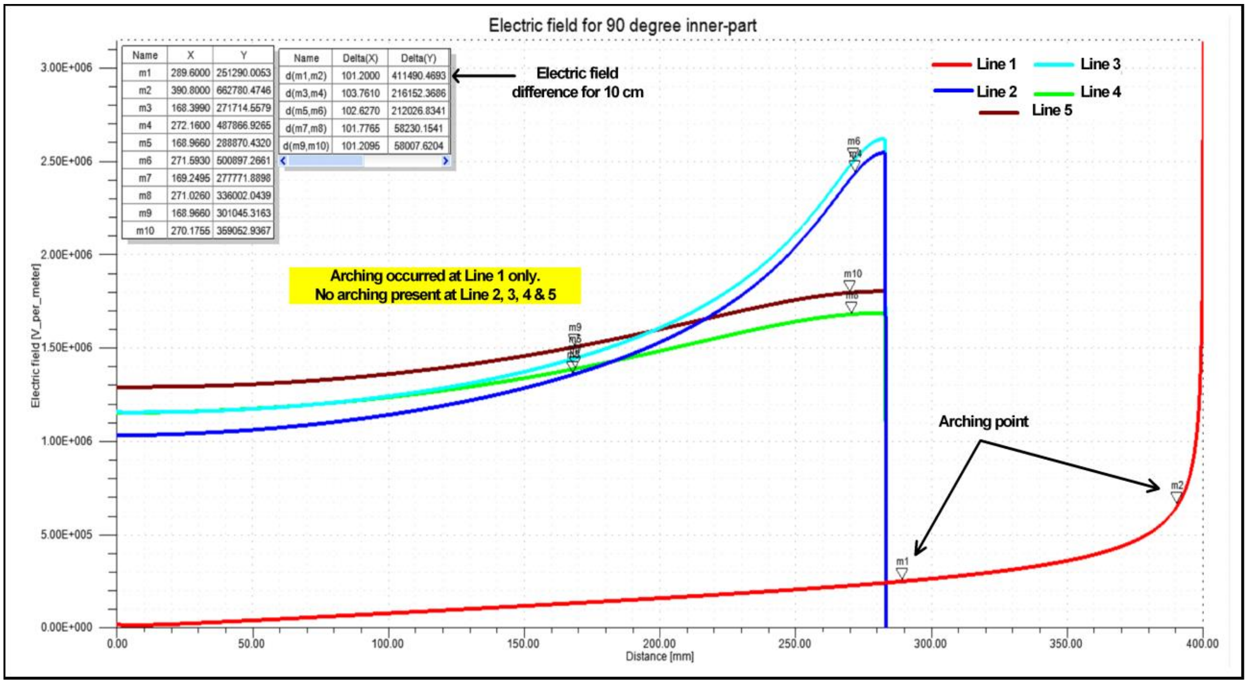


Figure 9 Inner-part of 120 degree angle with 40 cm separation distance



Name	X	Y
m1	289.6000	251290.0053
m2	390.8000	662780.4746
m3	168.3990	271714.5579
m4	272.1600	487866.9265
m5	168.9660	288870.4320
m6	271.5930	500897.2661
m7	169.2495	277771.8898
m8	271.0260	336002.0439
m9	168.9660	301045.3163
m10	270.1755	359052.9367

Name	Delta(X)	Delta(Y)
d(m1,m2)	101.2000	411490.4693
d(m3,m4)	103.7610	216152.3686
d(m5,m6)	102.6270	212026.8341
d(m7,m8)	101.7765	58230.1541
d(m9,m10)	101.2095	58007.6204

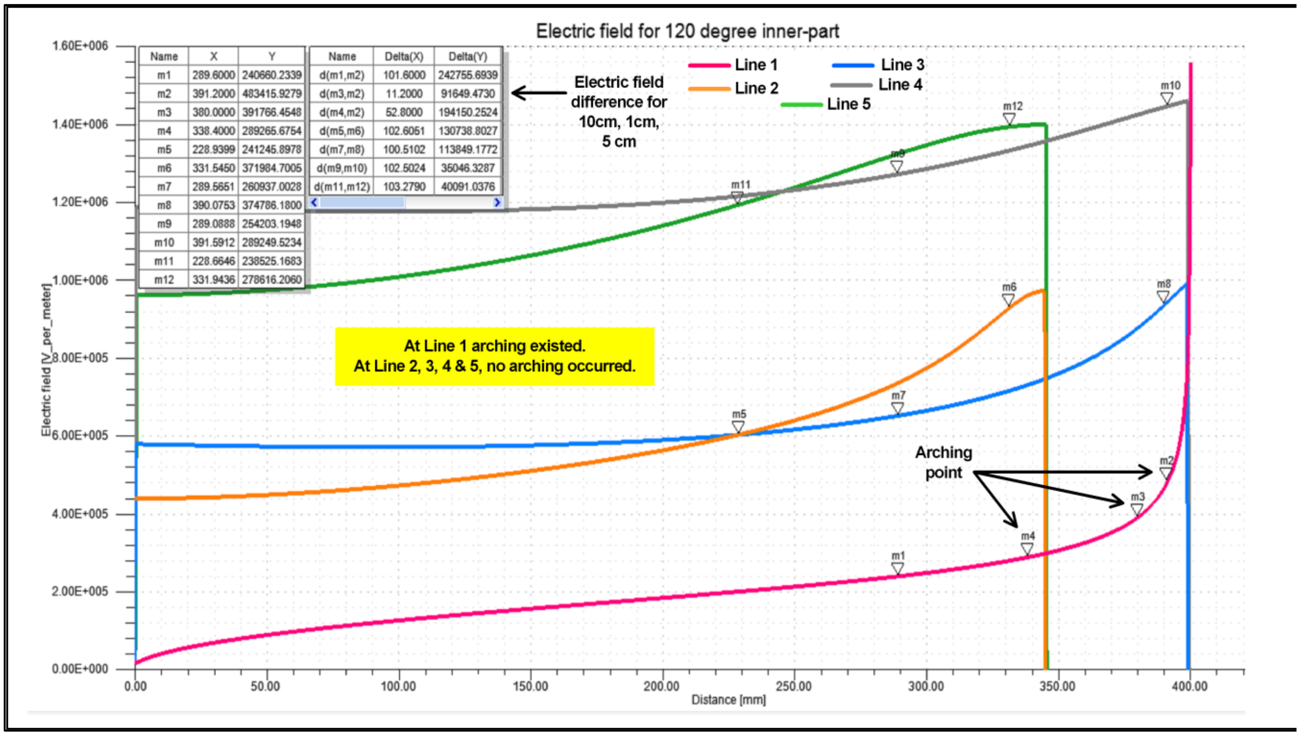
Figure 10 Electric field for 90 degrees with separation distance 40 cm

When the inner-part was bended to 120 degrees at separation distance of 40 cm from the wall, the ΔE in Line 1 exceeded the critical value of air for only 5cm only. This ΔE value is substantially lower in contrast to ΔE value at Line 1 for 90 degrees. In contradiction, at Lines 2, 3, 4 and 5 the ΔE are not overreach the critical value, thus arching do not occurred at these area. The summarized data for inner-part modelling are tabulated in Table 1. In general, both 90 and 120 angle has an arching at the inner-part as both values of electric field overcome the critical value. Particularly, 90 degree is more severe in arching than 120 degree because of the arching point is about 10 cm compared to 120 degree which is about 5 cm.

Table 1 Tabulated ΔE for inner-part bent area

Degree of bent	**Point of ΔE, (V/10 cm)**				
	Line 1	***Line 2***	***Line 3***	***Line 4***	***Line 5***
90	411490.5	216152.4	212026.8	58230.2	68007.6
120	194150.3 *	130738.8	113849.9	35046.3	40091.0

* Value of ΔE for 5 cm



Name	X	Y
m1	289.6000	240660.2339
m2	391.2000	483415.9279
m3	380.0000	391766.4548
m4	338.4000	289265.6754
m5	228.9399	241245.8978
m6	331.5450	371984.7005
m7	289.5651	260937.0028
m8	390.0753	374786.1800
m9	289.0888	254203.1948
m10	391.5912	289249.5234
m11	228.6646	238525.1683
m12	331.9436	278616.2060

Name	Delta(X)	Delta(Y)
d(m1,m2)	101.6000	242755.6939
d(m3,m2)	11.2000	91649.4730
d(m4,m2)	52.8000	194150.2524
d(m5,m6)	102.6051	130738.8027
d(m7,m8)	100.5102	113849.1772
d(m9,m10)	102.5024	35046.3287
d(m11,m12)	103.2790	40091.0376

Figure 11 Electric field for 120 degrees with separation distance 40 cm

Next, modelling result for outer-part of bent copper are depicted in Figures 12 and 13. For 90 degree copper, the distribution of electric field intensity is greater at the outer-part of bent area of copper bar compared with others. In 120 degree, the allocation of electric field intensity is mostly between the outer-part bent area of copper and tip of the rod. Both Figures 12 and 13 indicated that the outer part of the bended area has a significant effect on the electric field which the detailed distribution are described in Figures 15 and 16. Before that, Figure 14 shows the schematic diagram of electric field measurement for the outer-part of curved down-conductor. The electric field is measured along the Line 1 which is at 5 cm distance between curved area and the tip of copper rod. Line 2 is approximately 1 mm from the Line 1 that covered the curved part to the tip of copper. Next, Line 3 is measuring the electric field in between the copper rod and bar which is about 2 cm from the bent area.

According to Figure 15, at Lines 1 and 2, arching was presented in between the bended area of copper tape and tip of copper rod. The arching intensity was higher which exceeded the minimum value of critical breakdown. Line 3 which is measured 2cm away from the bent part does not indicate any arching activity as the electric field is lower than the critical value. Whilst, in relation to Figure 16, the highest ΔE is obtained at Line 1 and followed by Line 2, where arching happened due to higher critical breakdown value. Specifically, ΔE of 90 degrees is much greater than ΔE of 120 degrees. Nevertheless, along Line 3 the arching does not exist as the recorded ΔE is lower than the critical breakdown value.

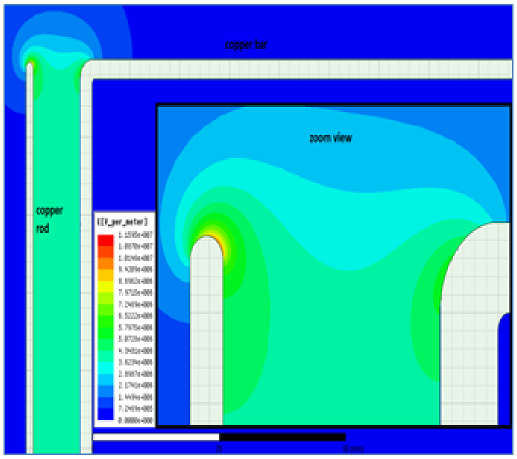


Figure 12 Outer-part of 90 degree angle

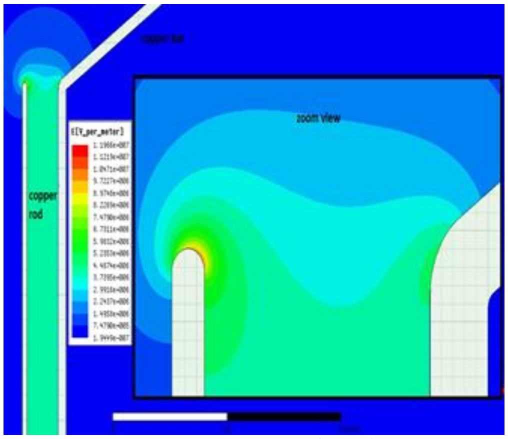


Figure 13 An outer-part of 120 degree

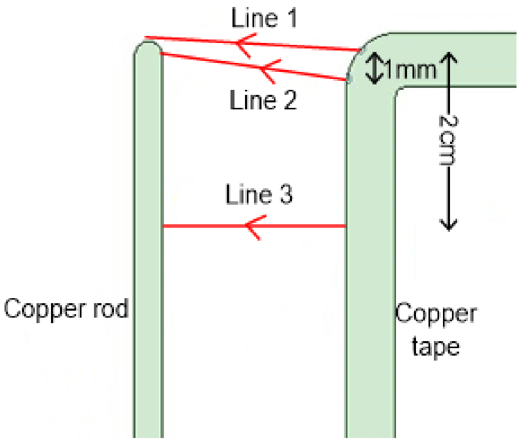
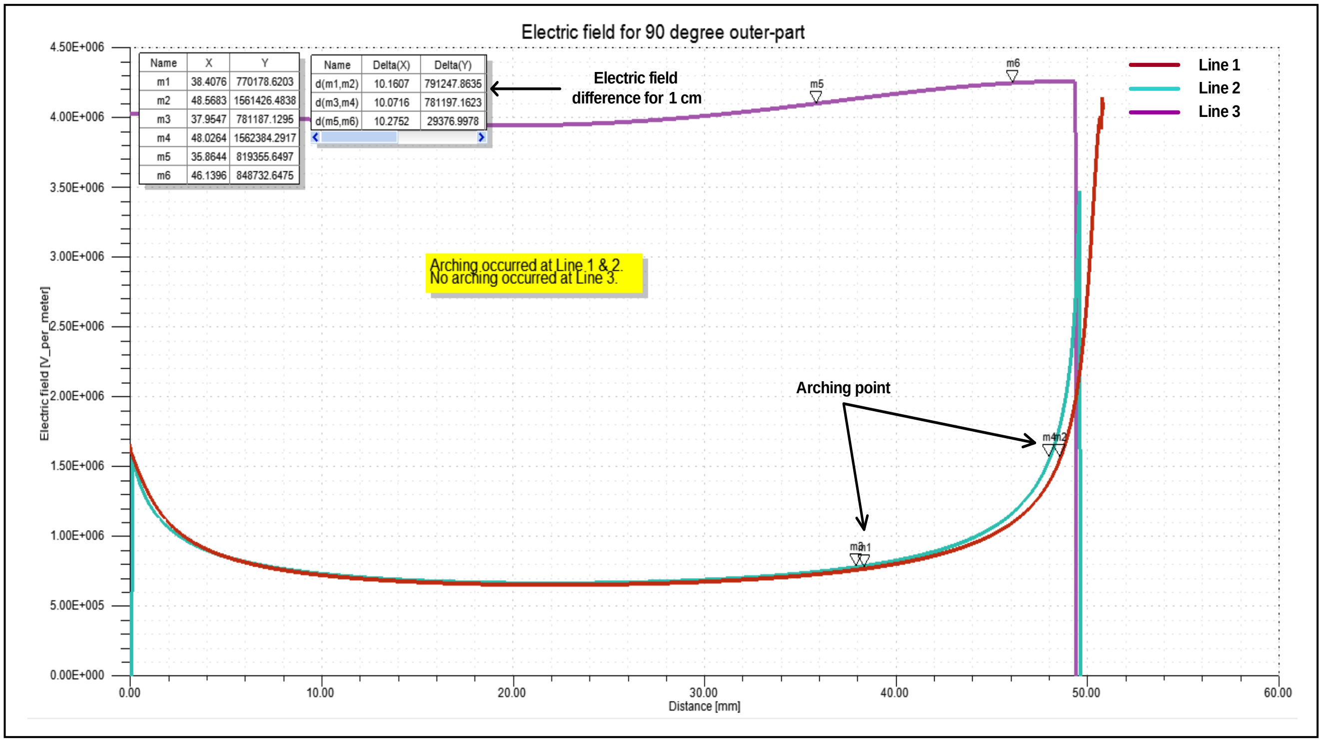


Figure 14 A schemetic diagram of electric field measurement for outer-part



Name	X	Y
m1	38.4076	770178.6203
m2	48.5683	1561426.4838
m3	37.9547	781187.1295
m4	48.0264	1562384.2917
m5	35.8644	819355.6497
m6	46.1396	848732.6475

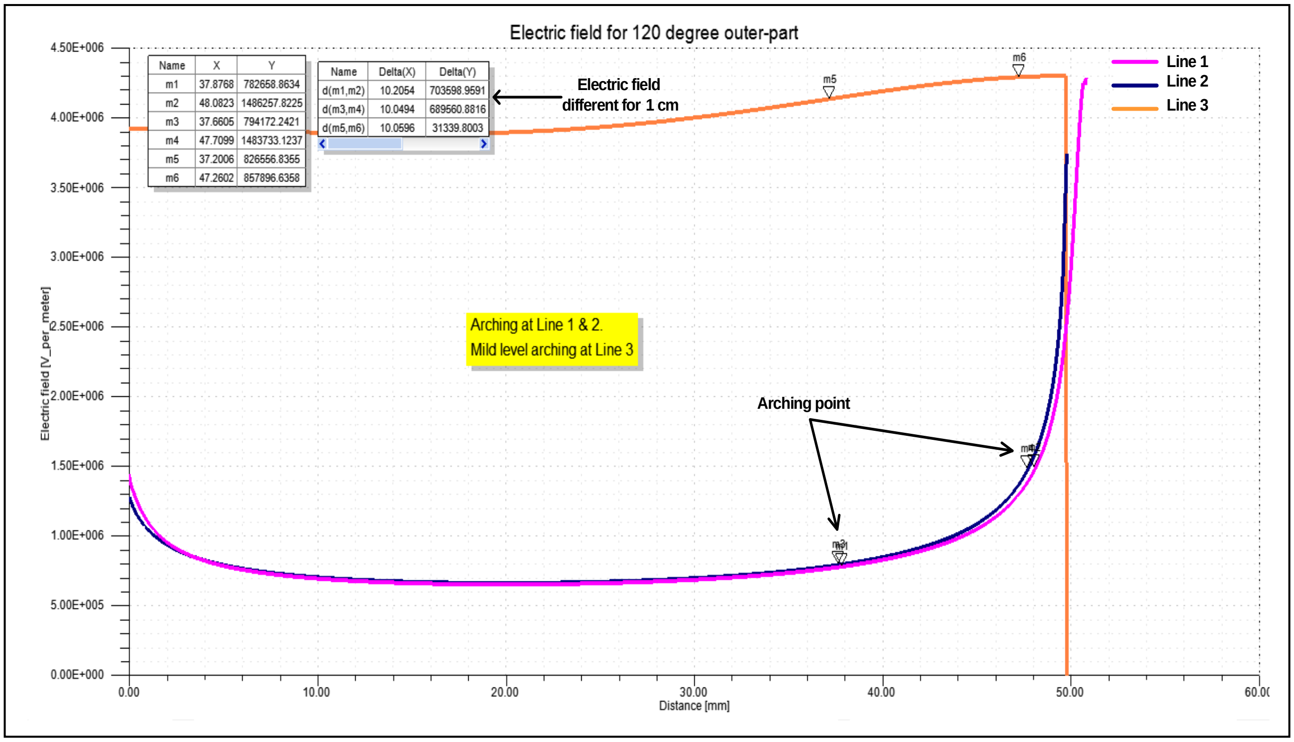
Name	Delta(X)	Delta(Y)
d(m1,m2)	10.1607	791247.8635
d(m3,m4)	10.0716	781197.1623
d(m5,m6)	10.2752	29376.9978

Figure 15 Electric field for 90 degree at outer-part

Table 2 tabulates the data for the outer-part simulation. From the Table 2, an arching exist at outer-part of 90 and 120 degree based on the ΔE. These are very significant since, almost of the outer-part for both angle has higher intensity of arching point due to greater value of electric field, in which it exceeded the critical breakdown of air. With regards of this matter, apart from the inner part, the outer-part has also a remarkable impact on electric field on the bent down-conductor.

Table 2 Tabulated ΔE for outer-part bend area

Degree of bent	**Point of ΔE, (V/1 cm)**		
	Line 1	***Line 2***	***Line 3***
90	791247.9	781197.2	29376.9
120	703598.9	689560.9	31339.8



Name	X	Y
m1	37.8768	782658.8634
m2	48.0823	1486257.8225
m3	37.6605	794172.2421
m4	47.7099	1483733.1237
m5	37.2006	826556.8355
m6	47.2602	857896.6358

Name	Delta(X)	Delta(Y)
d(m1,m2)	10.2054	703598.9591
d(m3,m4)	10.0494	689560.8816
d(m5,m6)	10.0596	31339.8003

Figure 16 Electric field for 120 degree at outer-part

■5.0 CONCLUSION

Literally, when both 90 degree and 120 degree are compared for three cases of modelling, the difference of electric field for 90 degree is much higher than the electric field for 120 degree. The results in this study revealed that the electric field intensity, for both angles, is much more greater at the bent area in comparison to the unbent (straight) section of the same down-conductor. The inner and outer-part areas of the curved down-conductor have also a significant effect on electric field intensity. Additionally, there are severe chances of arching will occur on both 90 and 120 angle as the value of electric field difference exceeds the critical breakdown value in air. These values of electric field depends on the voltage, current, separation distances and also the angles. In conclusion, it is best to install the down-conductor at a zero degree (straight) orientation since it has a uniform electric field intensity that may reduce the chances of arching. This study can be very helpful in designing the down-conductor of a building with limitations for installing.

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