'Calculating the Surface Potential Gradient of Overhead Line Conductors'

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On Calculating Surface Potential Gradient of Overhead Line Conductors

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***Abstract*—the surface potential gradient is a critical design parameter for planning overhead lines, as it determines the level of corona loss (CL), radio interference (RI), and audible noise (AN). The majority of existing models for surface gradient calculation are based on analytical methods which restrict their application in simulating complex surface geometry. This article proposes a novel method which utilizes both analytical and numerical procedures to predict the surface gradient. With this effective model, stranding shape, protrusions, proximity of tower, type of tower, bundle spacing and bundle arrangement can be taken into consideration when calculating surface potential gradients. A sensitivity study on the factors could affect surface gradient distribution is performed.**

***Index Terms*—surface gradient, finite element method, high voltage conductor, field, corona, radio interference, audible noise, Maxwell Potential Coefficient Method, Markt and Mengele's Method, Successive Images Method, Charge Simulation Method, bundle spacing, stranding shape, protrusion, twin bundle, triple bundle**

I. Introduction

The most important factor influencing generation of corona is electric field distribution in the vicinity of the conductor surface [1]. Thus calculation of the electric field strength on the surface of HV conductors when studying corona phenomena is of high importance.

The calculation of surface gradients on overhead conductor dates back to the 1950s when Maxwell's Potential Matrix was first employed as an analytical tool [2]. Over the past 60 years, due to the increasing power of computers a number of numerical methods have been applied to this subject. All these calculation techniques are based on a simplified model of transmission line conductors—a set of cylinders parallel to smooth, flat ground.

This article first summarizes the main methods employed by previous researchers to evaluate transmission line conductor surface voltage gradients. Five major methods are reviewed in detail and programmes using these methods, written using MATLAB, are briefly described. One of National Grid's transmission line configurations—L2 RUBUS—has been selected as an example to compare the results for the different methods, this being a typical configuration which also being deployed widely in the UK.

After the review, a new composite method of conductor surface field calculation is introduced. This method combines an analytical method with a numerical method, and has distinct advantages over the other techniques. For example, it enables evaluation of electric field for different stranding shapes, protrusions, proximity of tower, type of tower, bundle spacing and bundle arrangement.

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II. Review of the Existing Methods

Different methods for calculating electric field strength can be classified as being either analytical or numerical by their derivation principles.

Analytical methods are listed as (in order of increased complexity):

- Maxwell Potential Coefficient Method (MPCM)
- Markt and Mengele's Method and Its Extension

Numerical methods can be found in the literature are (in order of publishing date):

- Successive Images Method
- Charge Simulation Method (CSM)
- Boundary Element Method
- Finite Element Method (FEM)

A. Simplified Model for Surface Gradient Calculation

The major factors affecting conductor surface stress for an overhead line, as shown in **Error! Reference source not found.**, are:

- Conductor sag
- Proximity of towers
- Uneven ground surface
- Finite ground conductivity
- Conductor stranding and protrusions (scratches, insects and raindrops) [3]

By ignoring all the factors listed above, a simplified transmission line model can be produced which comprises a series of cylindrical conductors with infinite length, parallel to each other and placed above a smooth ground plane. The three-dimensional transmission line is thus represented by a two-dimensional model.

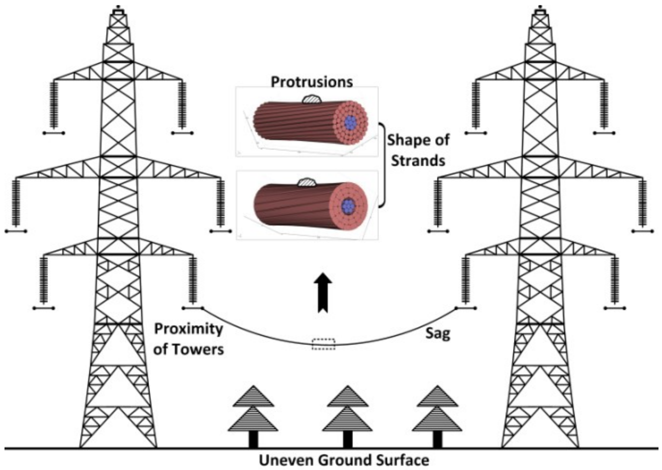


Figure 1 Diagrammatic drawing of a transmission line span

B. Maxwell Potential Coefficient Method

Temoshok [2] introduced 'Maxwell's Potential Coefficient' to compute surface gradient for transmission line system by determining the charge density for each conductor. Adams [4] explained the processes for this method through his calculating example on single conductor transmission line.

The MPCM assumes that surface charges are distributed uniformly around each conductor. Under this assumption, each conductor can be electrically presented as a single line charge, which simplifies the multi-conductor system into a multi-line charge system.

The MPCM produces acceptable accuracy only for single conductor transmission line system. When conductor bundles are considered, the uniform charge assumption becomes inadequate due to the non-uniformly distributed surface charge.

C. Markt and Mengele's Method

In order to address the problem of computing surface gradient for bundled conductors, Markt and Mengele [5, 6] modified the procedure of the MPCM. Conductor bundle is initially replaced by a single conductor with electrically equivalent radius. This simplifies bundle system into a single-conductor system, and the MPCM is then utilized to compute the charge density. The obtained charge density for each bundle is equally split into sub-conductors to calculate the surface gradient.

The 'Markt and Mengele's Method' is well known as an accurate analytical method for field calculation in high voltage transmission lines. However, bundled conductors are widely utilized in higher voltage level. The distance between sub-conductors is relatively small compared to distance between different phases. As a result line-charge simplification introduces large errors in calculating electric field distributions within bundles. Further improvement of calculation accuracy is thus required for bundle conductors. An improvement was introduced by King who suggested that the line charge used to replace each sub-conductor is not located at its central point but a small distance away from its central point [7]. This small distance is a function of the bundle's geometry. King further improved this method by replacing a sub-conductor by two line charges symmetrically displaced from the centre of the conductor [8].

D. Successive Images Method

The 'Image Method' comes from Lord Kelvin's publication [9] in 1848 when he discovered that the electric field of a charge in front of a conducting plane can be calculated by the charge and its mirror image. By using this basic idea of the image method, Hammond [10] presented a cylindrical conductor example which connected the 'image method' to transmission line field calculations. Based on this, Sarma and Janischewskyj published a similar paper [11] in 1969 on electrostatic field calculation of parallel cylindrical conductors using the 'Successive Images Method'.

The method of successive images initially allows 'central line charge' simplification (as introduced in 'Maxwell's Potential Method') to calculate the charge density of each conductor, and then consider the non uniform distribution of those charges around the surface of each conductor. An iterative procedure is employed to achieve the required results.

E. Charge Simulation Method

The 'Charge Simulation Method' (CSM) has been widely utilized to analyze electric field distribution in high voltage insulation components. The method dates back to 1969 when Abou Seada and Nasser employed CSM to evaluate the field strength in a twin cylindrical conductor [12]. Subsequently, Singer, Steinbigler and Weiss published a comprehensive paper [13] on the details of CSM. They extended the applicability of CSM from two dimensions to three dimensions, and gave an example of the calculation of electric field strength near a transmission line tower, using CSM. 'An optimized charge simulation method' was discussed by Yializis, Kuffel and Alexander in 1978 [14], and techniques for optimizing calculation speed by flexibly selecting simulation charge shapes were presented. More recent work employing CSM refers to surface field calculation of ±800 kV UHVDC transmission line in China [15].

The principle of the 'Charge Simulation Method' can be explained as 'using discrete fictitious charges to replace the non-uniformly distributed surface charge' [27]. Similar to the 'Successive Images Method', it is also a numerical method based on fictitious charges. However, the difference is that the images introduced in the 'Successive Images Method' are fixed at a certain position with a certain shape and charge density, while the fictitious charges introduced in CSM are flexible in both location and shape. As long as the fictitious charges have been set up, the charge densities can be calculated so that their integrated effect satisfies the boundary conditions. This is explained through a simplified example as follows:

As shown in Figure 2, N line charges have been introduced to simulate the surface charge distribution of a twin cylindrical bundle. The boundary conditions are satisfied by selecting N testing points on the surface (red points) and assuming their potential to be the conductor's voltage. As the potentials of the testing points can be calculated by superposition of fictitious line charges, N equations can thus be constructed with N unknown variables (fictitious line charge densities):

$$[P][\lambda]=[U] \quad (4)$$

The line charge densities can be found by matrix inversion:

$$[\lambda]=[P]^{-1}[U] \quad (5)$$

The electric field can thus be calculated from (1).

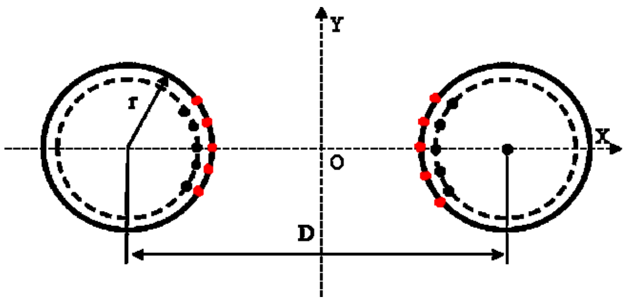


Figure 2 Isolated Two-conductor Bundle

Additional to these, Boundary Element Method (BEM) is an effective method in open field problem however has the limitation that cannot couple with different fields.

III. Methodology

A. Novel Method Combining FEM and CSM

The Finite Element Method can analyze geometries with irregular shapes coupled with different fields. However it is limited by the scale of geometries it can simulate. The largest number of mesh elements an 8 gigabyte PC can sustain is approximately one million. Taking the proposed transmission line parameters as an example, simulation for the whole span of overhead line will result less than two elements over a 1 cm length on the conductor surface. This number can be increased by using a finer mesh size in the vicinity of conductor surface. However this demonstrates the limitation of FEM in modeling the large scale transmission line environment. On the other hand, the 'Successive Images Method' can only simulate regular cylindrical conductors with smooth surface profile, but it can do so for a relatively large scale for two dimensions. The CSM has the advantage that it can be extended to simulate the effect of sag in three dimensions.

These characteristics make it possible to combine the three methods together to analyze the surface stranding effect within the whole scale of the transmission line environment.

The flow chart in Figure 3 combines the three methods in analyzing the surface field distribution. The 'Successive Images Method' and 'Charge Simulation Method' are employed to calculate the electric potential distribution in a relatively large scale (a whole span of a transmission line). 500 fictitious line charges were introduced for each conductor. Within this large scale, surface profiles and protrusions are negligible, so the calculation results obtained are within tolerable distortion (less than one percent). As long as the large scale results are obtained, a micro-scale domain (an equipotential surface) is extracted as boundary conditions for the FEA process. The accuracy is further improved by adding an iterative process which gradually approaches the best-fit boundary for FEA.

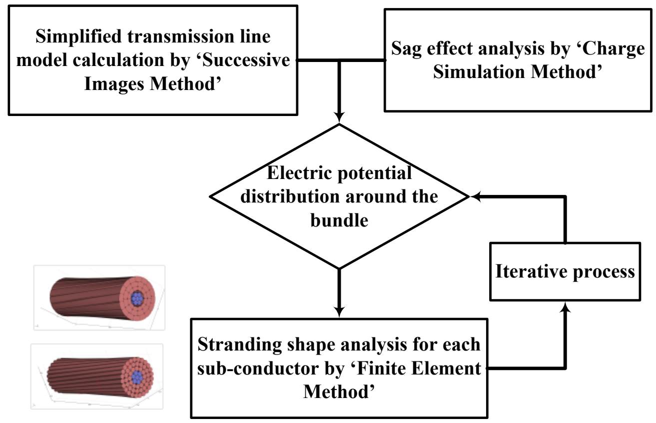


Figure 3 Comprehensive Method for Surface Stress Calculation

B. Meshing Technique for FEM

In order to evaluate the surface gradient enhancement when overhead line conductors passing through the supporting tower, a holistic FEA model is built in commercial software to simulate the tower, insulators and the conductors.

The challenge of performing holistic simulation using FEM is how to decide a proper strategy for mesh generation. If the scale factor (μ) is defined as:

$$\mu=\frac{l_{\max}}{l_{\min}}$$

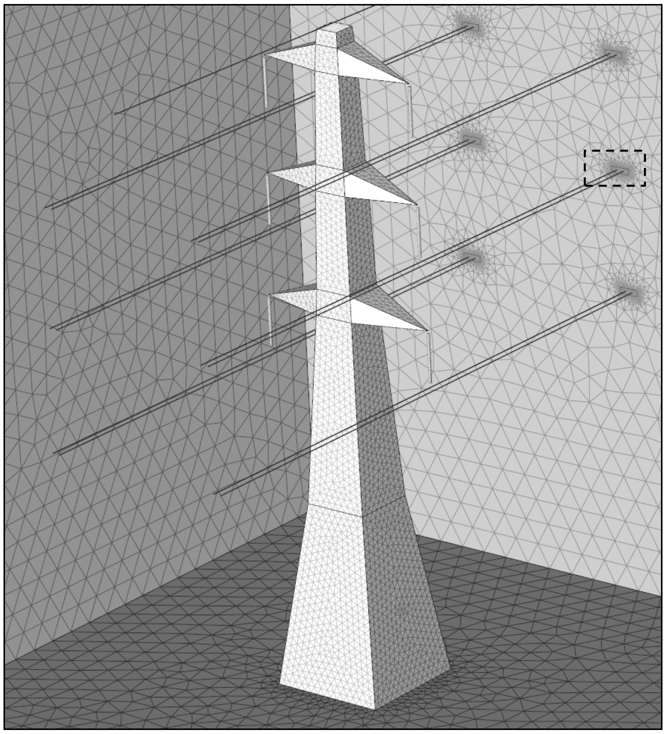
--where $l_{\max}$ and $l_{\min}$ refer to the maximum and minimum length of the geometry within the whole simulation

The minimum size within the geometry is overhead line conductors which have a diameter of 3.2 centimeters while the maximum size is the tower structure which is about 40 meters tall. This results a scale factor of more than 1000.

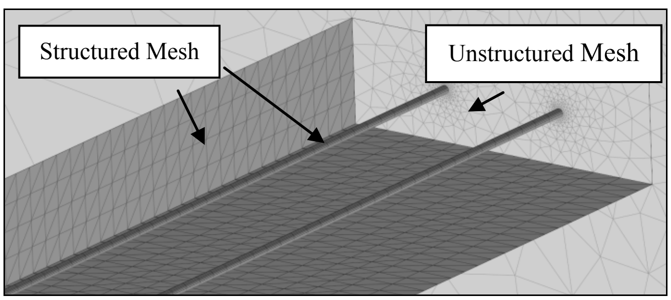
High degree of scale factor requires large computing memories in order to obtain an accurate result. This issue is addressed by combining structured and unstructured mesh and controlling the growing rate of the mesh layer around the overhead line conductors, as shown in Figure 4. Meshing details for this simulation are listed in TABLE I.

TABLE I
Mesh Statistics

Element Type	Number	Mesh Parameter	Statistics
Tetrahedral Elements	1745046	No. of Elements	4700846
Pyramid Elements	233000	Mesh Volume	80000 m^3
Prism Elements	2722800	Growth Rate (Max)	10.68
Triangular Elements	267350	Growth Rate (Ave)	1.584
Quadrilateral Elements	130000		
Edge Elements	43194		
Vertex Elements	234		



a)



b)

Figure 4 Mesh for the L2 tower: a). overall view of mesh; b) zoom in view at the dashed box in a).

IV. Surface Gradient for Different Stranding Shapes

With the advance of manufacturing techniques, various types of conductor have been created to fulfil the needs of modern power systems. For example, trapezoidal shaped strands achieve a higher fill factor (as shown in Figure 5), and are more efficient in current transmission compared to traditional round strands. The increasing use of trapezoidal shaped conductors pushes the need to study the surface gradient because all previous models have used heuristics based on circular strand cross-sections.

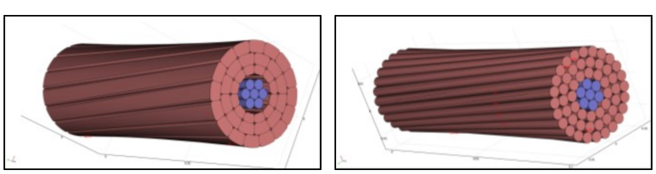


Figure 5 Trapezoidal Strands (left) and Round Strands (right)

As introduced previously, existing methods for surface gradient calculations ignored the shape of the strands. A cylinder was employed to represent all types of overhead line conductors. In order to obtain more information on surface gradients for different shapes of strand, a novel method developed here is applied to a typical tower configuration, L2 (Figure 14).

As explained in Figure 14, the left sub-conductor (conductor number 1) in the bottom twin bundle is analyzed:

From the electric field plot along the surface of the conductor, the following conclusions can be obtained:

- The round stranded conductor has a higher maximum surface gradient compared to a trapezoidal stranded conductor
- The maximum electric field for a trapezoidal shaped strand is located at the corners while the maximum electric field for a round shape strand is located at the tip of the circle furthest from the conductor centre
- On the circumference of a conductor fabricated with trapezoidal strands, there are large continuous lengths with approximately same surface voltage gradient
- On the surface of the round strands, the surface gradient varies along the strand surface and there is no continuous area with same voltage gradient

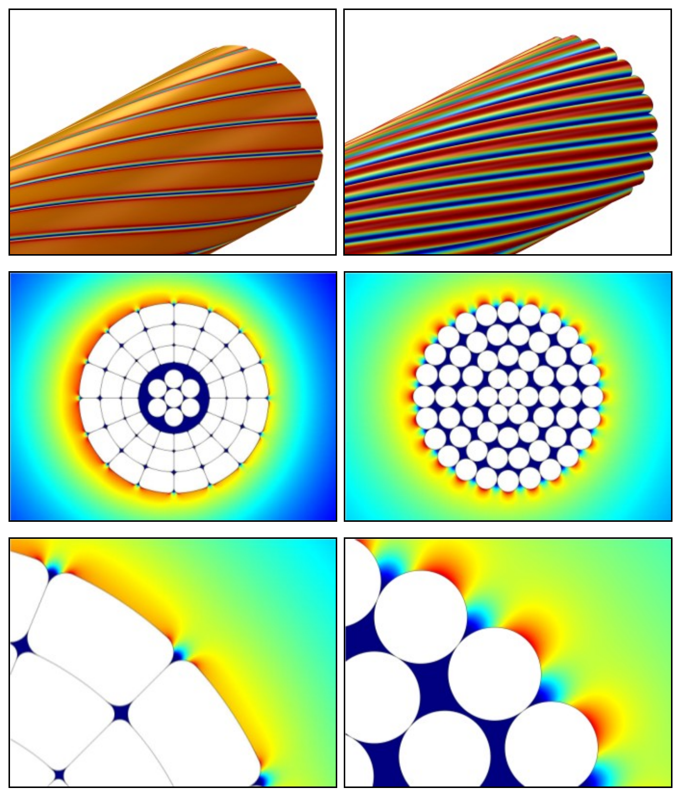


Figure 6 Trapezoidal strands (GAP) and round strands (AAAC) comparison

In Figure 7, the arc length along the edge of conductor strands is chosen to represent the surface distribution of electric field. The horizontal axis refers to the electric field strength and the vertical axis represents the integrated arc length which has a surface gradient value above a certain level. If 16 kV/cm is selected (dashed line in Figure 7) as a typical level to examine the field distribution, the trapezoidal stranded conductor has approximately 88 mm circumference above this level while the round stranded conductor has about 59 mm circumference above 16 kV/cm. If a higher level of electric field is selected as the threshold, take 20 kV/cm as an example, the round stranded conductor has a larger area above this value than the trapezoidal stranded one.

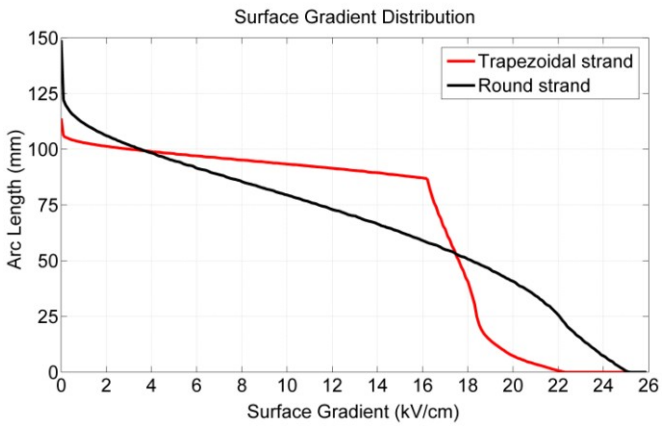


Figure 7 Arc Length with Surface Gradient above a Certain Level

V. Effect of Protrusions

Figure 7 described the circumferential length above a threshold value of voltage gradient. The next step is to decide the threshold value to be considered important.

A hemispherical protrusion is introduced to the existing model to compute the enhancement of electric field. As presented in Figure 8 and Figure 9, when a protrusion is applied to the surface of the conductor, the local electric field is increased due to the relatively large curvature created by the protrusion. This field enhancement is not only determined by the shape and size of the protrusion but also depends on the location of the protrusion.

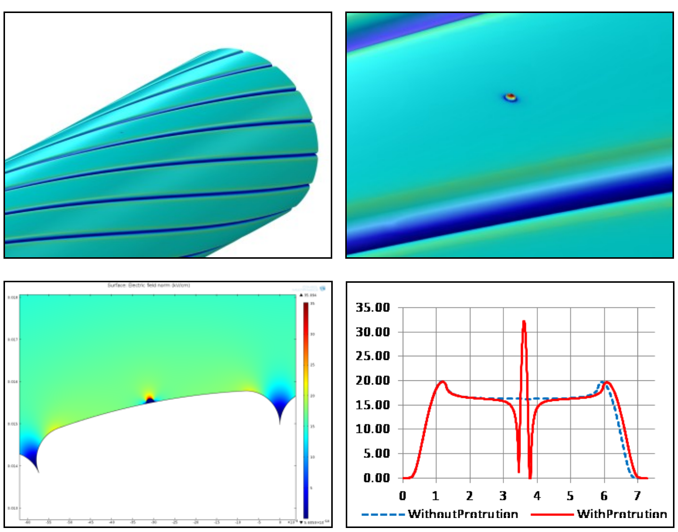


Figure 8 Protrusions on Trapezoidal Shape Strand

Hemisphere protrusion with a range of size (radius: 10um, 50um, 100um and 200um) is applied on both trapezoidal strands and round strands. Finite element method is employed to evaluate the electric field enhancement. By vary the location where the protrusion sits, the relationship between surface gradient with protrusion and without protrusion is established in Figure 10 and Figure 11.

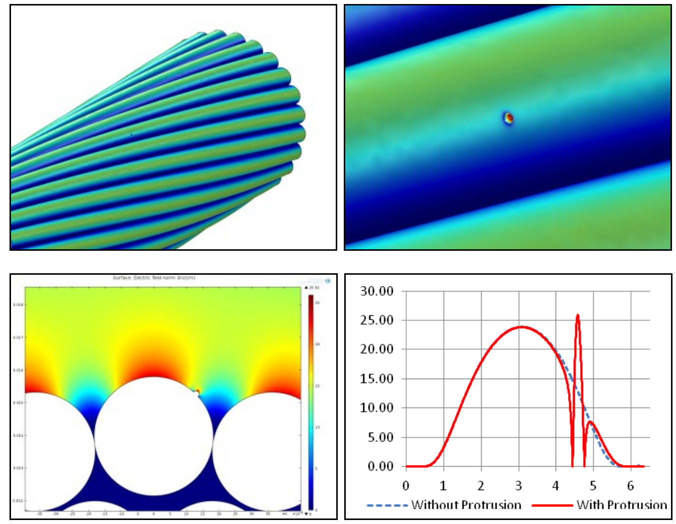


Figure 9 Protrusions on Round Shape Strand

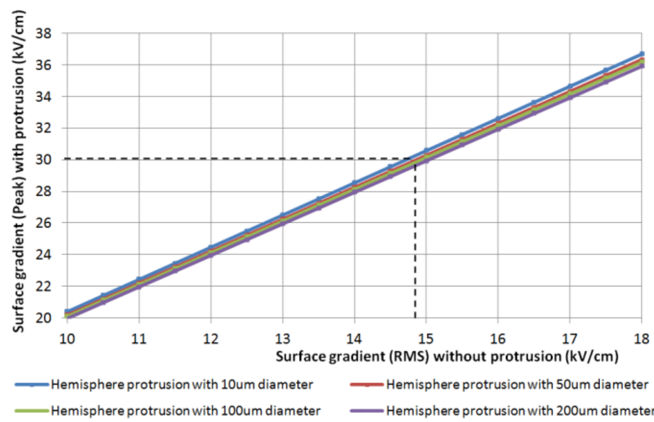


Figure 10 Surface Gradient Enhancement by protrusion for Trapezoidal Stranded Conductor

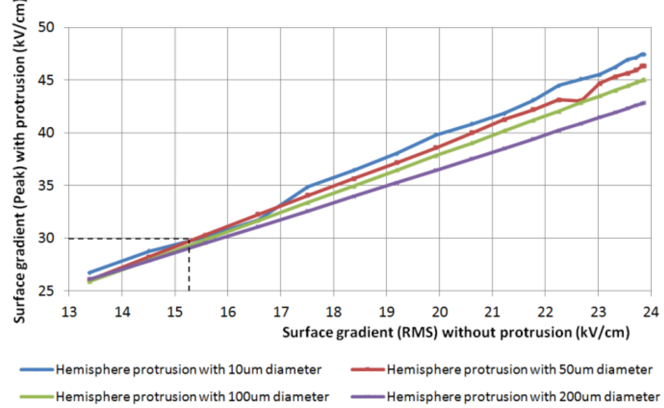


Figure 11 Surface Gradient Enhancement by protrusion for Round Stranded Conductor

Assume that the corona is initiated when the local stress exceeds 30 kV/cm. From Figure 10 and Figure 11, if the worst scenario is taking into consideration, the threshold value for surface gradient without protrusion is marked in dashed line (14.7 kV/cm for trapezoidal strands and 15.3 kV/cm for round strands). Referring to Figure 7, the correlated surface arc length for trapezoidal shape strands is approximately 88 mm while the correlated surface arc length for round shape strands is approximately 62 mm.

VI. Surface Gradient for Tower Effect

When overhead line conductors pass a metallic structured tower, the electric field on the surface of conductors is enhanced due to the short distance to ground potential (tower). In order to evaluate this effect, a novel finite element model has been built, taking into consideration tower shape, insulator strings, and conductor bundles.

A. Assumptions

The following simplifications are made in order to perform the large scale simulation:

- the metallic tower structure is a solid body rather than a lattice structure
- the insulator strings are simplified to a cylindrical shape of radius 100 mm and relative dielectric permittivity of 4
- conductors are simplified as cylinders
- the ground is assumed to be a perfect conductive plane
- the small degree of sag within the first 20 meters span is ignored
- the whole simulation extends 20 meters from the tower to both sides
- electrostatic analysis is performed and the time is selected at 0 s for evaluation

B. Voltage Gradient Distribution at 'Time 0'

The results are displayed at instantaneous time 0 as shown in Figure 12. The phase arrangement is a typical untransposed phase in National Grid. The voltage applied on each phase is listed in TABLE II.

TABLE II
Phase Angle and Phase Voltage at Time 0

	A	B	C	D	E	F
Phase Angle	-120°	120°	0°	0°	120°	-120°
Voltage (kV)	-163	-163	327	327	-163	-163

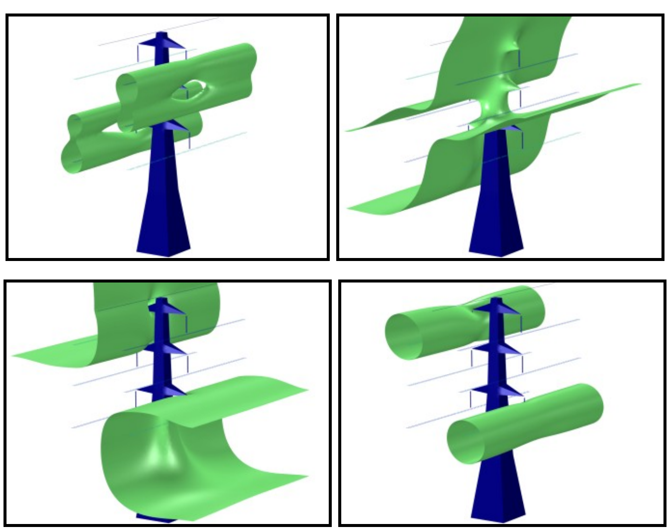


Figure 12 Equipotential Surfaces Surrounding a 400kV L2 Tower

C. Electric Field Enhancement

As described previously, when a simplified model was considered, the potential distribution does not vary along the axial direction of the conductors. Any equipotential surface in three-dimension is thus an extrusion of the equivalent two-dimensional equipotential line. As shown in Figure 12, due to the effect of the metallic tower adjacent to the overhead conductors, the equipotential surface is distorted. As a result, the electric field on the conductor surface is enhanced. For instance, on the plot 'equipotential surface V=45 kV', the potential drop from the top left phase to the equipotential surface is approximately 282 kV. According to electrostatic theory, when the potential drop remains constant, the shorter the clearance is, the higher the electric field on surface of the conductor will be.

The electric field along the surface of a single conductor ('conductor 1' in left hand tower in Figure 14) at time 0 is plotted in Figure 13, as a worst scenario. The surface gradient without tower (shown as a dashed line) is approximately 24.7 kV/cm (peak). When the L2 tower is included, the surface gradient increases to a peak of 26 kV/cm (peak). This plot applies along a horizontal line on the surface of conductor (red dot in the figure).

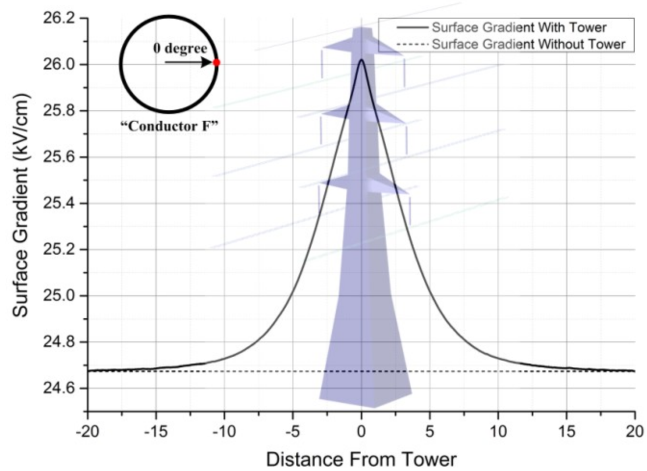


Figure 13 Electric Field Enhancement by Tower (x axis gives distance from the tower)

As a conclusion, the field enhancement on "conductor F" due to the proximity of tower is around 1.4 kV/cm (6%) maximum. If we assume that the electric field varies as sinusoidal wave within one cycle, the increased surface gradient in RMS term is thus calculated from peak value as 1 kV/cm.

VII. Effect of the Conductor Orientation

The conductor orientation varies due to the following factors:

- different types of tower (such as L2, L6, and the recently designed T-Pylon)
- different spacing arrangements (such as 300 mm, 400 mm and 500 mm)
- different bundle arrangements (single, twin, triple and quad bundles)

This section examines the sensitivity of the surface gradient values of overhead line conductors to these geometric factors. As the relatively large scale is the main concern, the simplified model with no sag and no tower effect is utilized to conduct surface gradient calculations in this part.

A. Different Types of Towers

A typical L2 tower and the new tower design, T-Pylon, are shown in Figure 14. These two configurations are used to study the effect of different types of tower configurations on surface gradient calculations. For comparison, all other parameters, such as conductor size (31.6 mm diameter), bundle spacing (twin 400 mm), voltage level (400 kV) and phase arrangement (untransposed), are kept the same for both calculations.

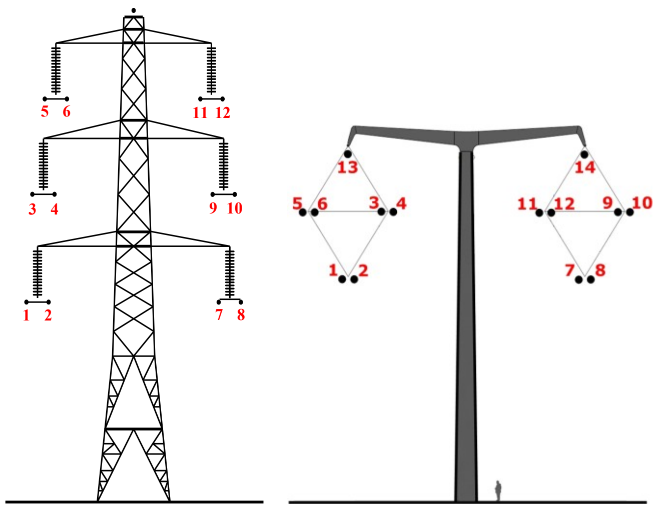


Figure 14 L2 Tower (Left) and T-Pylon (Right)

TABLE III
COMPARISON (T-PYLON WITH L2)

Conductor Number	L2 Tower		T-Pylon	
	E_{max} (kV/cm)	E_{ave} (kV/cm)	E_{max} (kV/cm)	E_{ave} (kV/cm)
1	17.43	16.46	18.19	17.15
2	17.64	16.62	**18.26**	**17.20**
3	17.54	16.53	17.57	16.48
4	17.37	16.41	16.75	15.88
5	17.41	16.44	17.39	16.47
6	**17.67**	**16.64**	18.07	16.97
7	17.64	16.61	**18.26**	**17.20**
8	17.43	16.46	18.19	17.15
9	17.37	16.41	18.07	16.96
10	17.54	16.53	17.39	16.47
11	**17.67**	**16.64**	16.75	15.88
12	17.41	16.44	17.57	16.47
Average	17.51	16.52	17.71	16.69
Maximum	17.67	16.64	18.26	17.20

By observing TABLE III, the following conclusions are drawn:

- L2 tower has lower surface gradients both in maximum and average value among all sub-conductors. The difference between these values on the L2 and T Pylon are approximately 1% (0.2 kV/cm) for average value and 3% (0.6 kV/cm) for maximum value
- If the variation between maximum and minimum values of surface gradient among all sub-conductors is taken into consideration, T-Pylon has a larger variation (8.3%) when compared with the L2 tower (1.7%).

B. Bundle-Spacing

Bundle spacing is the distance between the centres of two adjacent sub-conductors. Within National Grid UK, the bundle spacing varies from 300 mm to 550 mm according to voltage levels and tower configurations. In order to evaluate the effect of spacing on surface gradient values, a L2 RUBUS twin bundle (as shown in Figure 14) is taken as a prototype for stress computation. The spacing is increased from 50 mm to 550 mm at 10 mm intervals.

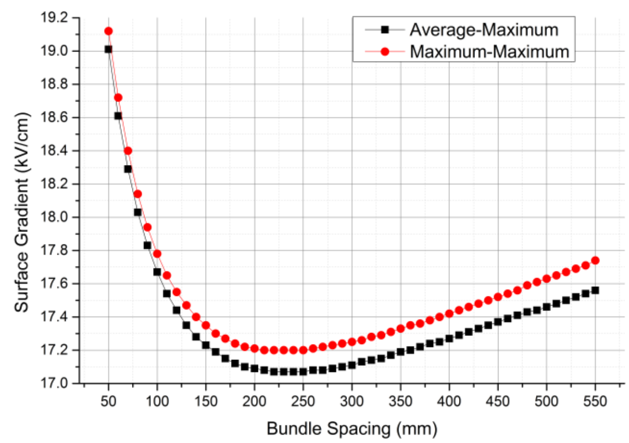


Figure 15 Maximum Surface Gradient with Bundle Separation

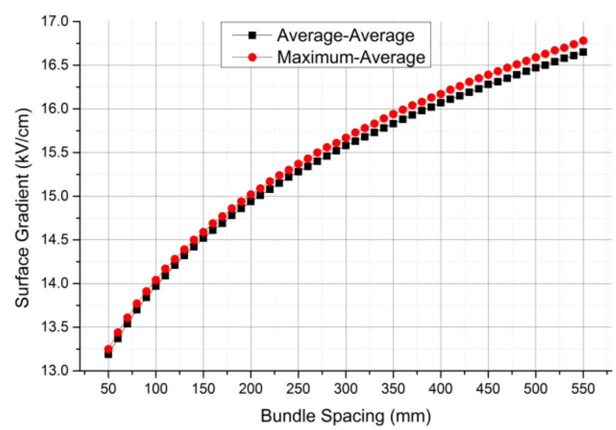


Figure 16 Average Surface Gradient with Bundle Separation

In Figure 15, the maximum value is first taken from the surface of each sub-conductor. The maximum and average values are then taken among all those sub-conductors. For example, the 'average-maximum' value means the following process:

- The maximum surface gradient is first measured around the whole circle of each sub-conductor. 13 maximum values are generated as there are 13 sub-conductors within the whole system.
- The mean value is taken among those 13 maximum values to obtain a single value to indicate the surface

gradient level within this calculation.

Similarly, in Figure 16, the average value is first taken around each sub-conductor. The maximum and average values are then generated.

It is observed that:

- Both 'maximum-maximum' and 'average-maximum' values reduce rapidly from 50 mm to 230 mm (Figure 2 40), but increase from 230 mm to 550 mm. So the surface gradient in this case is minimized at about 230 mm spacing. An increased bundle spacing or reduced bundle spacing from 230 mm will cause the maximum value of surface gradient to rise.
- If the bundle spacing is reduced from 550 mm to 230 mm, there is approximately a 3.5% drop on the maximum surface gradient value.
- In contract to Figure 15, the 'maximum-average' and 'average-average' values increase when the bundle separation increases (Figure 16).
- If the bundle spacing is reduced from 550 mm to 50 mm, there is approximately 27% drop in average surface gradient value.

C. *Different Bundle Arrangements*

The highest voltage level in the transmission system in the UK is 400 kV. The bundle arrangements include single, twin, triple and quad. Twin and triple bundles are most widely used in overhead line conductors. To evaluate the reduction of surface gradient values from twin bundle to triple bundle, L2 RUBUS (shown in Figure 14) is chosen as a benchmark model. The bundle spacing is fixed at 500 mm, surface stress calculations for both twin and triple bundles are calculated. The results are compared in TABLE IV. By introducing one more sub-conductor (from twin to triple), the surface gradient reduces by approximately 20% (3.5 kV/cm).

TABLE IV
COMPARISON FOR SURFACE GRADIENT (RMS BETWEEN TWIN AND TRIPLE)

Conductor Number	Twin		Triple	
	E_{max} (kV/cm)	E_{ave} (kV/cm)	E_{max} (kV/cm)	E_{ave} (kV/cm)
1	17.43	16.46	13.99	12.64
2	17.64	16.62	14.23	12.82
3	17.54	16.53	13.68	12.41
4	17.37	16.41	14.06	12.70
5	17.41	16.44	13.88	12.57
6	**17.67**	**16.64**	13.99	12.64
7	17.64	16.61	13.66	12.39
8	17.43	16.46	13.95	12.61
9	17.37	16.41	**14.29**	**12.87**
10	17.54	16.53	14.23	12.82
11	**17.67**	**16.64**	13.99	12.64
12	17.41	16.44	13.68	12.41
13	-	-	13.88	12.57
14	-	-	14.06	12.70
15	-	-	13.99	12.64
16	-	-	13.95	12.61
17	-	-	13.66	12.39
18	-	-	**14.29**	**12.87**
Average	17.51	16.52	13.97	12.63
Maximum	17.67	16.64	14.29	12.87

VIII. A STRATAGEM FOR EVALUATING SURFACE GRADIENT

Existing methods for surface gradient calculation on overhead line conductor only consider a maximum value with cylindrical assumption. As proved in IV and V, it is not the maximum value but the distribution of surface gradient which determines the corona generation. The distribution of surface potential gradient can be affected by both micro and macro factors such as:

- stranding shape
- protrusion size
- proximity of tower
- types of towers
- bundle spacing
- bundle arrangement

In order to exam the sensitivity of different factors to surface potential gradient distribution, a strategy is developed. The electric field strength is first calculated assuming a protrusion is applied on a specific location (area) of the surface of overhead line conductor. If this calculated maximum electric field exceeded 30 kV/cm, this area is then count as 'above threshold electric field'. A reference length of conductor (1 m) is examined, and the area 'above threshold electric field' is added up to reflect the potential area can initiate corona discharges.

For comparison purpose, indexes for different factors are defined in a 0 to 1 base, as shown in TABLE V.

TABLE V
FACTORS AND THEIR DEFINITION

Factors	Range	Min	Max	Increment
Stranding Shape	0, 1	round	trapezoidal	1
Protrusion Size	0~1	r=10 um	r=200 um	
Proximity of Tower	0~1	D=0 m	D=10 m	
Type of Towers	0,1	L2	T	1
Bundle Spacing	0~1	50	550	
Bundle Arrange	0, 1	twin	triple	

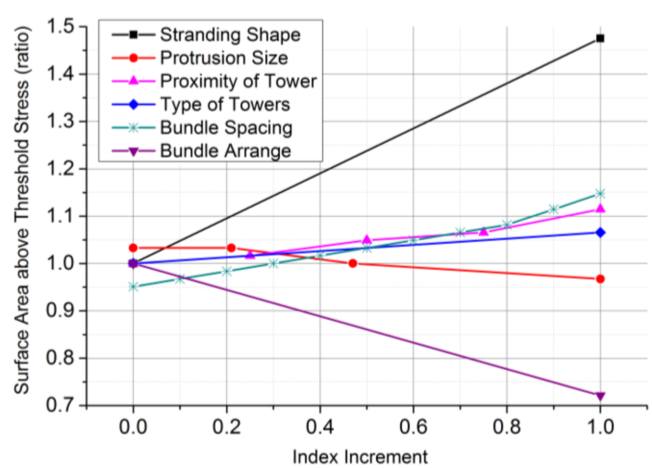


Figure 17 Sensitivities of Factors for Surface Gradient Calculation

The surface area above threshold electric field is computed and divided to a reference value to obtain the results in Figure 17. The horizontal ordinate is the index increment as defined in TABLE V.

The following conclusion is obtained:

- the most sensitive factor is the stranding shape as when the shape of strands changed from round to trapezoidal, the area of corona discharge increased for about 50%
- the second sensitive factor is the bundle arrangement, while the conductor bundle changed from twin to triple, the area of corona discharge reduced for approximately 30%
- when the bundle spacing reduced from 550 mm to 50 mm, there is around 20% reduction of the surface area with excessive corona discharge
- the maximum enhancement due to the proximity of tower is about 12% for surface area with corona, but this value reduced to negligible level when exam the location at 10 meters away from the tower
- larger protrusion leads to smaller area with corona discharge (9% reduction from 10 um to 200 um)
- T-Pylon gives approximately 6% increase of surface area with corona discharge

IX. Conclusion

A novel model is built for surface gradient calculation on overhead line conductors. It enables the consideration of stranding shape, protrusions, proximity of tower, type of tower, bundle spacing and bundle arrangement. It is found that the surface gradient distribution is sensitive to both stranding shape and the bundle arrangement (twin or triple). Other factors have relatively small influence on the field distribution.

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