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Improvements of EGM based on Electrostatic field calculation David Ruiz, Ruben Serna Aplicaciones Tecnológicas S.A. Valencia, Spain

Abstract—

Nowadays, in lightning protection standards, the “Electro Geometric Model” and its application by means of the “Rolling Sphere Method” is the preferred approach to design a Lightning Protection System. However, this method does not give information related to the probability of impact to a definite point, what can imply some problems for its application such as the over-protection of structures with flat-roofs and under-protection in some cases. In this paper, the probability of being struck will be determined for different points of the scenario, by means of an electrostatic simulation, what offers useful information for the design of the LPS. The advantage of this method over the purely geometric ones is that some aspects such as materials, electric field intensification factor in adjacent points, etc. can be included. These aspects are normally not considered for LPS design. Keywords— probability of struck, electrostatic simulation, electric field intensification factor, Electro Geometric Model.

I. INTRODUCTION

The well-known “Electro Geometric Model” is the basis of the “Rolling Sphere Method”, which is the most employed method in the designs of lightning protection systems (LPS). Its efficacy has been proved along the years by the scarcity of known noteworthy damages in the installations where it has been employed, and this efficacy has not been quantified with reliable statistics. Nevertheless, it has been also proved that this method has some limitations. The main one is that it assigns equal leader initiation ability to all contact points on the structure; namely, no account is taken of the influence of electric fields in initiating upward leaders, so it does not distinguish between likely and unlikely lightning strike attachment points. In other words, for a given prospective peak stroke current, the striking distance is a constant value [1]. For structures, it is well known that lightning preferentially strikes the corners and edges [2]. Therefore, “mechanical use” of the RSM can result in scenarios where protection is not applied
because, in theory, the prospective strike point is not touched by the sphere, but in reality the point has a much higher risk of being struck than an adjacent plane surface where the sphere does make contact. Recently, in this way, some papers have introduced the assignation of a probability of impact at the points evaluated by means of the RSM. The paper described by Kern et. Al.[3] obtains the probability by means of a purely geometrical method, discarding the enhancing of electric field effects, that is, the probability of impact is calculated taking into account the distribution of the peak current for lightning. This point of view does not consider the ability for launching upward streamers at the different points in the structure; this is the 'electric field intensification factor' which is the reason for which the corners and edges are most "preferred" points of impact. The probability of appearance of a lightning with current amplitude higher than a threshold is what determines the LPL, and is considered by the RSM choosing the radius of the sphere [4]; this relation is noted in formula (1), but no considerations are included related with the electrical properties of the facility to protect. So this paper describes a method based on the standardized RSM but complementing the result with electrostatic information which is used to determine the probability of impact at the points of the facility. II. FUNDAMENTAL DATA AND CONCEPTS

The present lightning protection standards define four different protection levels based on the current distribution probability of downward negative lightning defined by CIGRE [5], [6], so the radius of the "Rolling Sphere" is attached at different current levels with the formula (1). (1) In this way, the EGM "translates" an electrical parameter in a geometric one. This "translation" has its physical sense in the density function of the lightning current amplitude, which imposes de distance of the "final jump" and which is normally presented as a lognormal distribution [4]. (2) Where, for negative lightning (over 90% of G-E lightning) two straight lines are defined (first line for I>20kA and second line for I<20kA, line 1A and 1B respectively) μ=33.3kA and α=0.605 [4]. In the standards, there are statistical parameters related with the expected values of the lightning current, which allows the use of probabilistic terms to treat these data; nevertheless, the statistics related with the attachment of the lightning to the different points of the structure are no considered, but it is known that corners and edges have a higher probability to be struck than flat roofs. It is known that in a non protected structure, lightning attachment has approximately the following probabilities: A - Corners P>0,9 B - Horizontal Edges P>0,05 C - Vertical Edges close to A P<0,02 Figure 1: Lightning attachment on structures. The probability of impact is related with the "Electric field intensification factor", usually noted as Ki, and this relation has shown to be directly related, but with a non-linear relationship [7]. This approach has its sense in the fact that more prominent and higher points (that is, with a higher value of Ki) have a higher probability to be struck. At these points the electric field onset criterion (i.e 3 MV/m) is reached previously than in other points, so the first coronas appear at these points, but are vanished while the "self-propagation" electric field (i.e 0,5 MV/m) are not reached [8]. When a corona appears and is extinguished, an amount of electric charge is deposited in the air above the point; this charge decreases the electric field at its bottom, inhibiting the appearance of other corona until the deposited charge is reattached [8]. Evidently, the time between two consecutive corona discharges depends on the electric field, so points with a higher value of Ki will be 'launching' coronas many more times than other points with a lower value of Ki. So, when the "self-propagation" electric field was reached there exist higher probabilities that a point with high Ki launches a corona which becomes an upward connecting leader than other points. There is not known the exact relationship between the parameter Ki and the probability of impact, so, the calculus of probability will be based on a beta distribution which is widely employed because allows any type of density function shape (exponential, linear, bell curves, hyperbolic curves...) [9]. The density function in a beta distribution is defined by two parameters, the parameter α, also called 'shape parameter' and the parameter β, also called 'scale parameter'. The formula (3) shows the density function for the beta distribution when Ki is the variable. (3) Where Γ(x) is the Gamma Function. As shown in figure 2, many different density functions could be obtained varying the parameters α and β. Figure 2: Different representations of beta distribution CDF. Taking into account that the probabilities defined in formula (2) and formula (3) have not relationship, in order to calculate the total probability that a point with an electric field intensification factor Ki, will be struck by a lightning with an electric current of amplitude I, is the multiplication of the two probabilities, as shown in equation (4) and in a reduced form in equation (5) [9]. (4) (5) The probability of being struck is evidently divided by the different points of the structure so, adding the probabilities of all the considered points, the total probability becomes again the same as if no Ki was considered, that is, the formula (5) becomes the formula (2) again. This fact implies that the probabilities must be normalized in the way that adding the whole set of probabilities the result must be 1. [10] Finally, the method here described allows the protection of a structure or scenario in the same way as the standardized RSM does (in fact, the first step of the algorithm is to protect the scenario applying the RSM), but additional information is indicated about the points with a higher probability to be struck. III. NUMERICAL APPROACH A. Preparing the Scenario To evaluate the scenario it is necessary to have a 3D model of the facility to protect, where dimensions, shapes and materials are defined (if not, the structures will be considered as perfectly grounded). After this step, is necessary to introduce the facility into a scenario large enough to discard the boundary effects (i.e. a cubic scenario of 1000x1000x1000m. Afterwards, it is necessary to discretize the scenario, defining the points and meshing the surfaces and volumes. A good criterion to select the points to evaluate is to select all the corners, one point at the middle of each edge (two equally separated points if the edge is very long), one point at the centre of the flat roofs (more points can be considered depending the dimensions) and one point at each vertical edge close to the corner. In order to avoid a heavy computational load but obtaining enough resolution, a triangular variable size meshing has been used where the surface of the triangles varied from 0,36mm² near the evaluation points to 1m² at the less significant parts of the scenario. After the discretization, a Finite Element Analysis tool can evaluate the scenario indicating the electric field at the selected points and, applying the formula (6) the electric field intensification factor, Ki can be obtained. (6) Where Ei is the electric field at the evaluated point and Es is the environmental electric field. B. Calculation Method In order to determine the probabilities of impact for each point, a four steps algorithm is employed; in the first step the "Rolling Sphere" with a radius according to the concrete LPL, (namely 20m, 30m, 45m, 60m) is rolled over the scenario in order to determine the
points considered to be protected by the standards. Once the points have been identified, in the second step, an electrostatic simulation is done over the structure, in order to calculate the electric field intensification factors (Ki's) at the whole scenario. After calculation of the Ki's set, in the third step, the values of Ki at the points not considered by the RSM are compared with the smallest value of Ki in the points considered by the RSM (Ki_min) and those that are equal or larger than Ki_min, will be included in the calculus of probability so, in this way, some points excluded by the RSM could be now taken into account. In the last step, an algorithm is applied to calculate the probability of impact at each considered point employing the formula (3). Finally, an optional step could be applied detecting the points where the probability is quite small to be not considered. This step is not applicable at standardized designs but could be useful for studies, or research, for instance determining the effect of the materials or the previous electric charge at some points. In figure 3 the basic diagram of the algorithm is shown. Figure 3: Basic diagram of the algorithm. The "available" information related to the probability of impact, is qualitative, namely the maximum probability is associated with more prominent and higher points, and also experimental results show that the most probable points are the corners (P>0,9) and the edges (0,05 β). Applying a fitting algorithm with different basic structures, these parameters have been found. The obtained probability curve is shown in Figure 4. Figure 4: Assignations of probability based on a beta distribution. As noted in the point 2, if formula (5) is considered the density function takes the shape of the lognormal distribution noted in equation (2), but scaled in a factor determined by the value of Ki. In Figure 5 the curves show the probabilities that a lightning with an electrical current (I), strikes a point of the structure with an electric field intensification factor (Ki). Figure 5: Graphic result of ‘scaled’ log-normal distribution. In practice, only the formula (3) is considered because is the one related to the scenario to evaluate. The formula (2), which takes into account the distribution of the lightning current, is already considered by the EGM and the formula (1). This procedure allows to have still a standardized method, but including information that allows a better evaluation of the structure to protect in order to improve the placement of the air terminals near the points where the probability is higher, even when the RSM indicates that the structure is completely protected. IV. BASIC EXAMPLES AND RESULTS Here we will consider two different cases, the first case of a perfectly grounded structure and the second case when the materials, electrically represented by its relative permittivity εr and its electrical conductivity σ, are considered. A. Perfectly Grounded Structure In the next example it is shown a single multi cubic structure where the cube at the bottom has a dimensions of 20x30x15m, the second cube has dimension of 15x20x5m and the highest cube has dimensions of 10x15x10m and is going to be protected by RSM with LPL III (r=45m), in the first step, the sphere is rolled over the structure and the vulnerable points are shown. Figure 6: Structure evaluated by RSM with LPL III. In the second step the same structure is evaluated in an electrostatic analysis employing a F.E.M tool, in order to obtain the Ki factors in some relevant points of the structure. In this way, corners, edges and flat roofs are evaluated. Figure 7: Ki obtained at the different points of the structure. In the third step, if there are points, not considered by the previous RSM, with a Ki equal or greater than the Ki_min, then this points becomes considered (it doesn't mean that they should be protected, it will depend on the probability and the criteria of the designer). In this example, the minimum Ki of the points considered by the RSM is the point at the centre of the roof, which has a Ki of 1,62, that is Ki_min. In figure 7 is possible to determine that there exist many points with a Ki higher than this value, so these points will be included in the calculus of the probability. Table 1: Calculus of probabilities according the method described above. As noted in Table 1, the total probability must be 100%, this also implies that is assumed that the downward leader will strike a point of the structure evaluated (will not strike on the floor). In the last step of the algorithm, the probabilities are calculated for each considered point and its representation indicates with different colours the zones to be protected (according the RSM), and the probability calculated for each, as shown in figure 8. Figure 8: Probabilities calculated at different points. B. Effect of the materials When the materials of the structure, characterized by the electrical conductivity σ and its relative permeability εr, are taken into account, then, the electric field intensification factor is modified, because the isosurfaces do not involve completely the structure, such as in the case of considering a perfectly grounded structure, but these isosurfaces are partially in the internal side of the structure, as shown in figure 9. Figure 9: Effect of the materials. The isosurface pattern is different when a material is defined. Here it is possible to compare the effect of the materials in the Ki factor, and consequently in the probability of being struck. Firstly, the same structure that in the previous example has been evaluated as if it was made of perfectly homogeneous concrete (ρ=3-103 , εr=4.5).[11][12] As shown in figure 10, the probabilities are not affected considerably. This is because the material is still the same in the whole structure, so its influence is the same at any point. That is, the calculated Ki is smaller at all points, but the calculus of probability normalizes this effect, so the point with the highest value of Ki continues having practically the same probability to be struck. Figure 10: Probabilities calculated for three cubes made of concrete. A more relevant example is when different materials are considered. In this new example, considering again the same structure of the previous examples, each cube is considered of a different material (i.e. the cube of the bottom considered as steel (ρ=10-6 , εr=1), the second one concrete (ρ=3-103 , εr=4.5) and the third one dry wood (ρ=1-109 , εr=2)).[11][12] Evidently, the RSM would offer the same results than in the previous examples, but now, the values of Ki are different, so the probabilities are also different, as shown in figure 11. Figure 11: Probabilities obtained at the different points of the structure considering 3 different materials. In this case, the smallest value of Ki at the points considered by the RSM is in the center of the roof. In figure 11 it is shown that in this case, there are not points considered additionally to the ones considered by the EGM (the points not considered by the EGM have a smaller value than Ki_min, that is, a lower probability than the one calculated for the flat roof). This fact could highlight the validity of the RSM in real scenarios, where materials have its role, and also highlight the compatibility of this procedure with this standardized method. Figure 12: Probabilities calculated for the different points considering 3 different materials. Taking into account these probabilities, it could be possible to reconsider where the protection is really necessary or at least, where is ‘more’ necessary or more effective. So, at this point, the information related to the probability of impact could be useful to optimize the placement of the air terminals.
With the previously detailed information, some conclusions could be obtained for this structure: While RSM indicates that the center of the roof needs protection, our algorithm shows a really low probability of impact. This fact has been highlighted by many authors as the main fault in the RSM. [1] In fact, if no materials are defined (considering the structure as perfectly grounded), there are also some points with a higher probability of impact, but not identified by the RSM. (Figure 8). If the material considered is the same in all the parts, the effect in the probability is negligible. This is because the modification of $K_i$ affects equally at all points, so the preferential points continue being the same. When different materials are considered in the probability calculation, no additional points are considered by the algorithm (in this case). That is, the RSM indicates the same result as if the lowest probability to consider was defined by $K_i$. min. C. Protecting the Structure Once the probabilities are determined, it is necessary to evaluate which is the best option to protect the facility. In this way, as an example of utilization of the algorithm here presented, we will evaluate the two options, available in the market for standardized LPS: a. CONVENTIONAL AIR TERMINALS b. NON-CONVENTIONAL AIR TERMINALS

A typical strategy in the positioning of lightning interceptors is to place relatively short air terminals near the corners. In this example 1-meter Franklin Rods have been used to protect the structure. As in the previous cases, in the first step the RSM is applied in the scenario and the points where the sphere touches are marked. As noted in figure 13 are necessary 4 short Franklin rods to obtain a LPL III. Figure 13: Protection of the structure by means of 4 short Franklin rods. Other widely employed strategy is the use of fewer but higher air terminals and placed in a point near the centre of the roof. In this case, a 6-meter Franklin Rod has been used to protect the facility. As noted in figure 14 it is necessary more than one Franklin rod to obtain a LPL III. Figure 14: Protection of the structure by means of 1 long Franklin Rod. In this case, according the RSM, the first strategy offers better results than the second case. This effect is noted by many works [10] where a conclusion was that air terminals placed near the corners have a higher degree of protection than one the placed in other parts of the structure. In the previous examples, if the algorithm is applied, the probability of being struck in each 1-meter rod is 24.84% (99.36% in total), while in the second case, the probability of being struck in the 6m rod is 95.19%. Comparing the two previous examples is possible to obtain the next conclusions: Placement of air terminals near the corners is more effective than the placement in a flat roof. This improvement allows the use of shorter air terminals. The algorithm provides a method consistent with the results offered by the RSM. Further information could be useful in the placing process or to optimize the protection. b. NON-CONVENTIONAL AIR TERMINALS

Here we will be focused on standardized LPS, so only ESE technology will be discussed here. Evidently the electrodinamic pulsating or sparking effect of the ESEs could not be simulated by this method that is fundamentally static. But it is possible to include the effect that an ESE generates, launching an upward streamer in previous moments that any other points of the scenario. For the simulation it has been included an additional upward streamer over the ESE tip, with a length of $\Delta L$ and a charge density of 50µC/m, which is the minimal amount of charge to obtain a self-sustained propagation. [8] The results indicate that even employing an ESE with $\Delta L=15m$, the probability of impact in ESE is very high. Also is shown that the selection of an ESE with $\Delta L=15m$ has no sense in this structure, because the increment of probability is negligible, as shown in Table 2. Table 2: Probability of impact in an ESE air terminal for different $\Delta L$. Anyway, protecting the facility with a 6-meter Franklin Rod, the probability of impact in the rod is 95.19%, but if instead of the Franklin Rod we use an ESE air terminal with $\Delta L=15m$, then the probability of impact in ESE is 99.62%. Other way to indicate the previous data is that with the Franklin Rod, the probability of impact in the facility is 4.81%, and when the ESE is evaluated, this probability is decreased to 0.38%, which is comparable, in this example with the protection given for the use of 4 1-meter Franklin Rods. V. APPLICATION TO A COMPLEX SCENARIO

More complex scenarios can be evaluated employing this method but some questions arise related to the size of the zone to consider for the evaluation. Evidently the effect of other structures has an influence in the calculus of the probabilities. So, by means of different F.E.M. simulations it has been found that the influence of a structure could be considered as negligible when the point of evaluation is separated between 2 and 3 times the height of the structure (figure 15). So the criterion for the minimum area to consider is set as 3H, where H is the height of the structures at the boundaries of the structure or structures to protect. This result coincides with the equivalent area considered in the standards and defined as the collection surface of an isolated structure [14]. Figure 15: The influence of the strucutre a strucutre in the isosurface is in the range of 2-3 times the height of the strucutre. As said previously, applying the algorithm is possible to evaluate any 3D structure or scenario and protect it in a standardized way. In the next example, a complex scenario has been evaluated with this algorithm for LPL I $(r=20m)$. This scenario is composed by headquarter of Aplicaciones Tecnologicas S.A. and some facilities which are close to it. In the first step, as in previous cases, the standardized RSM is applied, showing the ‘vulnerable’ points. After the algorithm was applied to calculate de probabilities at the different considered points; the results are shown in the Figure 16. When the scenario is too large, only probabilities of impact higher than a concrete threshold (i.e. 1%) are shown and a code of colours helps to indicate the magnitude of the probability. Figure 16: “Impactable” points and probability of impact for each point in the scenario. It is also possible to determine the probability of impact in the evaluated scenario for each structure, adding all the points considered in the structure, as is also shown in figure 16. In the real case, an ESE with $\Delta L=60m$ is placed in the flat roof, so including this effect of this air terminal the result is shown in the figure 17. Figure 17: Effect of the ESE ($\Delta L=60m$). The effect of the ESE is evident in this case, not only at the zones protected by EGM. It is also shown that the ESE reduces significantly the probabilities of lightning strike at these points protected by the RSM. But, furthermore, it is also shown that in relatively distant points, not protected applying the RSM, the probability is also reduced as shown in figure 17. It is also shown that the reduction of the probabilities of impact at each structure is not the same; it varies with the height of the structure and the distance to the ESE. This fact highlights that the points where the probability is more reduced are the ones whose probability was higher when the air terminal was not placed. It seems logical to place the air terminals preferably near these points (i.e. corners and edges). This approach, is consistent with the work [13], previously quoted. VI. DISCUSSION
A method that complements the standardized RSM has been presented. This method shows information related with the probability of impact at any point of the scenario taking into account electrical considerations related with the electric field intensification factor which depends of the geometry, materials, other elements in the nearby, etc. This method has an advantage compared with the purely geometrical methods which don’t take into account the influence of any electrical aspect related with the facility to protect. This static method does not consider electrodynamical processes that involve the generation or vanishing of upward connecting leaders, so a direct consequence is that the ability to generate a streamer is only evaluated before the appearance of the first streamer when electric charges are not generated still above the evaluated points and the electric field is not reduced by the progression of an upward streamer. But anyway it is possible to determine some dynamic effects knowing how these effects have an influence in the scenario (i.e. is not possible to simulate an ESE pulsating system, but it is possible to simulate the effect of the generation of a streamer with a concrete length). This approximation takes into account the charge transferred by the upward streamer, but does not take into account dynamic aspects of previously generated corona discharges nor the propagation of the upward streamer. The effect of the materials in the scenario is not evaluated by any current standardized method. Nevertheless, the approach made here, allows its consideration which can modify the probability of impact as a function of the properties of the considered material. A simplification is made when materials are included in the simulation considering that the facility (or the block of a structure) is perfectly homogeneous. More accurate information could be taken into account, but the computational load would increase so much, necessitating a special computer to complete the whole simulation. The combination of the probabilities considered in the formulas (2) and (3), noted in formula (5), gives useful information that could be considered to evaluate the probability of lightning strike with a current amplitude higher than a value in concrete points of a structure improving the standardized designs of a LPS (as shown in figure 5). The method here exposed is able to be applicable at any kind of scenario, despite the complexity of the facility. REFERENCES


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