World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:12, No:3, 2018

Using Game Engines in Lightning Shielding: The Application of the Rolling Spheres Method on Virtual As-Built Power Substations

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Open Science Index, Electrical and Computer Engineering Vol:12, No:3, 2018 publications.waset.org/10008696/pdf

***Abstract*—**Lightning strikes can cause severe negative impacts to the electrical sector causing direct damage to equipment as well as shutdowns, especially when occurring in power substations. In order to mitigate this problem, a meticulous planning of the power substation protection system is of vital importance. A critical part of this is the distribution of shielding wires through the substation, which creates a 3D imaginary protection mesh similar to a circus tarpaulin. Equipment enclosed in the volume defined by that 3D mesh is considered protected against lightning strikes. The use of traditional methods of longitudinal cutting analysis based on 2D CAD tools makes the process laborious and the results obtained may not guarantee satisfactory protection of electrical equipment. This work describes the application of a Game Engine to the problem of lightning protection of power substations providing the visualization of the 3D protection mesh, the amount of protected components and the highlight of equipment which remain unprotected. In addition, aspects regarding the implementation and the advantages of approaching the problem using Unreal® Engine 4 are described. In order to validate results, a comparison with traditional 2D methods is applied to the same case study to which the proposed technique has been applied. Finally, a comparative study involving different levels of protection using the technique developed in this work is presented, showing that modern game engines can be a powerful accessory for simulations in several areas of engineering.

***Keywords*—**Game engine, rolling spheres method, substation protection, UE4, Unreal® Engine 4.

I. INTRODUCTION

BRAZIL is the country with highest incidence of lightning strikes in the world, accounting for approximately 50 million lightning discharges annually. In addition to causing the deaths of an average of 132 people per year, lightning strikes cause damage to equipment and structures [25].

From the perspective of the Brazilian electric sector, about 70% of the disconnections occurred in the transmission of energy are due to the incidence of atmospheric discharges [25]. This is due to the nature of the Brazilian energy matrix, which consists almost entirely of large hydropower plants that are far from the centers of load, and consequently, demand a large infrastructure of transmission lines and substations for energy transportation to the centers of consumption.

An effective design of protection systems is therefore vital to avoid shutdowns of this nature, mainly due to the application of outdated design standards even in new projects, which require more robustness and reliability.

The precise identification of which component is protected by the layout of lightning shielding in a substation following strictly the standards of the electrogeometric model established in the literature [5] is not a simple task without the aid of a 3D visualization tool.

Although the rolling spheres electrogeometric method, one of the most used for this purpose, is quite old, dating to the 1980s, few solutions are found in the literature using 3D technology for visualization of protection mesh (or shielding mesh) against lightning and no work was found using game engines for this purpose.

Game technology has received enormous amounts of investment, leading to its significant evolution in recent years. This is one of the reasons why professionals are beginning to work on technical problems using game engines in applications such as modeling, simulations and training. This paper describes a game engine approach to the problem of designing and simulating lightning shielding of electrical substations three dimensionally. This includes specifying which equipment is unprotected by the generated protection mesh and a new way of visualizing protected equipment highlighting parts of components which lie close to the end of the mesh.

The paper is organized as follows: Section II describes in detail the characterization of the lightning shielding problem in power substations. Technical, physical and environmental aspects are also addressed, such as a survey of the state of the art in the theme involving 3D technology. In Section III, a brief conceptualization about game engines and the technology used in this work is presented. Section IV details the implementation of the proposed solution. In Section V, the results obtained through the application developed here are compared with traditional methods described in the literature. And finally, conclusions and perspectives of future work are presented in Section VI.

II. LIGHTNING SHIELDING OF POWER SUBSTATIONS

Atmospheric discharges are large-scale, high-intensity discharges that occur due to the accumulation of electrical

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charges in localized regions of the atmosphere, usually within storms. Discharge begins when the electric field produced by this charge exceeds the insulation capacity, also known as dielectric strength, of air at a given location in the atmosphere, which may be within the cloud or near the ground. Once the dielectric strength is broken, a rapid movement of electrons from a region of negative charges to a region of positive charges begins [13].

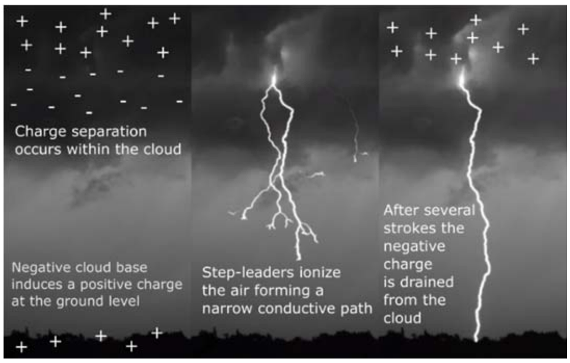


Fig. 1 Phases of atmospheric discharge

Atmospheric discharges can occur from cloud to ground, from ground to cloud, within a cloud, from cloud to any point in the atmosphere, the so-called air discharges, or even between clouds. Among all types of discharges, the intra-cloud is the most frequent, partly due to the fact that the insulation capacity of the air decreases with the height due to the decrease of air density, which is in some part due to the proximity of regions of opposite charges within the cloud, since they are normally closer to each other than in the case of any other lightning strikes. However, cloud-soil discharges are the most studied due to their destructive nature. They can be divided into two types or polarities, defined as a function of the signal of the actual charge transferred from the cloud to the ground: negative and positive [12], [13].

Negative discharges, which are about 90% of all discharges, transfer negative charge (electrons) from a negatively charged region within the cloud to the ground. In the case of positive discharges, electrons are transferred from ground to cloud. Although lightning may seem to the human eye a continuous discharge, in fact it is generally formed of multiple discharges, called return discharges, which succeed each other in very short time intervals [13].

Discharge formation occurs in two stages. The first step is air ionization. Then there is the occurrence of the first so-called stepped leader, which propagates out of the cloud following a non-linear path in steps. In this process, the stepped leader branches through multiple paths, but most of the time only one branch reaches the ground. When this occurs, a return discharge of high intensity of charge and brightness returns through the same path from the initial discharge towards the clouds. The current associated with the stepped leader is small, in the order of 100 A, while the magnitude of the return discharge current is of the order of tens of kA. Subsequent discharges, also called direct leaders, tend to occur soon after the first discharge, taking advantage of the ionized path left by the air. Fig. 1 illustrates the whole process of discharge formation [12].

Discharges last on average around a quarter of a second, although values ranging from a tenth of a second to two seconds have been recorded. During this period, trajectories ranging from a few kilometers to a few tens of kilometers travel in the atmosphere.

In order to protect the installations and equipment against atmospheric discharges, atmospheric discharge protection systems (ADPS), are used. In physical terms, the installation of a protection system against atmospheric discharges has the purpose of neutralizing the growth of the electric potential gradient between the ground and the clouds, through the permanent flow of electric charges from the environment to the earth, offering discharges an alternative and favorable route, reducing the risks of its incidence on structures and equipment.

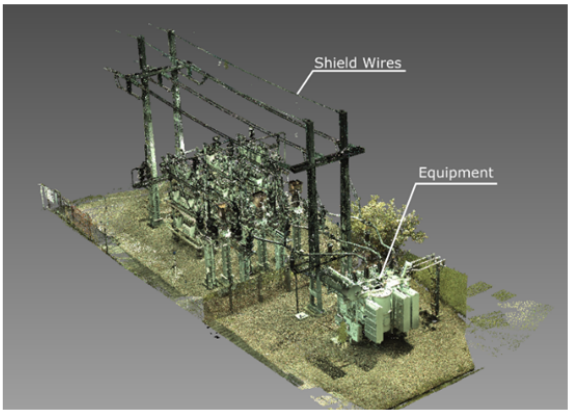


Fig. 2 Arrangement of shielding wire on the component to be protected in an energy substation

In power transmission substations, an ADPS is composed of shielding wire (usually made of steel) arranged in a catenary format on the component and interconnected to the substation ground mesh. Fig. 2 was drawn from the point clouds acquired through laser scanning in a small power substation and shows shielding wire arranged on the component to be protected. This way, shielding wire is responsible for conducting current surges from the atmospheric discharges to the substation ground mesh, which, due to its low impedance and to its connection to the terrain, dissipates this energy in the ground [17].

A. Electrogeometric Model (EGM)

Current scientific literature reports some methods used to properly design an ADPS, and the choice among those methods depends on the characteristics of the installation to be protected. The electrogeometric model is based on studies made from photographic records of the measurement of lightning parameters, high voltage laboratory tests, and the use of simulation techniques and mathematical modeling. This model introduces the concept of critical attraction distance, which is the distance at which the stepped leader of a discharge current is drawn by an object. The critical draw distance is proportional to the load density of the stepped leader. The return discharge current, in turn, is proportional to the charge density of the next leader and, since the return discharge is a widely measured and recorded parameter, the critical approach distance can be expressed as a function of the current intensity of the return discharge, according to (1) [17].

$$R = 10 \times I_c^{0,65}\ [m] \tag{1}$$

where, *R*: radius of the sphere; *Ic*: return discharge current.

ADPS projects in energy substations normally make use of the electrogeometric model. The most common way to implement it is through the rolling spheres method, which will be explained below.

B. Rolling Sphere Method

The Rolling Sphere Method involves rolling an imaginary sphere of radius R, equal to the attraction distance, on the protected structure. The attraction distance adopted is dependent on the discharge current and is calculated by (1).

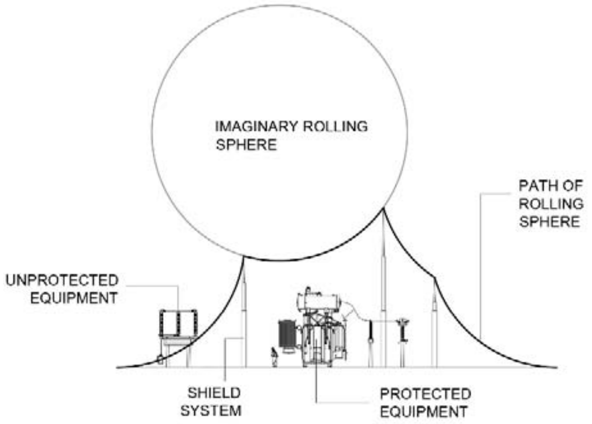


Fig. 3 Rolling sphere method applied to a generic substation

The protection area is obtained as this imaginary sphere travels the surface around the protected region and is supported in this case by the substation shielding wire. The elements under the surface formed by the sphere during its course will be protected. However, any substation component that touches or penetrates the sphere will not be protected [17]. Fig. 3 shows an application of the Rolling Sphere Method applied to an energy substation. In this method, it is assumed that the direct leader travels vertically towards the ground in steps within a sphere whose radius depends on the charge of the cloud or the current of the discharge, and will be diverted from its path by some grounded object. The discharge will occur at the point where the sphere touches this object or on the ground, whichever occurs first [17]. The radius of the sphere is called the distance of attraction or disruption distance. To apply it on structures some simplifying hypotheses are admitted, which are presented next [17]:

1) Only negative discharges initiated in the clouds are considered;
2) The direct leader goes downward, and is vertical and unbranched;
3) Discharges occur in a sphere of radius equal to the attraction distance;
4) The final discharge occurs towards the nearest grounded object, regardless of its mass or grounding conditions;
5) The vertical rods and the horizontal conductors have the same power of attraction;
6) The probability of the ground being hit or other grounded structure being hit is the same.

Although these hypotheses deviate a little from reality, the model remains valid and widely used until the present day.

C. State of the Art in Lightning Shielding Using 3D Technology

Most of the existing lightning protection techniques make use of the Rolling Sphere Method in the context of power energy, not only in hydroelectric substations, but also in solar and wind power plants. Rodrigues et al. [18] state that most damage in wind power plants are due to lightning. They report the development of a computer simulation tool for assessing risks related to lightning protection.

Charalambous et al. [4] propose a method for assessing external lightning protection and earthing designs to be installed in large-scale solar plants, allowing engineers to perform comparisons between the use of isolated and non-isolated lightning protection systems and to select suitable surge protection equipment.

Xie et al. [23] make use of a 3D graphics approach to the Rolling Sphere Method, or rather, a variation called Collection Surface Method, which makes it possible to model all objects in the shielding model by means of a 3D triangular mesh. The shielding collection surface is, therefore, a simple sum of all collection surfaces related to each object. The authors claim that their work produces similar results as the traditional method but significantly faster, and the time required for the computation is not subject to the complexity of the scene.

McDonagh and Klopotan [14] also using the Rolling Sphere Method, propose a 3D approach which analyses the designated air termination structures and then defines stationary shapes around them. Rather than focusing on where the spheres can go, the work focuses on where they cannot go. Thus, the produced shapes are a combination of sections of concave cones, spheres and cylinders.

Recently, in 2016, the same group (Xie et al. [24]), which proposed the 3D graphic approach back in 2009, proposed a shielding failure evaluation, also using the Collection Surface Method, enhanced by 3D computer graphics technology. Empty areas where no substation component is to be protected are eliminated and thus are not considered in the failure analysis. The work claims that the computation is fast and that there are no geometrical restrictions for its application and presents an example of application in an electrical energy substation.

As for commercial solutions in the market for the subject, there were found: Primtech of Entegra [6]; Bentley Substation of Bentley [2]; and Substation Design Suite of SBS [20]. All are engineering software for the design, construction and documentation of power substations. They have solutions for visualizing 3D protection mesh also constructed based on the rolling spheres method. However, as far as the applications of 3D technology to lightning shielding of substations are concerned, none of the abovementioned papers and commercial solutions were developed using a game engine. Neither was found any application that had a characteristic to provide the individual specification of equipment protected by the shielding mesh in addition to its visualization.

III. ADVANTAGES OF USING GAME ENGINES

Nowadays, video games are created and developed by means of specially designed systems called “game engines”. They are responsible by rendering, memory management and physics simulation (it provides collision detection, for example) [16].

Although the first game engines were created to ease the process of developing digital games exclusively, with entertainment only in mind, their application outside this field is becoming increasingly more popular. Recently, researchers from several fields of science recognized the potential that lies with game engines for applications to help with their research. Examples of such cases are everywhere: In medicine they have been used in the visualization scheme for the representation of cardiac arrhythmias [11]; in criminal forensic science to help reconstruct crime scenes [7]; in computer science to foment learning of programming languages [21]; and, finally, in the electrical engineering field, where game engines have been applied several times using virtual reality technologies, for example in Abichandani et al. [1], the Unity Game Engine served as a tool to recreate virtually the behavior of wind turbines and in Rosendo et al. [19] where an open source engine was used to develop a training platform for electricians that deals with energized power lines.

Another reason why the popularization of the game engines has been increasingly is the recent change in the distribution policy of the development toolkit of the main game engines currently available in the market. Companies such as Epic Games, Unity and Crytek have decided to sell their engines for a low subscription fee [22] and also to provide them completely free for research purposes.

In recent years, the gaming industry generated more income than the music and film industry. Rob Foote, in his article at KFVS12 [8], cites polygon.com, stating that the global revenue for video games estimated for the year 2014 was around $83.6 billion, whereas in the same period, the film industry made only about $36.4 billion, according to the Motion Picture Association of America. Besides, by 2015, the gaming industry total revenue only in the U.S. jumped 5% from a year earlier [15] and continued growing in the following year. With all this demand, manufacturers are encouraged to keep their game engines always updated, to provide good tutorials online, to answer frequent questions from developers through forums, and also to maintain its engines using efficiently, the potential and capabilities in the graphical processing units (GPUs) and providing high performance in computing time with accurate results using ray tracing algorithms, for instance. In computer graphics, ray tracing is a rendering technique for generating realistic images by tracing the path of light through a 3D scene [3]. It is capable of simulating a wide variety of optical effects, such as reflection and refraction, and scattering and dispersion [16].

Most modern GPU cards use a Physics Engine and a Physics Processing Unit (PPU) in order to deal with the complexity involved in the ray tracing algorithm used by a game engine. A physics engine consists of computational algorithms to simulate rigid bodies, particles, waves, deformable objects such as tissue and also to detect collisions between objects. A PPU is a dedicated microprocessor responsible for handling and accelerating the complex calculations involved in the tasks performed by a physics engine in the development of a video game [16].

Among the advantages of using game engines rather than CAD software are: the possibility of visualizing the model in an immersive virtual reality environment using HMDs; the possibility of rendering a mesh in order to highlight equipment that are dangerously close to its surface; generation and visualization of the mesh in real-time during the editing of the system; high fidelity graphics; and the fact that it is totally customizable and has free distribution for the purpose of the problem.

IV. PROPOSED SOLUTION

In order to guarantee the accuracy of the location of each substation component in the scene and to provide reliable results from them, it was necessary to carry out a survey of the point cloud of the studied area by laser scanner arriving at the as-built model. Based on the point cloud, the entire substation was modeled in a single low-poly 3D model. The 3D modeling of the equipment was done using the software 3D Studio Max and Blender, and for 2D design and creation of textures, Photoshop was used.

Subsequently, the low-poly substation model was imported for the project in UE4 (Unreal®Engine 4). Among the features that led to the choice of this game engine in this work, a few are worth mentioning: intuitive interface; free for the purpose of the work; possibility to program both in C ++ and Blueprint (visual scripting language of UE4); having a diversity of free tutorial videos available; having support for multiple desktop and mobile platforms as well as support for VR with HMD devices such as GearVR, Oculus Rift and HTC Vive.

With the low-poly mesh that represents the entire substation in hand, different equipment were identified and catalogued for detailed modeling. In this study case, a total of 20 pieces of equipment have been identified, such as, for example, voltage transformer, current transformer, and disconnect switch, etc. This equipment was then individually modeled in more detail from the initial low-poly model following strictly the dimensions and characteristics of the real equipment.

After that, the detailed models were imported individually into the UE4 project, where they are called assets. The assets of the equipment as well as the power cables of the entire study area of the substation were then placed exactly in their corresponding positions, based on the guide model of the low-poly substation. With the substation equipment properly positioned, the scenario, materials and other elements of the substation were created. However, all equipment can be moved in the real-time scene without loss of location information of the actual as-built position.

For each piece of equipment, a simplified collision mesh was created through the automatic collision creation tool of the UE4. For the protection surface collision, a per-poly collision function was used in which the collision mesh is the own polygonal model of the object.

The scenario creation and the concern with the graphic quality of the scene are due to the future immersive application for the project, where the engineers will be able, in addition of visualizing the mesh and making simulations, also perform a walk-through visiting the virtual substation; thus, saving costs with personnel transportation in trainings and demonstrations of equipment for newly hired electricians, as well as maintenance planning.

In order to encourage the development of the proposed approach, a survey about how the traditional 2D method is applied for protection studies in substations to date was made. With this method, when applying a new level of protection for the verification of protected equipment, that is, a new value of radius using the electrogeometric method, all the work for tracing the circles referring to the rolling sphere for each cut-off image must be redone, which involves a lot of effort and rework. On the other hand, with the proposed application, simply changing the value of the radius variable and re-executing the application is enough to accomplish such a task.

A. Implementation of the 3D Protection Mesh

The concavity of the protection mesh is defined by the radius of the rolling sphere used and directly influences the final result of the equipment protection algorithm. For example, a particular piece of equipment may be considered to be protected by being fully inserted in the protection volume for a radius of 30 meters (protection Level II, see Table II), and in the meantime, to be colliding with the mesh for a radius of 20 meters (Level I of protection), being considered unprotected in this case. Thus, the radius parameter was set to 20 as a default value, which is the lowest value accepted in the literature [5], making substation components protected for all the other subsequent values due to their higher radius value and consequent greater volume of protection. Since the value can range from 20 to 60 according to the protection levels [5], the radius parameter has been programmed to allow values only within this range.

UE4 has two instruction processing modes: the run-time mode, which corresponds to all processing that occurs from the moment the application is run by pressing the play button, and editing-time mode, called in the UE4 as construction script, which is executed with each alteration in the scene, being the change of value of a variable of a blueprint class or the repositioning of an asset in the scene.

The mesh algorithm was entirely designed within the project construction script. That way, when some parameter of the mesh is changed, the user can verify it visually in real-time without the need to recompile or run the application. This was made possible by engine's efficiency in implementing procedural meshes (see Section IV *A* 6).

1) Lightning Rod Section

The arc of a circle is, for the purpose of the protection volume creation, a recurrent item that will be reused several times to form approximations in different sections of the volume. The Rolling Sphere Method consists of a sphere translating the scenario to form a volume between the ground ($z = 0$ plane) and the lower section of the sphere (arc) to contact with an atmospheric protection point (shielding wire or lightning rod).

The mesh of a lightning rod is constructed by rotating an arc between the ground and the highest point around the pole on the z axis in the plane normal to the point of the pole and the point on the ground (plane $z = 0$), since the rod's height is smaller than the rolling sphere radius. For one end of the lightning rod, it is necessary to enter the end-points of other sessions formed by it.

2) Curve-Plane Section

When there are two or more point rods, the arc generated by the sphere that touches three rods or the arc between two rods of radius R, the sphere will roll on this curve generating a surface. To explain how this surface is generated, it is necessary to know where the sphere will be to find its center when it touches both the plane and the curve.

Given a plane and a curve, for each point on that curve, if its distance from the plane is less than a diameter, there are at least two points that we can use as the center of a sphere with that diameter.

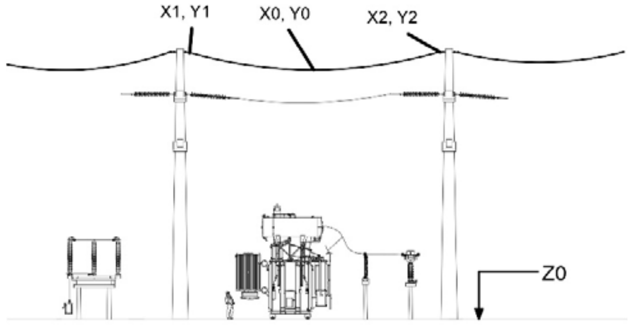


Fig. 4 Catenary curve demonstration

By parameterizing the curve, we can traverse it in the 3D space, R3. The scalar product between the tangent vector of the curve at the point and the normal of the sphere at the point is zero, since the vectors are orthogonal. We then have an equation for the system. We know that the distance from the position of the sphere to the point of the curve and the distance to the plane are the radius of the sphere, so we have two more independent equations.

We then have a three independent equations system and three variables, as described below, and hence, a possible system. The solution of this system is the two possible positions for the sphere.

$$\begin{cases} \vec{r}'(t).\vec{n} = 0 \\ |\vec{r}(t) - C| = R \\ \left|C.\overrightarrow{(0,0,1)}\right| = R \end{cases} \tag{2}$$

In the system, $\vec{r}(t)$ is the parameterized point curve, $\vec{r}'(t)$ is the tangent vector to the point in the curve, C is the sphere's center *(X0,Y0,Z0)*, as shown in Fig. 4, and $\vec{n}$ is the sphere's normal vector in the point $\vec{r}(t)$. In this case, as the plane is the ground, $z = 0$, it is possible to conclude that $Z0 = R$, since the sphere's center must be above the plane in $Z > 0$ coordinates. Only *X0* and *Y0* are left.

3) Parameterizing the catenary

The catenary is a curve that translates the behavior of a loose wire, given by:

$$Y = a.\cosh(\frac{x-x_0}{a}) + y_0 - a \tag{3}$$

In order to draw this equation, we need to estimate the parameters *a*, *x0* and *y0*. The inputs in the question are two points, *P1(x1,y1)* and *P2(x2,y2),* and the length of the chord.

To facilitate when setting up the ADPS, the cable length is given by a parameter that multiplies the distance between the two ends of the sensors according to the equation:

$$S = a.|P2 - P1| \tag{4}$$

The chord *(S)* length, being made the line integral of (4), will be given by:

$$\sqrt{S^2 - V^2} = 2.a.\cosh\frac{D}{a} \tag{5}$$

where *S* is the length of the curve, *V* is the height difference and *D* is the distance in the x-coordinate between the points. If we make an approximation by Newton's method, we still have to find the values of *X0* and *Y0*. For this, we use the equation of height difference.

$$V = a.\cosh(\frac{x_2 - x0}{a}) - a.\cosh(\frac{x_2 - x0}{a}) \tag{6}$$

The above equation is also transcendental, but derivable; so Newton's method was again used to estimate the value of *X0*, having the value of *X0*, we need to substitute it in (3) to find the value of *Y0*. Thus, given any pair of points *(X,Y)*, we can trace the catenary. For *R3*, the *X* axis is rotated in the *Z* axis and the *Y* coordinates are assigned to the *Z* axis.

4) Curve-Curve Section

Analogous to the Curve-Plane-Rolling Sphere solution, if the distance of all points on a curve is less than the diameter of a sphere, for each point on one of the curves, you have two centers of a sphere that "fits" in both curves. An analogy would be a loose sphere on an irregular rail. It is possible to use the same idea of solving a product system, described below, of a sphere's normal at the point and tangent of the curve at the point. This, and the point-to-center distance equations, give us a possible system with two solutions to the center of that sphere $C = (X0,Y0,Z0)$.

$$\begin{cases} \vec{r}'(t_1).\vec{n}_1 = 0 \\ \vec{s}'(t_2).\vec{n}_2 = 0 \\ |\vec{r}(t_1) - C| = R \\ |\vec{s}(t_2) - C| = R \end{cases} \tag{7}$$

5) Defining Parameters for the Mesh

The user-adjustable protection mesh parameters are: the radius of the rolling sphere; the position of the lightning rods; the connection points of the shielding wires (here called end-points); and the length multiplier of the shielding wires. With this information, it is possible to generate a vector of vertices and vector of vertices indexes for each triangle of the shielding mesh by the Rolling Sphere Method. As for mesh resolution, two parameters, *I* and *J*, were created to define the amount of polygons used in each section of the mesh, and, consequently, the total number of vertices generated and its density. The application also allows you to set these parameters (*I* and *J*) automatically by defining the width of the smallest component in the scene in cm. The purpose for creating this parameter is to guarantee a polygonal density so that no piece of equipment is disregarded by the detection algorithm because it is located exactly in a region between the mesh vertices.

6) Vertex Generation

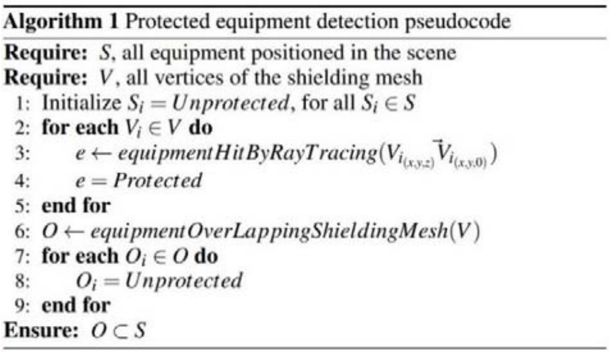
For the section between curves, in a *i* iterations loop, an arc is traced with *j* points, where *I* is defined by the integer part of the division of the distance between extremes of the longest curve by the distance of precision. *J* is defined by the integer part of the division of the half-circumference length by the precision distance (worst case). For the curve and plane session, in an iterations loop, an arc between this end and the ground with *j* points is also traced. *I* is defined by the integer part of the division of the distance between the ends of the curve by the precision distance. *J* is defined by the integer part of the division of a quarter of the arc divided by the precision distance. Finally, for the captors' end section, in a *i* iterations loop, an arc with *j* points is again traced. *I* is the integer part of the division of the quarter's length of the circumference with radius of the rolling sphere by the precision distance. *J* is defined by the arc formed by the position vectors of other neighboring sections of the shielding wire.

7) Procedural Mesh

The vertices and triangles then fill in the procedural mesh [9] which is a component of UE4 that allows the generation of the 3D model given a vertex vector and an index vector representing each triangle of the mesh. It also features slicing, which allows to split the surface into smaller meshes, and automatic collision creation which was essential for the protected component detection algorithm.

B. Protected Equipment Detection Algorithm

As previously mentioned, all equipment contained within the protection volume defined by the mesh, without touching its surface, are protected. Algorithm 1 in Fig. 5 expresses the pseudocode developed in this work for the detection of protected equipment.



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Algorithm 1 Protected equipment detection pseudocode
Require: $S$, all equipment positioned in the scene
Require: $V$, all vertices of the shielding mesh
1: Initialize $S_i = Unprotected$, for all $S_i \in S$
2: for each $V_i \in V$ do
3:     $e \leftarrow equipmentHitByRayTracing(V_{i_{(x,y,z)}} \vec{V}_{i_{(x,y,0)}})$
4:     $e = Protected$
5: end for
6: $O \leftarrow equipmentOverLappingShieldingMesh(V)$
7: for each $O_i \in O$ do
8:     $O_i = Unprotected$
9: end for
Ensure: $O \subset S$
```

Fig. 5 Algorithm 1: Protected equipment detection pseudocode

Firstly, all equipment is marked with the unprotected status, in that state, a material is applied to the equipment's polygonal models that keeps blinking and oscillating between red and yellow colors in order to make them evident. In the UE4, a material is an asset applied to a mesh to control how it looks in the scene. In more technical terms, it calculates the iteration of light with the surface of objects [10].

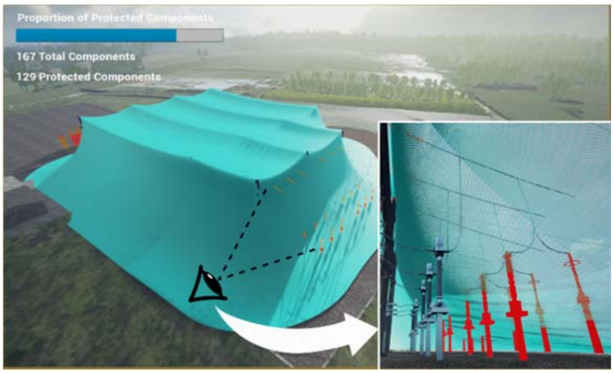

Fig. 6 3D shielding mesh rendering above substation with protected equipment indication

The iterations start at the moment of project execution. For every vertex of the 3D protection mesh a function named *equipmentHitByRayTracing* (line 3) is called, which executes a ray tracing vertically, straight from the point of the vertex to the ground. The UE4 also provides the possibility of visualizing the path of the rays for a stipulated amount of time. This *equipmentHitByRayTracing* function returns the list of equipment that its collision meshes were hit by the ray tracing algorithm. The state of such equipment is then changed to protected with its material changed to normal state.

Finally, the algorithm of collision mesh overlapping the equipment (line 6) detection is called. This is done through the *equipmentOverLappingShieldingMesh* function of UE4 that uses the collision loop of the scene objects to check and return the list of overlapping equipment that will be set to the unprotected status. These components are all those that appear across the collision mesh in Fig. 6, where part of the mesh was left purposely incomplete to demonstrate the functionality of unprotected equipment presentation in the present work. Thus, following the protection rules of the electrogeometric model, only equipment contained in its totality below the 3D protection mesh remains with the protected status.

For each state change of any piece of equipment, the protected and unprotected components counter is updated by providing a bar with the proportion of the protected ones in relation to the total amount of equipment in the scene, as well as the number of substation components and the number of protected equipment in the scene. This information can be observed in the upper left corner of Fig. 6, as well as the perspective from within the mesh in the lower right corner.

C. Visualizing the Shielding Mesh and Equipment

In the case of very strong winds that usually accompany storms with atmospheric discharges, the shielding wires can suffer deformations generating a catenary that tends to be parallel to the plane of the ground ($z = 0$), instead of transversal to it; this phenomenon can alter in centimeters the virtual protection mesh arrangement. This deformation tends to be stronger at the point equidistant between the end points of a cable segment in the case where the cables are attached to the pole. This, while being subtle in the case of distance, may cause some equipment to become vulnerable momentarily during periods of stronger winds that generally coincide with the occurrence of atmospheric discharges.

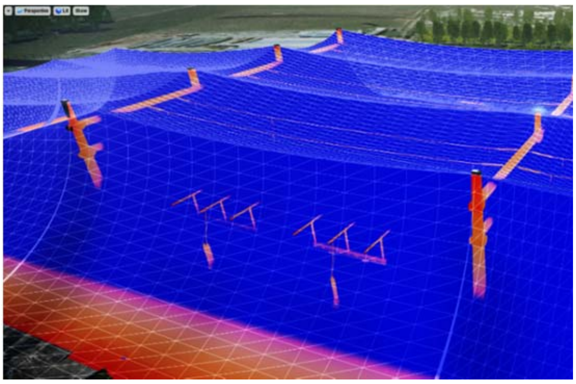

Fig. 7 Pixel depth masking translucent material applied to the shielding mesh

In order to assist the engineers in the identification of such pieces of equipment, a material specifically for the protection mesh was also developed in the present work. The result of which can be observed in Fig. 7.

For the composition of this material, shaders were used that subtract the pixel depth of the objects within the mesh with the depth of the scene, and multiplies them by the predefined color channels. It is done by masking objects that are at deep levels of the mesh and highlighting those which are close to its surface according to a scale of proximity that varies from white to red. With this, we obtain a material that works as a visual complement to the study of the equipment protection in the scene, highlighting those that, even if protected, are in sensitive areas in which any change in the configuration of the lightning makes them susceptible to electrical atmospheric discharges.

V. ANALYSIS AND PROOF OF THE RESULTS

In order to validate the solution developed in this work, a case study was conducted using the 230 kV section of a medium-sized real electric substation with an area of approximately 6,700 square meters. According to the engineers of the power company, the lightning protection project of this substation is a standard project applied to all substations of the company's 230 kV class, so the electrogeometric model was not used strictly according to the previously mentioned standards [5]. In this way, two objectives were achieved: 1 - to validate the efficiency of the proposed solution by comparing the outputs of the application (the list of protected objects and the 3D visualization of the shielding mesh) with the study of 2D cut-offs in CAD tools (traditional method); 2 - to verify the correct installation or configuration of the current substation's protection meshes from the as-built model, allowing to suggest changes or adaptations according to the system's result.

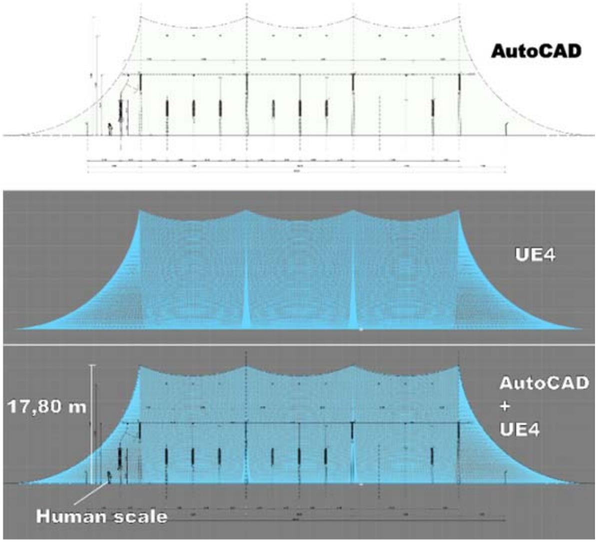

Fig. 8 Comparison between the cut-off from the original substation generated in AutoCAD with and the one from UE4 3D scene

The traditional way to apply the Rolling Sphere Method is to perform lateral and longitudinal cut-offs in the design of the substation by analyzing case-by-case, if the components are properly contained below the shielding surface, and consequently, protected against the lightning strikes. As the method of construction of the 3D mesh using procedural mesh is not trivial, as described in Section IV.A, we chose to verify the credibility of the 3D model of the mesh developed with the traditional method in 2D mentioned before. For this, a cut-off of the scene was first generated based on the original design files of the substation in the CAD platform; in this case, it was used a pointing cut that coincides with the top of the first transmission bus. Then, following the traditional standards, the protection mesh was drawn using the AutoCAD drawing tool (AutoCAD image in Fig. 8) with 20 m applied as the radius value (protection Level I).

TABLE I
COMPARISON BETWEEN PROJECTED VOLUME AREAS GENERATED FROM UE4 SCENE CUT-OFFS WITH DIFFERENT 3D SHIELDING MESH RESOLUTIONS

Shield mesh cut-off (m^2)	Resolution used	Area dif. (m^2) from 972.97	Max. dist. Between mesh polys and electrogeometric surface
972.972	40x80	0	0
975.463	10x29	2.491	0.08
996.261	3x5	23.289	0.053

Subsequently, the cut-off of the 3D scene was plotted in the UE4 environment at the same cutting point mentioned. In order to reach the level of resolution of the mesh suitable for such comparison, three 3D meshes with different resolutions were generated, as shown in Table I. As can be seen, the first column of the table shows the projected area of the protection volume for the cut-off according to the resolution shown in the second column. The third column shows the difference between the area measured in the AutoCad image (972.97 m2), shown in Fig. 8, and the measured areas of column 1 using a precision of three decimal digits. And the fourth column describes the maximum measured distance between the mesh polygons and the electrogeometric surface (m) for each of the three resolutions. With this, it is observed that the difference increases exponentially with the deterioration of the 3D model. This happens because vertices of the 3D mesh touch the lines of the electrogeometric model at intervals that, when connected by the polygons, describe volumes external to their line. However, as the decrease of this difference is also exponential, the 40 × 80 resolution value (UE4 cut-off in Fig. 8) has already proved sufficient to virtually zero out the perceived difference between the two models. This statement indicates that the 3D shielding mesh was properly implemented in this work using the UE4 environment according to the standards of literature [5].

After completing this verification study of the generated protection mesh, two more experiments were executed with the proposed application. In the first, the entire substation grid was applied according to the current layout of the shielding wires in the study area of the current substation. The minimum spacing parameter (described in Section VI.A.5) was set to 45 cm according to the collision mesh of the smallest piece of equipment in the scene. The four protection levels with their respective radius values were applied obtaining the same result: All 167 substation components were designated as properly protected, demonstrating the effectiveness of the current protection system of the substation in question. As the equipment was modeled and positioned according to the as-built model of the substation, extracted from a laser scanner, the experiment indicates that all equipment in the study area of the substation are currently adequately protected according to the electrogeometric model of the rolling spheres. However, when applying the material described in Section IV, it can be verified that some equipment may be dangerously close to the surface of the protection mesh, for instance, the three-phase disconnecting switches that are shown in Fig. 6. This information was reported to the engineers responsible in the power company and can justify future upgrades and improvements in the substation.

Considering that in the first experiment all equipment was considered protected, a second experiment was proposed maintaining the same parameter values, however, altering the arrangement of the shielding wires in order to create a protection volume in which some equipment was deliberately exposed, but just barely. That way, it would be possible to compare the amount of equipment identified as visually unprotected with the amount reported by the application and to verify the results for each level of protection.

The protection against lightning is described in standard NBR 5419 based on IEC 61024-1-2. This standard defines lighting protection system (LPS) levels that estimate a measure for protection effectiveness. The standard has four levels, with Level I being the one with the highest protection with a radius value equal to 20 m for the rolling sphere, and the Level IV of less protection with a value of radius equal to 60 m, as can be observed in Table II.

TABLE II
COMPARISON OF DIFFERENT PROTECTION LEVELS OF THE ROLLING SPHERES METHOD APPLIED TO THE PRESENT WORK

Protection Level	I	II	III	IV
Radius	20	30	45	60
Vertices ($\times 10^3$)	408	728	1357	2154
Equipment	129	144	154	162

Table II shows the results for the experiment. The first and second lines of the table show the described levels and values of the radius of each level in meters. The third line shows the number of vertices that make up the polygonal model of the mesh according to the defined radius. A larger radius value means that the area covered by the mesh is also larger because the number of vertices that make up the mesh also increases. The fourth line shows the number of protected equipment out of 167 in total for each level of protection, 129 of which are protected to the lowest level (Fig. 6 is used to explain the operation of the application) and 162 for the highest level of protection.

With this experiment, it was possible to perform a reliability analysis of the application by comparing the amount of equipment identified as visually unprotected with the amount reported by the application and verifying the results for each level of protection, and by doing so, solidifying the importance of the correct arrangement according to the standard to ensure the safety of all substation equipment against atmospheric discharges.

VI. CONCLUSIONS AND FUTURE WORK

At first, on our project, one of the chosen engine's main selling points were the native support of C++, which is widely used worldwide, from trivial commercial automation software to heavy data processing in the search for new algorithms in the field of computer science. Therefore, the Epic Game's Unreal Engine 4 seemed like the ideal choice. However, during the development, the use of C++ programming language deemed unnecessary for the Unreal Engine's visual script called Blueprint, which has shown again and again its capabilities and versatility even when dealing with complex calculations, and overall, it provided the necessary organization for huge and complex projects that are usually accomplished with more traditional methods and languages such as C++, Java and C#. Being so, all scripts used on the project were made with Unreal's visual scripting proving that the Blueprint scripts can be versatile and robust, not only for the programming of 3D virtual environments, but also for complex algorithms involving large amounts of computations.

Not long ago, generating an as-built model of an area with geometrically complex equipment such as an electric power substation could be considered extremely costly and often impractical. However, with the increasing demand for this type of service, new manufacturers and products appeared in the market, reducing both the cost of equipment and service involved in laser scanning. On top of that, the advancement of technology and sophistication involved in both laser scanner equipment and graphic design software tools also led to the simplification and reduction of time and money involved in the process.

One possible use for the present project is aiding in the planning of new substations by engineers of the power company. Mainly because the regulator of the Brazilian Electric System has recently signaled that such specific projects against atmospheric discharges should be developed for the new substations that operate with higher voltages, which was not required until then. This use is possible because the developed protection mesh itself is highly customizable and can be changed by just indicating where the end points are located in the scene. In addition, a data base of equipment assets was created that can be freely positioned by the existing virtual scene or in a new blank scene allowing a new substation to be designed from scratch in the future.

As future work, it is planned the development of a module that automatically suggests positions of the mesh end-points based on the polygon model of the poles in the scene, as well as an immersive virtual reality environments using current market HMDs.

ACKNOWLEDGMENT

This work has been developed by the OneReal Research Group within the R&D project PD-6491-0299/2013 proposed by Copel Geração e Transmissão S.A., under the auspices of the R&D Program of Agência Nacional de Energia Elétrica (ANEEL).

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