Comitê de Estudos B3 - Subestações e Instalações Elétricas
TP1 - Gestão de ativos no contexto de mudanças climáticas, emissão zero e expansão das fontes renováveis

Automated lightning protection method including low current lightning strikes to enhance substation design processes based on BIM 3D models

L. GUEVARA[1]*, S. HEUSER[2], J. PIÑEROS[3]
ENTEGRA[1,2], XM S.A. E.S.P. COLOMBIA POWER SYSTEM OPERATOR[3]
Colombia[1,3], Germany[2]

ABSTRACT

The increasing demand for continuous energy supply - driven by the energy transition, global digital transformation and electrical grid expansion - poses significant challenges for power system operators. One critical concern is the threat posed by lightning strikes, particularly in high voltage (HV) and medium voltage (MV) substations. In regions experiencing rapid grid development, the complexity of ensuring effective lightning protection systems is further heightened by a shortage of experienced engineers. This results in a continued reliance on manual methods, which are time-consuming and prone to errors in substation design and verification.

This article addresses the challenges associated with substation lightning protection, focusing on low current strikes that can compromise the integrity of power transformers, MV equipment and cause operational disruptions. A comparative analysis of manual versus automated verification methods is provided, with a specific focus on risk discussion, efficiency, and compliance with international standards such as IEEE 998, IEC 62305, ABNT NBR 5419, and Brazil's ONS requirements. The article presents real-world examples demonstrating the importance of thorough analysis during both the engineering and operational stages of electrical substation projects.

An innovative approach utilizing the rolling sphere method for low current lightning strike analysis is proposed, integrated within a 3D Building Information Modeling (BIM) environment. By automating the generation of protection zones, this method offers improved accuracy and operational security for substations including lateral lightning strikes. The article also explores the benefits of transitioning from manual to automated solutions, underscoring the relevance for countries with growing infrastructure demands and a decreasing pool of skilled engineers.

KEY WORDS

Lightning Protection, Substation Engineering, Design, BIM, 3D Model, Verification Methods, Operational Security, Compliance, Digital Transformation.

*Luis Arturo Guevara Cano - l.guevara@primtech.com

1. INTRODUCTION

Worldwide, the energy transition, digital transformation, expansion, and upgrading of electrical grids are being continuously pushed forward by the dynamics of modern society [1], [2]. The requirement for power capacity and continuous energy supply has increased, bringing tougher challenges for the system operators and demanding safer electrical facilities. Lightning strikes cause a significant threat to the safety and functionality of power grids, particularly in substations, because of equipment damage leading to the prolonged duration of loss of the energy service [3]. This becomes especially relevant in countries with relevant keraunic levels, where numerous new projects are underway to expand the power grid.

Currently, the process for designing lightning protection systems for substations has several challenges - in addition to the problem of the availability of qualified and experienced engineers [4], [5]. First, the quality problem, which is because of the diversity of criteria and methods to apply the design methods, for example, the rolling sphere method - that can be done in 2D or 3D manually, semi-automated, or fully automated. Second, the radius of the sphere has several issues for the selection, including how to manage different voltage level equipment and interfaces. Third, the real insulation failures show the design problem. Real-based cases and examples are illustrated to highlight the relevance of adequate analysis of the lightning protection systems during engineering stages for long-time operating assets due to network requirements and climate change. Fourth, the need for integration with 3D models in the process flow - considering the maximum efficiency-effectivity - is required to avoid problems in the operation of the electrical substations.

This article presents, in section 2, a discussion of the challenges of the worldwide standards for external lightning protection in substations, such as ABNT NBR 5419 [6], IEEE 998 [7] and IEC 62305 [3], are analyzed in relation to low current lightning strikes and the requirement regarding the performance against lightning strikes given by the ONS (Operador Nacional do Sistema Elétrico) of Brazil (Submódulo 2.6 Requisitos mínimos para subestações e seus equipamentos) [8].

In section 3, the lightning protection verification methods, such as manual verifications and automated verifications, are illustrated and compared in terms of risk mitigation, effectiveness, efficiency, and difficulty. Processes and considerations for an effective lightning protection verification in operating assets are addressed, including artificial intelligence-based solutions for efficient substation BIM digitalization and integrated calculation for an automated generation of protection volumes and zones.

An innovative method, applying automated lightning protection verification, is presented in section 4, using the rolling sphere method considering low-current lightning strikes. The method is implemented in software and integrated into a substation 3D BIM environment. Examples of the analysis for HV and MV substations, to effectively identify unprotected zones and assess risks for improving operational security of the assets, are presented.

Finally, the article examines, in section 5, the necessity and advantages of using automated software for lightning protection analysis instead of manual methods - demonstrating how it aids engineers in proactively addressing the challenges associated with lightning strikes, thereby considering the importance for countries experiencing growing demands for electrical infrastructure and a lack of skilled professionals.

2. LIGHTNING PROTECTION DESIGN IN ELECTRICAL SUBSTATION

In this section, a review of international standards, such as the IEEE 998 and IEC 62305, is done in regard to the needs of lightning protection for low current strikes. Additionally, a Brazil-specific scenario is reviewed according to the ONS requirements and, challenges, risks and consequences of lightning protection design in low current scenarios are revised.

a. Introduction to IEC 62305 and IEEE 998 considerations for lightning protection design

The IEC 62305 and IEEE 998 standards for lightning protection in electrical substation differ in their approach to selecting the rolling sphere radius. IEC 62305 [3] is based on risk calculation, defining four

predefined levels of protection, each with different sphere radius. The risk calculation considers various factors, including loss of human life and loss of public service. When it is properly calculated for high and medium voltage substations, the result should normally be that substations are critical facilities with very low tolerable risk. Engineers applying IEC standards often apply different criteria for the risk assessment depending on the country or region where they are working and specific criteria related to all the factors involved in the IEC risk calculation process. Traditionally, most HV substations tend to be validated with sphere radii of the higher classes (III or IV). For critical substations, normally, classes I or II are selected. However, the insultation conditions and specific risk areas with medium voltage equipment that are vulnerable to low current lightning strikes are traditionally not considered.

The IEEE 998 standard, on the other hand, takes a highly technical approach by focusing on insulation failure in substations when a lightning strike hits the substation equipment. While the IEEE standard is very detailed for HV substations, it is commonly not well understood for MV levels, as the calculation can result in a very small critical current and then a very small sphere radius. IEEE 998 [7] in subsection 6.3.6, recommends a limit for the minimal current, which most engineers are unaware of. This relates to a physical fact about lightning behavior, specifically that a certain minimum current - or electrical charge - is needed to break the air and generate the lightning strike, and it makes it very unlikely for a strike below 2kA to occur [9]. The probability of low current lightning strikes varies by country, and while rare, they do happen. The fundamental problem, as is described in [10], is that lateral low current lightning strikes can cause a significant impact when they hit equipment e.g., transformers bushings, thereby generating destructive effects and loss of public service for very long durations.

Once a radius is defined for the rolling sphere method, only the IEEE 998 standard provides further details on how to manage different voltage levels (section 6.3.5 of [7]), but interfaces exposing equipment terminals bushings of medium voltage levels are not described in detail, and these components do not have the same Basic Insulation Level (BIL) as the HV equipment. Traditionally, the very low probability associated with low currents lightning strikes is the reason why no special considerations about them are included in the calculations by some engineers and also why it is not deeply analyzed in the standards.

In summary, the IEC and IEEE standards remain open to discussion regarding HV - MV interfaces that are present, for example, in power transformers and in MV areas. Engineers often assume that these interfaces are covered by the HV lightning protection system but in reality, they are not always covered. This is due to the differences in level of insulation. During the operation of electrical substations, some real events had shown that MV terminals, bushings, and, in general, MV-HV interfaces are relevant to be protected properly to avoid blackouts [11]. It is well documented that traditional methods, with traditionally selected currents in the range of 5-20kA, can have failures because the range does not cover 100% lightning protection for HV substations and even less so for MV substations [12] [13]. In [14], a real case of a direct impact to a MV substation busbar was reported by a digital newspaper. The event occurred in Colombia with significant equipment damage (more than 200.000 USD) and very long times of power outage.

b. Lightning protection requirements of substations in the main grid of Brazil according to the ONS and compliance with NBR 5419 methods

In Latin-American countries, we encounter special risks related to lightning strikes due to e.g., the geography of the region. In comparison with some European countries - where the required stroke current is elevated for the lightning leader to generate the strike - in Latin America, the high altitudes above sea level, among other variables, allow lower currents to generate a strike and makes it more complex to verify the external lightning protection system. In Brazil, the “Operador Nacional do Sistema Elétrico” (ONS) requires that there cannot be a lightning protection system failure for currents above 2kA [8] and because of it, special verification procedures are needed due to the small sphere radius (approx. 15m) for the rolling sphere method and the height of the structures for 220kV and 500kV, as it will be explained in sections 3 and 4.

The challenge for analyzing and preventing the risks for lateral discharges resides on the precise and efficient rolling sphere modeling to ensure that the substation is fully protected. The base indications given in the Brazilian standard ABNT NBR 5419:2015 [6] describe the risk and present an example on how to approach these situations of "high structures" for lightning rods. However, for the shielding wires, we need to do a deeper analysis of the base of the rolling sphere method, because in this case the sphere would roll under the wire potentially exposing some components to lateral discharges as presented in the Fig. 1.

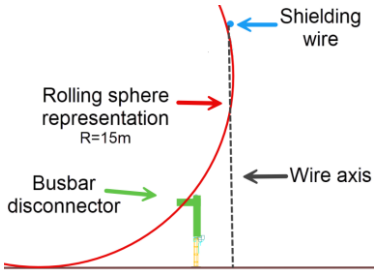


Fig. 1 Example of sphere under-rolling at shielding wire

Currently, 2D verification methods for the external lightning protection (LP) of substations are widely applied in the industry but they represent high risks of non-verification of complex positions in the substation and exposure of the facility to lightning strikes due to the high dependency on the engineer's experience and the pressure on the team to deliver in short times because of the project deadlines, as explained in section 3 and 4. To reduce the mentioned risks, increase the efficiency and quality in the projects, an automated 3D verification has been implemented to efficiently verify the LP when the sphere radius is lower than the protection elements height - as requirement for many cases in the Brazilian main electrical network - and will be explained in section 4.

c. Challenges in lightning protection for electrical substations

There are many challenges in lightning protection for electrical substations, starting with how the rolling sphere method is applied. Most engineers worldwide still apply the method with 2D drawings [12] [15] [16], which is not reliable enough. This approach often leaves areas - particularly at the HV-MV interfaces and substation corners - inadequately covered during manual verification due to limited angles and views (see Fig. 2).

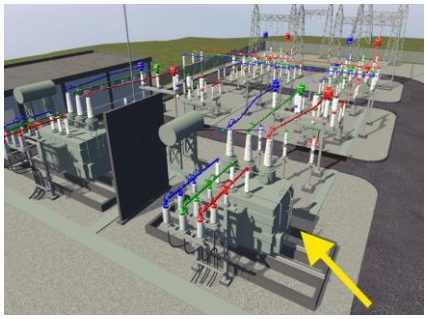


Fig. 2 Substation corner and HV-MV interface at risk of lightning strike

Current technology provides 3D models for lightning protection analysis, but most engineers worldwide are using manual or partially automated methods for the application of the rolling sphere method. When the 3D process is manual, there might still exist areas not correctly verified. Usually, partially automated methods present an issue regarding the low current verification risk, as this scenario is normally not automated. This issue is mainly caused by the available algorithms, as they are only for large sphere radii, and they do not correctly support the low current (small radii) values because small spheres may produce inconsistent behaviors like rolling under the protection elements of the substation and leading to error in the algorithms or wrong results. For High, Extra High and Ultra High Voltage (HV, EHV, UHV) substations the issue of very low sphere radii is more difficult because in theory, the sphere rolls on the ground and over the elements but due to the high structures it also rolls under the protection elements - increasing the risk for lateral discharges on equipment. The lateral discharges should be

properly analyzed for avoiding failures in e.g., HV-MV interfaces [10] [13], present in power transformers [11] or MV equipment in line bays or busbars connections between air insulated substations and switchgears.

A relevant question in substations is what to do when, e.g., the facility has three switchyards of different voltage levels. In the experience of the authors and supported by the IEEE 998, it is not practical to consider the lowest possible current for the whole substation and it is incorrect to select the highest current for the rolling sphere of the entire facility. From the point of view of the technical-economic practices, every switchyard of the substation should be verified according to its own critical current, calculated based on each insulation level to avoid failure of HV-MV equipment and overcosts due to the overprotection of the facility.

The incorrect approach for lightning protection design mentioned above, increases the risk for lightning strike impacts on equipment located at the substation's corners [10] [11]. The risk is increased on MV bushings, equipment and connections such as the interface between e.g., air insulated elements at the switchyard and insulated cables for connection to the switchgears, because even if low current strikes have low probability, they are more likely to produce an insulation failure on MV equipment when it is not properly protected. Additionally, when a lightning strikes a substation structure, the risk for additional branch discharges striking at another point is well known, and the criticality is increased when not all structures are grounded due to the floating electrodes phenomenon, as mentioned in section 4. The problem is that the consequences of the mentioned events are very high, as transformer and bushing damages represent high economical losses and long-term blackouts [10].

All the problems mentioned above can be found in several incidents affecting busbars or power transformers. In [11] a case of a HV bushing damage of a transformer exposes the discussed risks and problems. The survey [12] of past years reveals that incidents of lightning protection shielding failure are more frequent than expected.

3. TRADITIONAL AND BIM-INTEGRATED LIGHTNING PROTECTION VERIFICATION METHODS

The traditional 2D verification method for lightning protection design is still widely used in the substation industry, so it is relevant to review the process and the inherent risk of it. By understanding it, a comparison between the different methods may be undertaken. Among these methods to be reviewed and compared are the 3D manual verification - presented in this section - and the 3D automated method presented in section 4.

a. Review of traditional 2D verification

The process usually starts with the defining of a unique sphere radius for applying the rolling sphere method, normally for the HV yard according to the defined insulation level (IEEE 998) or the risk calculation (IEC 62305). If there are several voltage levels, it is required to define every insulation and sphere radius needed according to the voltage level and it is a risk not to consider them independently. This means, it is a risk not to verify every voltage level equipment with the radius of the sphere according to the insulation level.

The next step is the 2D verification process, is normally based on the views of the substation drawings. Every side of the substation must be covered during the verification. Some section drawings are often needed to guarantee a minimum quality level. One of the risks in this process is to not consider the required views - including sections that need a special angle - to ensure the proper coverage of the lightning protection system. 2D views are considered risky because objects are shown aligned in the views and it needs a person with enough experience to decide which views are necessary to comply with the minimum quality of the rolling sphere method.

Currently, the reality of many consulting companies is that only the front, rear, right and left sides views are considered, but other necessary views or sections are not verified, e.g., the corners with sections considering angles (normally because of the symmetrical equipment location including steel or concrete

structures). Other risky locations in substations - derived of the low-level of verification due to the limited views available in 2D drawings - are the substation line entrances and the transformers HV & MV bushings interfaces, including power cables (mainly in MV).

Angle based methods avoid the limitations of the 2D views, but they can present failures [12], especially for lateral strikes [10]. The verification of the substation corners is critical in many cases and the wrong design approach at these zones is very risky for the operation. In addition to substation corners, it is necessary to take a closer look at the interfaces between different voltage levels and transitions to sub-transmission and distribution lines, as they have higher probability to suffer an insulation failure than a transmission line due to the lower BIL. The special attention to the transition to outgoing lines becomes relevant as, normally, the structures are less protected at the substation borders and outgoings.

The protection against lateral or side lightning strikes is very relevant in countries where there is a more lightning activity with low currents and with irregular terrains. Over the years, 2D verification by rolling sphere method has had a weak point due to the lack of sources of the views and updated versions. The authors had multiple experiences in projects where, among various reasons, the last-minute changes, lack of communication and outdated-documentation and inconsistent 2D views, led to errors during the verifications.

b. Review of traditional 3D manual verification

The 3D manual verification process also begins with the calculation of the sphere radius, as the 2D process. Then, in past experiences, a 3D model was generated only to assist the lightning protection design and it took considerable time, but it is currently a common requirement of substation engineering for many analyses and designs. Without doubt, with a 3D model, the rolling sphere verification is better from the point of view of the possibility of rolling the sphere in several directions and angles - the manual rolling and modeling process is time consuming in comparison.

In the authors experience, the rolling sphere verification in a 3D environment is highly dependent on the algorithm or applied manual method to move the sphere. In manual processes, normally, only some prioritized areas are verified, such as the busbars, but the risk of lateral discharges at equipment gets less or no attention. The authors consider that manual sphere movement - human with a computer mouse - is more tedious than moving the circle in the 2D verification process.

In the same way as with the 2D verification process, it can occur that some angles or corners are not well verified if the engineering experience and expertise in 3D CAD environments of the person performing the verification is not enough, given the complexity of the manual process. This increases the risk of lower quality of the verification and lower operational security.

c. 3D automated verification integrated in BIM engineering software

Every day, the Building Information Modeling (BIM) methodology is becoming increasingly important in the energy industry. Given the special electrical and electromagnetic conditions of an electrical substation - that are not present in the buildings and civil infrastructure industry - combined with the high importance of these facilities for the continuous development of the society, the BIM for substations needs to be integrated with automated and specialized calculations, verifications and simulations [17] to provide securer assets for the operation.

There are software solutions in the market like *primtech* that allow an integrated verification and optimization of the external lightning protection (LP) in the engineering BIM environment, as presented in [17] and [18]. The integrated LP verification is a feature that allows the evaluation of the LP through the rolling sphere method by automatically recognizing the shielding wires, lightning rods and other supporting elements for the sphere, like the substation's fence and grounded metallic objects. This integrated feature allows companies to evaluate the situation on greenfield projects and on brownfield operating substations, in order to assess potential risks for the operation and mitigate them before the failures occur, as presented in section 5.b.

As explained in section 4, the integrated LP verification in the BIM software has been further developed in order to support the special case of a sphere radius (R_s) smaller than the height of protection elements (H_{pe}) present in multiple countries in the Latam region. In Brazil, the ONS requires that all substations must be protected against strikes of 2kA (R_s~15m) [8] and it makes it especially difficult in HV, EHV and UHV substations where the H_{pe} - e.g., shielding wires and lightning rods - is higher than the given R_s of ~15m. The extension on the LP feature complies with the indications of the ABNT NBR 5419:2015 [6] for H_{pe} is higher than R_s, and it enables a more precise approach to the risks for lateral strikes in short times on e.g., busbars or power transformers as mentioned in section 2.c.
This automatic method is considered the easiest, most efficient and accurate of the presented methods in this section due to automatically recognizing the protection elements - as well as generating the protection volumes and zones for scenarios of $R_s > H_{pe}$ and $R_s < H_{pe}$ and thereby covering the lateral lightning strikes scenario. Additionally, it is better qualified with regards to risk mitigation for external lightning protection of electrical substations, as multiple scenarios may be evaluated in short times according to each voltage level, thereby assuring a higher quality and security for the operational phase of substation assets.

Table 1. shows a summary of the comparison of the 2D-3D manual and automated methods for verification of the external lightning protection by the rolling sphere method. In section 4 a time comparison of the effort required to do a lightning protection verification by different methods is presented.

Table 1. Comparison of lightning protection verification with rolling methods

Aspect	Verification method		
	2D manual	3D manual	3D automated
Required time / efficiency	Medium	High	Low
Quality / effectiveness	Low	Medium	High
Difficulty	Medium	High	Low
Risk mitigation	Medium	Medium	High

4. APPLICATION OF AUTOMATED LIGHTNING PROTECTION VERIFICATION

Substations in Latin America are exposed to low and high current lightning strikes as introduced in sections 2 and 3. This situation represents an additional challenge for the evaluation of the external lightning protection systems in comparison to some European countries such as Germany, where the substations are mainly protected only against high current lightning strikes. In Latin America, sometimes due to space limitations, the substations are built with multiple equipment levels thereby increasing the height of the lightning protection elements (H_{pe}) and generating the scenario of a sphere radius (R_s) lower than the H_{pe}. In Brazil, the scenario of $R_s < H_{pe}$ is common due to the ONS requirement for the substations to be protected against low current lightning strikes (2kA, R_s~15m).

Engineers and drafters are commonly using 2D section views in specific positions of the substation to verify the scenario of $R_s < H_{pe,}$ but this method is very time consuming and the risk for the lack of evaluation of critical position is high - as mentioned in section 3.a. In the coming years, this risk will increase as the experienced engineers retire and fewer new engineers are graduating. Nowadays, most of the commercial software for lightning protection only cover the rolling sphere method for the scenario of R_s higher than H_{pe} but not the scenario of R_s lower than H_{pe} - which is the most complicated scenario to verify and to model. When $R_s > H_{pe}$, the sphere rolls on all the protection elements, but when $R_s < H_{pe}$ the sphere crosses the vertical axis of the shielding wires and may expose the facility to lateral strikes, as shown in Fig. 1.

The *primtech 3d* solution, a software for BIM engineering of electrical substations with integrated calculations and simulations, has been extended in its external lightning protection (LP) verification to cover the scenario of $R_s < H_{pe}$. The solution now allows the evaluation of the rolling sphere for $R_s > H_{pe}$ and $R_s < H_{pe}$ according to the IEC 62305 classes, IEEE 998 stroke current and user defined sphere radius (R_s), used for e.g., radii given by national/local standards. For the evaluations, the user can easily

automatically or manually select the protection elements that are to be considered, as shown in Fig. 3 and listed below:

- Lightning rods/masts
- Shielding wires
- Edges of the grounded metallic objects and substation fences

Given the added complexity for the modeling of the scenario when $R_s < H_{pe}$, the interface has been extended to easily select if $R_s > H_{pe}$ or $R_s < H_{pe}$. When $R_s < H_{pe}$ the user needs to activate the "Underrolling" method and the calculation takes a longer time in comparison to the scenario when $R_s > H_{pe}$ due to the modeling complexity. In Fig. 4 shows the software's interface for selecting the verification method: Evaluation standard - rolling sphere (IEC, IEEE or user defined) or VDE, stroke current and sphere radius, creation of protection volumes or heights/sections, layer for drawings generation, ground level for substations with multiple levels, underrolling ($R_s < H_{pe}$) and selection of protection elements and tolerance. In Fig. 5, the recommended workflow is presented for the application of the automized rolling sphere method in electrical substations.

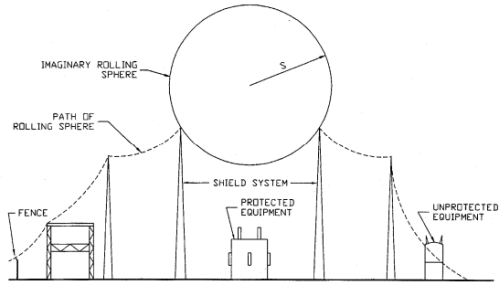


Fig. 3 Rolling sphere with multiple protection elements [7]

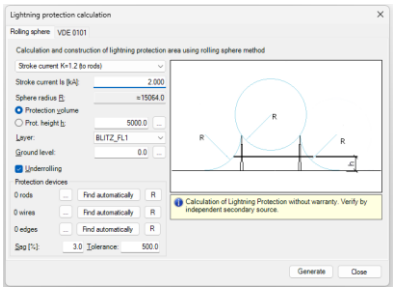


Fig. 4 Interface for the selection of lightning protection verification method

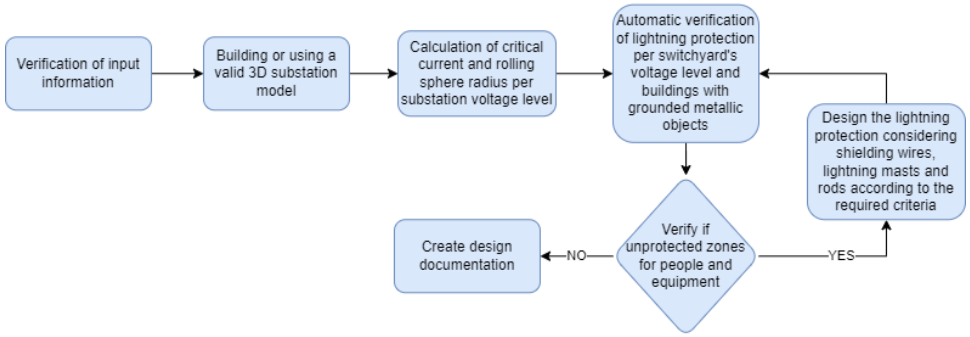


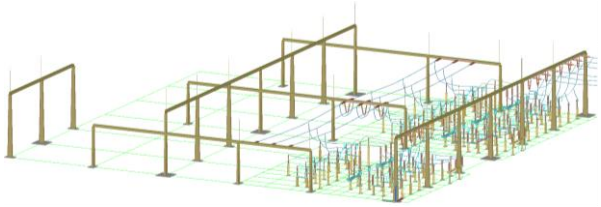
Fig. 5 Workflow for the automated rolling sphere method in electrical substations

In Fig. 6, it is possible to find the results given by the automated 3D verification presented as protection volumes for validation of the protected and unprotected equipment. Fig. 6a presents the example of a 220kV switchyard. Fig. 6b shows the external lightning protection (LP) of the 220kV switchyard with a sphere radius (R_s) of 60m (Class IV of IEC62305 [3]) that represents a case of a R_s bigger than the height of protection elements (H_{pe}), the generation of the protection volume took 5.45s and graphically shows that everything is protected in the switchyard. Fig. 6c shows the example of a lightning protection for the 220kV switchyard with an R_s of ~15m (for stroke current of 2kA according to IEEE 998 [7]) that represents a case of an R_s smaller than the H_{pe}, the generation of the protection volume took 2min20s and shows that the switchyard is not protected. As a comparison, the time-effort between the automated and manual verification methods are presented in Table 2.

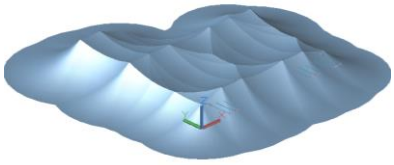
Table 2. Duration comparison of lightning protection verification methods for a 220kV switchyard of Fig. 6 when R_s ~ 15m

Aspect	Verification method		
	2D manual	3D manual	3D automated
Estimated duration	Hours	Days	Minutes

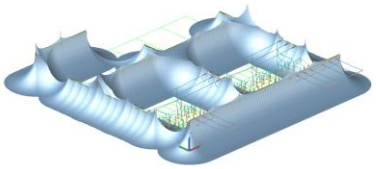
The cases in Fig. 6 represent the clear need for insertion of more lightning protection elements in a substation when low current lightning strikes are to be considered. The need for a quick evaluation of designs is addressed with the automated 3D methods within BIM engineering solutions. Even the optimization analysis for protection elements can be directly done within the same environment to analyze potential location of additional e.g., lightning rods, masts or shielding wires.



a. 220kV substation switchyard



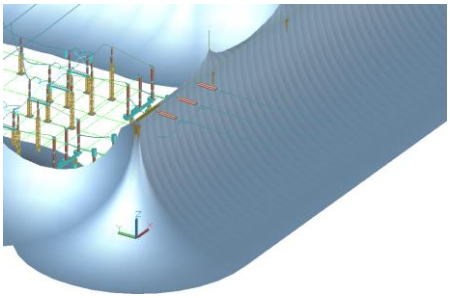
b. Class IV (60m) lightning protection



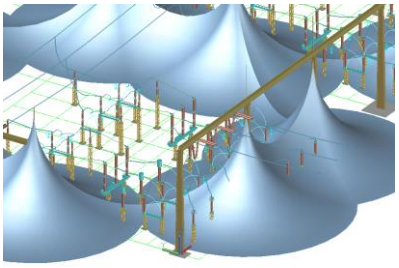
c. 2kA(~15m) lightning protection

Fig. 6 Lightning protection of 220kV switchyard

The correct assessment of the lightning protection system is of immense importance. Steps like the grounding of all metallic objects that are not meant to be energized are critical for the prevention of floating electrodes in the substation that increase the risk for a lightning strike. A floating electrode in high voltage refers to the metallic objects that are not grounded and are exposed to electric fields, e.g., during a thunderstorm, and could generate a partial discharges or flashovers [19]. Assuming that all these metallic objects are grounded, Fig. 7 shows the impact in the analysis of considering versus not considering the grounded metallic objects, such as masts and beams, in the lightning protection verification. Fig. 7a presents the scenario considering the grounded metallic objects and Fig. 7b shows the case when those objects are ignored.



a. Lightning protection with grounded metallic objects



b. Lightning protection without grounded metallic objects

Fig. 7 Comparison of lightning protection verification

The examples generated in Fig. 6 and Fig. 7 provide an example of the efficiency of 3D automated verifications of lightning protection and the need for the precise addressing of conditions of the substation by rolling the sphere on all the elements. An example of special conditions, refers to the scenario of multiple voltage levels in a substation, where the sphere radius would be different for the evaluation of each switchyard, as presented in section 5.a.

Traditional methods presented in section 3.a and 3.b present a higher risk due to the high dependency on the engineer's expertise and the drafter's capabilities. The automated verifications presented in

section 3.c and 4, for the different scenarios, the job is done in short times with lower risk during operation of the assets as the engineering process is less dependent on individuals but on software solutions.

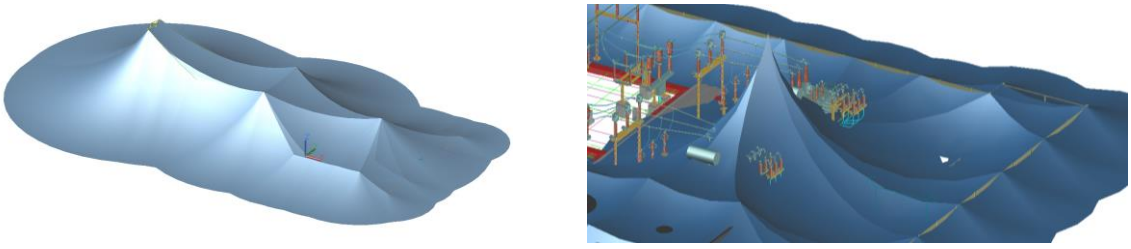
5. REAL-BASED EXAMPLES AND EVALUATIONS FOR BROWNFIELD SUBSTATIONS

The correct verification is as important for greenfield substations, as for operating brownfield facilities. Nowadays, the protection requirements are stricter worldwide, as presented in the next subsections - the lack of verification of conditions in existing substations represent a constant risk for the operational security. To prevent direct impacts on substation's components, it is possible to utilize solutions for efficient evaluation of the actual protection of the different insulation levels - to mitigate the present risks.

a. Unprotected medium voltage transformer bushings and assets, when verifying with low stroke current

Fig. 8 shows a real-based case example that is used to describe the discussion in the previous sections. The substation in Fig. 8 is a HV substation with two line bays and two load power transformers. As can be seen, the transformers are located at the end of the substation with medium voltage bushings to the opposite side of the substation. The voltages levels are 220 kV (HV) and 34.5 kV (MV).

In operation, it has been documented that in such substation layouts, lightning has impacted at the transformer because of the exposed corner and MV components. It has been seen that during the engineering phase, the applied 2D verification process did not detect the unprotected zone and it led to hundreds of thousands of dollars in damages, similar to the case of [11]. Additionally, as previously described, the error of considering only one voltage level, as Fig. 8a shows, will lead to an unprotected zone involving the bushings of the transformers for low current lightning strikes, as Fig. 8b describes.



a. Class IV protection of IEC 62305 b. 2kA (~15m) of IEEE 998

Fig. 8 calculation scenarios for a 110kV substation

In the experience of the authors, another risk factor in this real case is that the exposure of the MV connections at the power transformers increase the probability of failure of the transformers. If a direct lightning strike impacts the MV equipment, conductors or the first structure of the MV, the energy supported by the MV surge arresters will normally not be enough for a direct strike with a relevant current. This is because, in insulation coordination, the current that surge arresters are facing is normally a partial current after the lightning is divided by the earthing cables and structures.

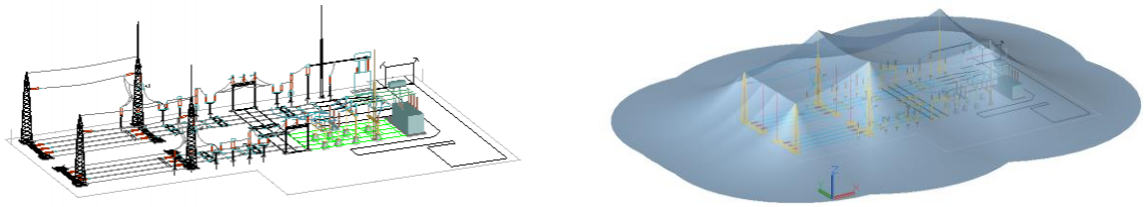
b. Evaluation of external lightning protection for brownfield substations

In electrical networks, there are electrical substations that were constructed decades ago with requirements less strict than the requirements applying nowadays. It is of great relevance to reevaluate the conditions of the existing substations to prevent catastrophes, such as the one presented by A. Shemshadi and H. Haghighi in [11]. In [11], is shown the case in which due to the wrong initial design of the lightning protection, a lightning strike hit a power transformer bushing, as in the example of Fig. 9.



Fig. 9 Lightning strike at a high or medium voltage bushing of a power transformer

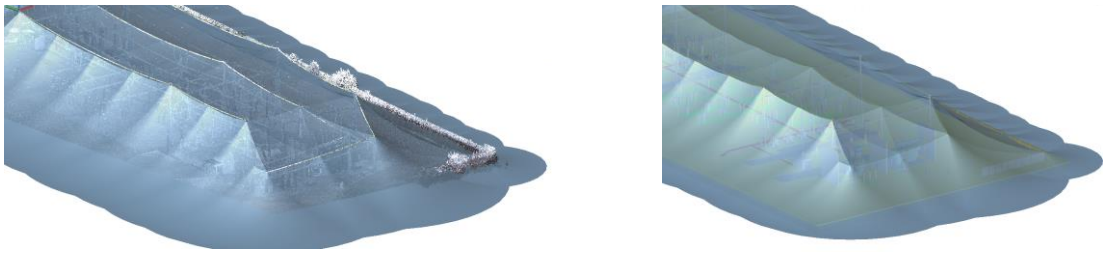
In order to increase the reliability of the power systems, all the substations must comply with the regulatory requirements and must be properly designed and revised. However, to evaluate with manual methods is a difficult and time-consuming task as presented in section 3.a and 3.b. The automated verifications allow to easily evaluate the protection of the constructed facilities against lightning strikes, whereas mentioned in Table 2. the duration of the automatic method is in terms of minutes - for manual methods, it is hours/days. It is possible to evaluate the lightning protection of a facility using hybrid modeling by combining the 2D as-built drawings with e.g., 3D or BIM models new bays of an extension project as explained in [18] and shown in Fig. 10. In Fig. 10a, the hybrid model 2D and 3D is shown, and in Fig. 10b the lightning protection for the hybrid model is presented.



a. Hybrid model b. Lightning protection volume

Fig. 10 External lightning protection verification of hybrid 2D-3D models with automated methods

Another option for evaluating the lightning protection of an operating substation, is to use the digitalized substations that have been transformed from a laser scan to a point cloud and then to a BIM 3D model using the software's Optical Symbol Recognition (OSR) technology with artificial intelligence for implementation of a digital twin of operating assets as presented in [2]. The resources and results of digitalization projects can be utilized for evaluating the lightning protection of the substation facilities. It is possible to evaluate the lightning protection with the point cloud itself (Fig. 11a) and/or with the substation BIM model (Fig. 11b).



a. Lightning protection with point cloud b. Lightning protection with BIM model

Fig. 11 Evaluation of lightning protection of existing 220kV substation
with IEC 62305-1 Class III (45m)

In countries like Brazil, the 220kV substation of the example above would be evaluated against lightning with stroke currents of 2kA. As an example of the evaluation of the substation of Fig. 11 but for a Brazilian scenario, then Fig. 12 is presented. In Fig. 12, it is visible how the arms of the busbar disconnectors are exposed to lateral lightning strikes and the substation lightning protection should be overworked in order to comply with the ONS requirement mentioned in section 2.b.

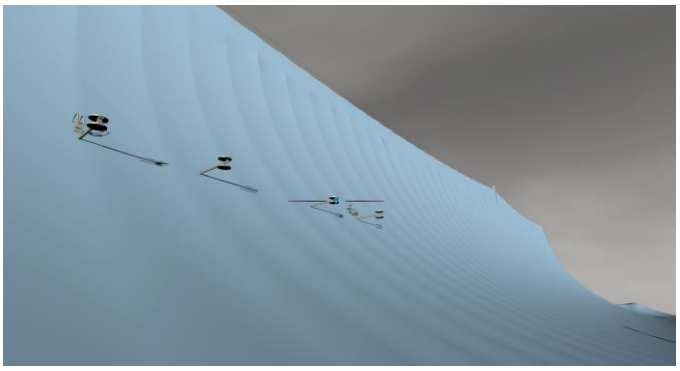


Fig. 12 Evaluation of lightning protection of existing 220kV substation with stroke current of 2kA (~15m) - Exposed busbar disconnectors

For brownfield substations, the recommendation is to use point clouds and digitalized BIM 3D models instead of "as-built" drawings as they are usually not representing the current state of the facilities.

6. CONCLUSIONS

The presented discussion of the stroke current problems in substation lightning protection design - supported by real facts and events of insulation failure during lightning strikes - highlights the need for higher quality and precision in order to increase the operational security of critical assets such as electrical substations - which traditional manual methods cannot reliably ensure. Lightning protection design for electrical substations must be based on standards and assessed by the fundamental concept of insulation failure for each voltage level to prevent property damage and public service loss.

In conclusion, the shift from manual 2D-3D methods to fully automated 3D processes in lightning protection verification presents significant advantages that cannot be overlooked. The newly proposed automated method in this work has demonstrated that it is possible to conduct the rolling sphere method for lightning protection design and verification while accounting for low-current and lateral strikes - areas traditionally neglected in manual assessments. Automated solutions, not only enhance the efficiency and accuracy of risk assessments, but also address the growing demands for robust electrical infrastructure during a shortage of skilled professionals. By integrating advanced simulation tools, these methods allow engineers to quickly identify vulnerabilities, optimize protection systems, and comply with increasingly stringent regulatory standards. This shift also significantly reduces execution time, improving technological availability and ensuring that every voltage level is adequately protected.

As the electrical engineering landscape continues to evolve, adopting automated processes will be essential in safeguarding power grids from lightning strikes, thereby enhancing the reliability and safety of electrical substations worldwide. Moving forward, the precision and adaptability provided by these systems will play a critical role in ensuring uninterrupted service and operational security, particularly as lightning events become more unpredictable, and infrastructure becomes more complex.

BIBLIOGRAPHY

[1] C. Breyer et al., "On the History and Future of 100% Renewable Energy Systems Research," in IEEE Access, vol. 10, pp. 78176-78218, 2022, doi: 10.1109/ACCESS.2022.3193402.

[2] S. Heuser, L. Guevara, W. Eyrich, F. Pizarro and A. Schuetz, "Aplicación de BIM y Gemelo Digital en ingeniería de subestaciones, O&M y beneficios del uso de modelo de realidad virtual

integrado con gestión de activos", XIX Encontró Regional Ibero-Americano do Cigre, Foz do Iguaçu, May. 2023.
[3] International Electrotechnical Commission (IEC). "Protection against lightning series", 2010
[4] A. Tayebi, J. Gómez and C. Delgado, "Analysis on the Lack of Motivation and Dropout in Engineering Students in Spain," in IEEE Access, vol. 9, pp. 66253-66265, 2021, doi: 10.1109/ACCESS.2021.3076751
[5] Becker, F. S. (2010). Why don't young people want to become engineers? Rational reasons for disappointing decisions. European Journal of Engineering Education, 35(4), 349–366. https://doi.org/10.1080/03043797.2010.489941
[6] ABNT NBR 5419. "Proteção de estruturas contra descargas atmosféricas - Protection of structures against lightning - Procedure", 2005
[7] IEEE Standards Association. "IEEE 998- 2012 Guide for Direct Lightning Stroke Shielding of Substations", 2012
[8] Operador Nacional do Sistema Elétrico, "Submódulo 2.6 - Requisitos mínimos para subestações e seus equipamentos", Submódulo 2.6 [guide]-2022, Aug. 2022
[9] S. Chum, M. Mahmudul and O. Chang, "On the Striking Distance for the Design of Lightning Protection System for Substations in Selected Countries", IEEE Asia-Pacific International Conference on Lightning APL 2023, June. 2023
[10] A. Loannidis, and T. Tsovilis, "Evaluation of the Direct-Stroke Shielding Performance of Substations Through Stochastic Modeling of Lightning Attachment", IEEE transactions on electromagnetic compatibility, vol. 66, no. 2, Apr. 2024.
[11] A. Shemshadi, H. Haghighi, "Design of an Effective Hybrid Protective Guard System in High Voltage Substations", The Institution of Engineers (India) 2024, Jun. 2024.
[12] A. Mousa, R. Wehling, "A survey of industry practices regarding shielding of substations against direct lightning strokes", IEEE Transactions on Power Delivery, Vol. 8, No. 1, 1993.
[13] F. Rizk, "Modeling of Substation Shielding Against Direct Lightning Strikes", IEEE transactions on electromagnetic compatibility, vol. 52, no. 3, Aug. 2010.
[14] La Nación, "Daños en la subestación El Bote ascienden a mil millones de pesos"; https://www.lanacion.com.co/danos-en-la-subestacion-el-bote-ascienden-a-mil-millones-de-pesos/, https://www.youtube.com/watch?v=VHrI_BIeubE, 14 September 2022
[15] V. Udaya, R. Katari, S. Kalyani, "Design of Direct Stroke Lightning Protection by Using RAZEVIG Method For 400/220/33kv GIS Substation Which Include Outdoor Equipment's", 2023 IEEE 3rd International conference on SEFET, 2023.
[16] C. Pruthak, K. Rinkesh, P Mukesh and A. Parmar, "Various Cases and Studies of Direct Stroke Lightning Protection on Different Substation", International Journal of Engineering Research & Technology (IJERT), Apr. 2016.
[17] S. Heuser, W. Eyrich and M. Kokorus, "Optimization of effort and cost structures in substation design using a 3d substation engineering software with integrated design calculations", XVII Eriac Encuentro Regional Iberoamericano de Cigré, Rio de Janeiro May. 2017.
[18] S. Heuser, W. Eyrich and M. Kokorus, "Smart substation information model - challenges in the development of a Building Information Modeling (BIM) based software for substation design", International colloquium building smarter substations Cigré, Mexico, May. 2017.
[19] F.Roman, V. Cooray and V. Scuka, "Corona from floating electrodes", Institute of High Voltage Research, Uppsala University. Hushvborg, S-752 28 Uppsala, Sweden, Jan. 1996.