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Applicability of the risk assessment in international standards to HVDC converter stations

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***Abstract*—The risk assessment is a methodology to assist during the design of lightning protection systems. However, the available standards do not have clear guidelines for its application to HVDC converter stations. This results in unfeasible expectations and misunderstandings between designers, utilities and insurance companies, among others. This paper highlights some of the practices of the industry and discusses their relationship with actual international standards. The publication is expected to highlight the areas of improvement in future editions of the standards to include HVDC converter stations.**

Keywords: Lightning; Risk; Power Systems; HVDC;

I. Introduction

The design of the lightning protection systems for substations and transmission lines is based on measurements and statistics of data collected historically of lightning discharge characteristics [1]-[2]. Based on such statistics empirical models were proposed to describe the striking point of the discharges [3]-[7]. Based on the different proposals available in the literature, some of them have been accepted and recommended in international standards such IEEE [8] and IEC [9].

HVDC converter stations consist of outdoor and indoor environments. Outdoor environments are commonly referred as yards, e.g. AC yard or DC yard. Indoor environments are divided in high voltage and low voltage systems. The high voltage system contains high voltage equipment for power transmission and commonly known as hall e.g. valve hall or DC hall. The low voltage systems contain medium and low voltage systems used to control the converter station operation and are commonly known as building, e.g. control and auxiliary system building. Consequently, the lightning protection of HVDC converter stations requires a coordination between outdoor and indoor environments to warranty faultless protection of living beings and equipment against direct lightning strikes.

To be able to perform a lightning protection of HVDC converter stations, it is required to combine protection principles available some of them summarized on international standards, such as IEEE 998 [8] for outdoor yards and IEC 62305 [9] for indoor halls and buildings.

However, a clear guideline regarding the risk assessment to design lightning protection stations for electrical substations with indoor and outdoor environment is not available in the literature, and it has not been addressed in the international standards such as IEEE or IEC.

Therefore, with the great increase of the use of HVDC interconnections worldwide, it raises the necessity to clarify the applicability of different standards for the protection against direct lightning strike.

II. Lightning Protection Design Practice for HVDC Converter Stations

An HVDC converter station comprises two different environments, outdoor and indoor. The equipment on the AC and DC sides of the station are located outdoors. The location where converter valves are located is indoors and known as valve hall. The low voltage systems are located in the control and auxiliary system building.

Figure 1. Aerial view of HVDC converter station.

A. *Converter station outdoor switchyards*

The lightning protection system of a converter station outdoor yards against direct lightning strikes have been done with methods described in IEEE 998 [8]. The lightning protection system can be achieved with overhead shield wires or with the use of masts.

The placement of shield wires and masts is often implemented by using the well-known rolling sphere method, a useful engineering and proven method to determine the reliability of a lightning protection system.

As general practice for outdoor yards, the areas close to indoor high voltage halls, e.g. bus-works leading directly in to valve halls, have been built in accordance with effective shielding [8]. For other areas, it has been permissible to have non-effective shielding as long as the shielding failure rate of the converter station is less than that of the overhead transmission lines [10].

Surge arresters are used to protect the high voltage equipment in HVDC converter stations. Thus, the selection of the allowable lightning return current (I_s) is to be coordinated with insulation coordination studies. In this manner, the lightning protection system is designed to capture all strikes with currents above the withstand capability of the equipment. For events of direct strike to equipment, the lighting current do not exceeded the withstand capability of the equipment.

B. Converter station buildings

The lightning protection of indoor converter station halls and buildings against direct strikes have been done by the available methods given in IEC 62305 [9]. In general, the selected method is related to the national civil regulations and practice of the location where the HVDC converter station is erected. The angle, mesh and rolling sphere methods are used.

As general practice, indoor high voltage halls are provided with a lightning protection systems to avoid damage to the building structure rather than the personnel and high voltage equipment. The reasons are that:

- The personnel occupation level, defined as the ratio between workers present in the high voltage hall and workers present in the converter station during operation is negligible. Moreover, the high voltage halls are often interlocked during operation and thus not accessible.
- High voltage equipment in the halls is designed to withstand higher voltage stresses during the converter station operation than the ones caused by indirect lightning strikes.

Indoor low voltage buildings, i.e. control and auxiliary system buildings, are provided with a protection system to avoid damage to the workers present in the converter station, the building structure and the control and auxiliary system equipment.

The selection of lightning return current (I_s) for buildings can be addressed through the risk assessment described in IEC 62305-2. However, as general practice a lightning protection level (LPL) III, corresponding to $I_s = 10$ kA, for HVDC converter buildings has been a reliable design level verified through operational experience.

III. RISK ASSESSMENT FOR LIGHTNING PROTECTION

The risk assessment for lightning protection design is a powerful tool. A risk assessment is done and compared with a tolerable risk level that can be accepted. The international standards propose different methods to evaluate the risk and its tolerable level.

A. Risk assessment based on IEEE 998

The risk assessment in this standard is based on the concept of collection area and the probability of appearance of lightning strikes with a determined current level. Figure 1 shows the CIGRÉ approximated log-normal distribution from measured natural lightning strikes with a mean of μ=31.1 kA and standard deviation of σ=0.484.

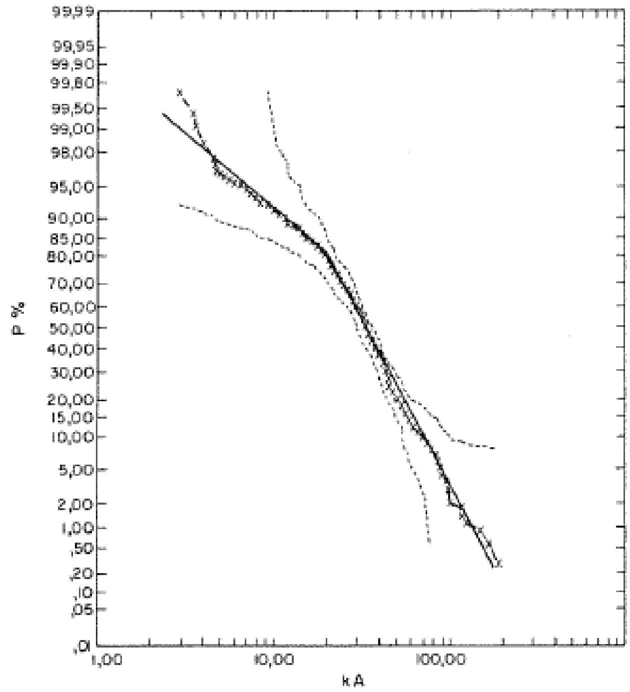

Figure 1. CIGRÉ log-normal distribution and simplified approximation on measured negative lightning peak currents [7].

A simplified approach to the log-normal distribution is often used in the main international standards to represent the probability distributions of negative strikes. Equation (1) is the cumulated probability distribution function for lightning currents equal or greater than I_s.

$$P(I_S) = \frac{1}{1+\left(\frac{I_S}{31}\right)^{2.6}} \quad (1)$$

where I_s is the lightning return current in kA and $P(I_s)$ is the cumulated probability.

The total collection area (2) is obtained through the number of strikes per unit area expected in the vicinity of the station and the surface area of the station.

$$N_S = 0.12\, T_d\, A \quad (2)$$

where N_s is the number of strikes to the station area in flashes/year, T_d is the number of thunderstorm days per year and A is the station area in km^2.

The final evaluation leads to a quantified risk, expressed as the number of years between direct lightning strikes with currents equal or less than I_s. This permits the designer to evaluate the need of a lightning protection system and to quantify the degree of protection and acceptance of the associated risk of failure of the lightning protection system.

It is important to not mistake the concept of lightning protection failure, commonly referred as lightning shielding failure [8], with an outage/failure of the protected system or structure. The lightning shielding failure is defined as a lightning strike that do not terminate in the lightning protection system. This may or may not lead to an outage/failure of the system or structure protected depending on other design parameters, e.g. equipment withstand capability.

Regarding the tolerable risk level, this standard does not give a tolerable risk level for design. The tolerable risk shall be decided by the utility, the manufacturer or agreement between parties. However, values around 10^{-2} flash/year or 100 years between strikes are provided in the standard.

B. Risk assessment based on IEC 62305

The definition of lightning risk in the IEC 62305-2 is shown as the value of probable annual loss (humans or goods) due to lightning, relative to the total value (human or goods) of the structure to be protected. In order to do that the standard evaluates the effect of lightning as a hazard, including possible hypothetical situations that might result from a lightning strike to a structure.

According to the standard, the hazard to a structure can result in damage to injury to live beings in or close to the structure, to the structure itself and to its contents and cause failure of associated electrical and electronic systems. Four types of risks are considered in the IEC 62305-2:

- R1: risk of loss of a human life,
- R2: risk of loss of service to the public,
- R3: risk of loss of cultural heritage,
- R4: risk of loss of economic value.

According to IEC 62305-2, to evaluate the risk of lightning striking to the structure, the structure is usually divided into zones. The division is made considering the vulnerability to lightning of the different areas of the structure.

The total risk is evaluated by the sum of partial risks. The partial risks are related to the source and the type of damage that can hypothetically occur. Thus, the partial risks evaluated are for strikees to the structure, strikees near the structure, strikees to a line entering the structure, strikees near a line entering the structure and strikees to another structure to which a line is connected. Each partial risk is obtained through the product of the assessment of the number of dangerous events N_x, the assessment of the probability of damage P_x and the assessment of the amount of loss L_x.

After the evaluation, a final quantitative value for each risk is compared with the tolerable risk level. The recommended tolerable risk values given in the standard are,

- RT1=10-5 1/year for loss of a human life,
- RT2=10-3 1/year for loss of service to the public,
- RT3=10-4 1/year for loss of cultural heritage,
- RT4=10-3 1/year loss of economic value.

The evaluation of the need of a lightning protection system is done by comparison between R and R_T. If $R \leq R_T$, lightning protection system is not necessary. Otherwise, measures shall be adopted to reduce the all partial risks until all risks are below the tolerable level.

IV. Discussion

A. Lightning Engineering Parameters and Risk Evaluation

The lightning current parameters used as a base for lightning shielding design are based on the measurements published in different CIGRÉ reports [1] and [7]. Such reports were based on lightning measurements performed in the past, under the limitations of measurement equipment. Nowadays, several countries perform lightning measurements to be able to fulfill the knowledge gap on the area [11]-[14]. However, statistical data is not yet enough to improve the lightning peak current statistics reported in CIGRÉ. For this reason, continuous efforts are taken in to measure natural lightning current amplitudes at different latitudes, topographies, among others.

Therefore, it is worth noting two aspects of interest to design engineers from this data:

- First, the recognized minimum lightning strike current in IEEE and IEC standards. The limit of lightning of 3 kA of measured atmospheric lightning strikees of the lightning peak current.
- Second, the wide spread on the cumulative probability calculated from measured data from atmospheric lightning strike. It can be seen that a large standard deviation exists in the range between 3 kA-20 kA, which is used for lightning protection system design.

Accordingly, as pointed in the standards, a full (100% reliable) lightning protection system cannot be achieved in practice. For this reason, lightning protection engineers are entitled to assume such facts during the definition, the design and the assessment of lightning protection systems.

B. Risk assessments on international standards

It is understood by the authors that the standards, during its publication, were not intended to cover some of the aspects addressed in this discussion section. However, it is considered relevant to the authors to highlight the aspects of concern and improvement in future editions.

On one hand, the risk assessment method proposed in the IEEE 998 standard has its strong point to address design methodologies and engineering practices concerning the power transmission and distribution industry. The calculation of collection area and associated cumulative probabilities can be easily compared to operational experience of overhead transmission lines. However, its applicability to outdoor yards leave the indoor areas of HVDC converter stations out of the standard.

On the other hand, the risk assessment method proposed in IEC 62305-2 has its strong point to include all type of structures and possible risks. However, its strong point is at same time its weakness. The following items are an example of the challenge of generalization of the standard:

- The standard focuses on low voltage buildings. Although the standard claim to be applicable to any structure, it can be seen by the tables given in the standard, that it is mainly applicable to residential and urban buildings as hospitals or museums. This fact results that the standard cannot be directly applied to power systems and stations where withstand levels are higher than hundreds of kV.
- The risk loss of cultural heritage (R3). The loss of cultural heritage has no grounds for its evaluation for HVDC converter stations. There are no goods considered as cultural heritage in converter stations. Even the case of risk of loss of cultural heritage, as a consequence of loss of service is unreasonable because it is not possible to evaluate all points that are interconnected to the power line. The responsibility to supply energy to final consumer will be of the distribution and transmission system owners, as well as, to ensure redundancy at the particular power system to avoid loss of power. Moreover, uninterruptible power supply (UPS) units are installed for critical buildings to avoid power loss.
- The risk of loss of economic value (R4). It can be stated that although such evaluation is possible for a cost/benefit comparison, it is often unnecessary. For HVDC converter stations due to the cost of high voltage equipment will not compensate to eliminate the lightning protection system. Even in that case, insurance policies force the final operator to install a lightning protection system to reduce the risk of damage. In some cases the highest degree of protection of the lightning protection system has been enforced due to insurance policies regulations rather than operational experience.
- The risk assessment is based on hypothetical cases. Although, the methodology of this standard results in a powerful tool for the assessment, operational experience is necessary for an evaluation based on facts. There is no available figure or relation between direct lightning strikes and cause of failure or damages to the structures. This fact is probably the most questionable, as it leads to uncertain reliability of the final design independently of what is the final obtained result.

In general, the fact that the IEC risk assessment requires many tables to include all the possible scenarios and structures to the detriment of the easiness of use and the application to specific industries, e.g. power systems, makes the its use administrative rather than an engineering task.

V. Conclusion and Proposal

The paper presents the problem of applicability of IEC and IEEE standards to perform a risk assessment to HVDC converters stations. The first has a lack of applicability to power system stations and focus on common low voltage buildings. The second does not consider the applicability of indoor power stations.

Therefore, to improve and generate a common understanding of the lightning protection system of HVDC stations, it would be advisable to create a working group dedicated to study the applicability of the standards and use the actual operational experience. The tolerable risk values to design lightning protection systems for HVDC converter stations based on the operational experience, should include outage rates due to lightning strikes at the station area so they can be effectively compared to other sources of outages for an effective design.

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