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# Standardized risk and the use of lightning hazard forecasting

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***Abstract*— The international standard on lightning protection offers a framework to describe the risk of lightning damage for a given object to be protected and offers design tools to achieve proper protection with primary or secondary protection. Although it may be useful to improve the usability of this framework by simplifying some points, there is no doubt that the notion of risk and its application is currently covered extensively in the document. However recently more and more papers discuss the use of lightning hazard forecasting in lightning protection. The notion of risk in the international standard is not yet proper to discuss the application of such solutions nor would it be safe to directly use the standard to evaluate a solution like that. This paper aims to discuss the new problem that using forecasting means as opposed to primary or secondary lightning protection. Also it suggests the use of an adaptation of the notion of risk to be able to incorporate the using of forecasting.**

***Keywords-risk evaluation, lightning hazard forecasting, international standard***

## I. INTRODUCTION

Since the international standard on lightning protection defined risk [1] there have been numerous discussions on numerous accounts on its applications and applicability. The cost oriented definition of risk aims to place lightning protection into the domain of management and to translate the problem of lightning damage onto understandable notions for the decision makers.

A key question of risk is how human life is treated and due to the nature of risk, human lives are monetized as well (of course not neglecting non-monetized human values). The international standard contains strict rules to consider human lives and the tolerable risk levels clearly reflect this. The primary purpose of lighting protection is to protect human lives.

However there are certain scenarios in which protection simply cannot be achieved with the current equipment – Franklin rods, down conductors and earthing cannot be installed at each location where humans are endangered by lightning. Such scenarios include open air masses, transfer of highly flammable or explosive liquids or gases or people doing maintenance work on tall buildings.

The common feature of these scenarios is that people are only temporarily exposed to lightning: open air masses do not take place all through the year, hazardous material are not necessarily transferred constantly and maintenance work is done only occasionally. Hence besides not necessarily being feasible to install a complete lightning protection system, it is almost sure that it would be too costly.

In order to handle such cases suggestions were made to use lightning hazard forecasting as a warning to avoid the development of lightning hazard. There were multiple experiments presented on devices capable of producing an advanced warning decades ago [2], [3]. More general approaches appeared recently due to the evolution of instrumentation. Some solutions involved providing simple advance warnings of a fixed time (5-10 minutes) [4], [5] and more complex solutions placed emphasis on designing a warning system considering the action taken to avoid danger – the latter being known as preventive lightning protection [6], [7]. As it is based more on theoretical foundations, we'll refer to preventive lightning protection later as the framework of our analysis.

Since these cases are different by nature than protecting a static object, it is required to investigate if the notion of risk – as defined in the international standard – is an appropriate measure or it is required to refine or to extend it.

The main focus of this paper is to do this analysis and finally to suggest an extension to the risk in order to handle these cases. The second section will provide the detailed analysis on the notion of risk, it enumerates various issues raised so far regarding the risk (focusing on fundamental questions rather than individual cases). In the third section a model describing the background process of using lightning hazard forecasting is described emphasizing impacts on risk. It also briefly describes a proposal to extend risk to handle the non- static protection and illustrates with a practical example of open air events. The final conclusions are given in section four.

## II. RISK AND LIGHTNING HAZARD FORECASTING

The first item to clarify related to the risk and the standard is what should be meant as *object to be protected* for the protection and the calculation. In the standard the object to be protected is defined as the ‘structure or service to be protected against the effects of lighting’. Whereas this definition is practical, it has some very important properties and limitations: the object to be protected is a static object. Both its size and its exposure can be taken as constant.

When lightning hazard forecasting is used, there size of the object to be protected may change – one can think of open air masses here, the area that people will occupy during the event may not always be predicted, hence the exposure may also change. So whereas primary protection will be used to protect a given static building or area, the object to be protected may be more dynamic when hazard forecasting is to be used.

It is also vital to clearly separate *hazardous events* as referred to in the standard and *lightning hazard*. While the former is associated to an annual number, the latter is an alarming condition. They are explained later in details.

As a consequence of this it is required to investigate risk further. The international standard on lightning protection gives a clear definition on risk, defining it as the expected relative annual loss related to lightning damage. This basic notion itself is a handy approach and is acceptable regardless of the type of protection. The following expression summarizes the notion:

$$R=N*P*L \qquad (1)$$

In (1) $N$ denotes the expected number of hazardous events (practically the lightning strikes); $P$ denotes the probability of damage (between 0-1) and $L$ denotes the loss in a given currency.

Due to the simplicity of these terms it is tempting to accept the calculation in its current form. Yet due to the dynamism in using forecasting in lightning protection it is required to analyze each component separately.

### A. The number of hazardous events

Here $N$ denoting the number of hazardous events, the lightning strikes that may cause damage to the object to be protected. Attempts have been made to re-scale risk solely by weighting the occurrence of hazardous events for the assumed exposure [8]. Still, most cases do not offer this luxury.

A simple example is an open air mass which is held annually and it has a short duration – these cases are typical scenarios where the application of forecasting is the only cost-effective solution. When considering a simple down-scaling of the number of lightning strikes (in whatever approach), this would result in an almost-zero number of hazardous events which would yield a negligible risk (irrespectively of other parameters). There were already examples when such events resulted in lightning accidents.

Taking an open air mass event held annually, a possible solution to avoid the problems caused by simple rescaling would be to use a weighted average lightning density by taking the monthly lightning density weighted by a normal distribution. This always yields a non-zero value even in months when normally no storm is usually observed (e.g. in winter months lightning activity is typically low, however in the current climate conditions where extreme weather may occur even in winter months approximating lightning density with zero would be misleading).

$$N_{g\sim} = \sum_{i=1..12} N_g[i] * p_w[i] \qquad (2)$$

In this expression $N_g$ refers to the strike density (strike/km2) measured monthly and $p_w$ refers to the probabilistic weighting function (in this case a discrete function is assumed as both – using a continuous function may not make sense). The weighting function spans the 12 months in the year and sums up to 1. The following figure shows an example with theoretical data.

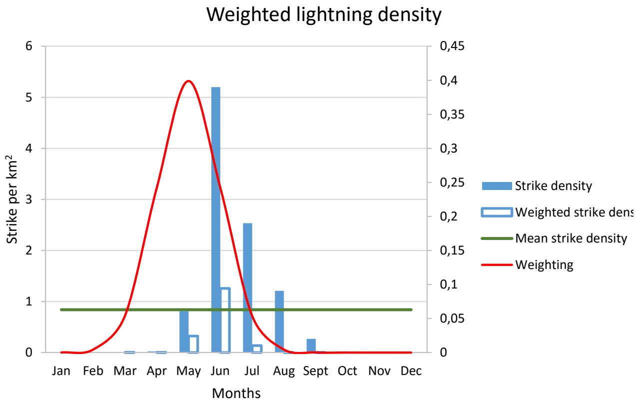

Figure 1. Probabilistic weighting of the lightning strike density

The figure assumes that the event which is to be protected happens only once per year in May, hence the weighting is centred on this month. The resulting strike density could be calculated simply by calculating (2). The solid blue bars show the monthly lightning distribution and the green line is the annual lightning density value as a reference. The empty blue bars show the monthly strike density multiplied by the corresponding value of the weighting function. The latter is drawn in red and is depicted here as a continuous function for simplicity. In practice a discrete distribution would be adequate.

The weighted average lightning density is basically obtained by summing the empty blue bars.

Obviously it would result in higher values than only expected for May thereby including the possibility of higher lightning activity. Also it would yield in an expected strike density higher than the annual mean thereby accounting for that the event takes place at a time when lightning hazard is higher.

### B. *The probability of damage*

The probability of damage is described by $P$ in (1), which basically denotes the probability that the object to be protected will suffer damage. This applies to any case (in general). It is used in the same way for deciding the necessity of protection and when estimating protection efficiency. The standard contains various calculation methods for primary and secondary protection. Yet the use of hazard forecasting are different in nature, hence the methods defined in the standard are not proper.

Putting it another way the probability of damage in case of primary or secondary protection is the probability that despite the protective measures the lightning still may cause damage. This could mean a lightning strike that was not considered during the sizing of protection; despite the placement of the lightning rod the lightning stroke the object to be protected or that the secondary protection did not manage to protect a sensitive device from overvoltage.

When using preventive actions of whatever nature for protection this probability denotes – similarly to primary or secondary protection – that despite the execution of the action damage is caused. Practically it means that people sent to a place protected against lightning still suffer injuries; flammable materials ignite despite being transported to a protected location, etc.

However in case of using forecasting there is another layer of uncertainty, besides the possible failure of the preventive actions, the preventive actions may not be executed timely also resulting in increased risk. This is discussed in further details in the third section.

### C. *Loss due to lightning strike*

The final term is $L$ denoting the loss associated to lightning damage. For a wide range of elements this may be easily calculated and as mentioned before the items which cannot be monetized directly – like human life and the cultural heritage – are also have cost approximation methods designed in the standard.

The standard defines the expressions for loss calculations to include human lives.

$$L_X = \left(n_p / n_t\right) * \left(t_0 / 8760\right) \tag{3}$$

This expression (see pp. 117 expression C.1 in [1]) contains the ratio of people endangered compared to all people in a structure and the ratio of the time exposed (in minutes). The first issue about this expression is that the exact number of people is not explicitly included. However having one person exposed to lightning hazard versus a hundred should make a difference in the calculations. The second problem is that the time of exposure is also present as a statically estimated term.

This raises another issue regarding the use of forecasting, that is related to the object to be protected. The dynamic behavior of the object to be protected does not only relate to the exposure, but also to the contents, hence the associated costs.

The best example again is an open air mass, which may have various volumes of attendees starting from a few dozen people to several thousands and may change over time. Obviously the potential losses estimated by the standard are to be different for each case. Currently the standard only handles if there is human life at stake or there isn't and it takes a static estimate of the loss, but cannot consider any changes over time.

Moreover it is important to note that the loss will necessarily change during the execution of the preventive action. So besides that estimating the loss is problematic, it cannot even be considered with a single value. It is possible to use the same down-scaling approach as mentioned in case of the number of hazardous effects – it is already present at some point through term 2 in (3). However that would yield the same problems, namely that it could yield negligible loss especially when the exact number of people endangered is not explicitly considered in the calculations.

In the next section the underlying processes will be described where – among others – this is also mentioned.

## III. THE UNDERLYING PROCESS WHEN USING LIGHTNING HAZARD FORECASTING

### A. *Forecasting as an additional layer of uncertainty*

The technology of lightning hazard forecasting has developed significantly in the last decade. The improved lightning detection sensors made it possible to identify and accurately track a thunderstorm cell through its lifecycle. Hence not only the cloud-to-ground lightning activity is available, but the intra-cloud and cloud-to-cloud lightning can be used to draw up the total extent of a thunderstorm cell, approximate its trajectory more accurately than before (when using CG lightning only).

The purpose of obtaining all these properties of the thunderstorm cloud is to be able to estimate if the thunderstorm cell would endanger the object to be protected. *Lightning hazard* develops, when an active thunderstorm cell gets near to the object to be protected as in this case a CG lightning may cause damage. In the framework of preventive lightning protection the zone within this distance is denoted as the *Danger Zone.*

It is vital to note that an 'active' thunderstorm cell denotes a cell that exhibits **any** lightning activity, not necessarily CG lightning – the rationale behind this definition is that thunderstorm cells do *not* necessarily produce a CG lightning as a first lightning strike during its lifecycle [9]. Hence the CC/IC activity may suggest following CG strikes as well.

Despite that the thunderstorm cell's lifecycle can be monitored properly, it is a very complicated (and computation-heavy) task to determine the size and properly estimate the exact trajectory of a cell. It has long been observed that wind is by far not a perfect predictor of thunderstorm movement [10], hence there is always a certain degree of uncertainty about estimating if a moving thunderstorm cell will endanger the object to be protected.

This can be described by the event space of preventive lightning protection [11], [12]:

TABLE I. THE EVENT SPACE OF PREVENTIVE LIGHTNING PROTECTION

| **Hazard develops** | **Alarm given** | |
|---|---|---|
| | Given in time | Not given in time |
| Develops | *Accurate alarm* | *Late alarm* |
| Does not develop | *Unnecessary alarm* | *No alarm* |

Each case has its corresponding probability, resulting in 1. Note that this event space is specific to every case when an estimate is given on if a thunderstorm cell produces lightning hazard. In practice however this event space is interesting to decide if an alarm is to be given to execute a preventive action or not.

The event space describes the additional layer of uncertainty compared to primary or secondary lightning protection. Whereas these two protection methods are always present in case of lightning hazard, the preventive action is executed only in case when the forecasting system signals that there is a higher probability that lightning hazard will develop.

### B. Estimating risk – two approaches

Two approaches have been proposed earlier to deal with this uncertainty [13]. A discrete approach is that the timing of the alarm is not considered (this completely corresponds to the event space in table 1). In this case the alarm was not given in time is denoted with a simple probability. To approximate risk in this case it is only required to weight the risk when the object to be protected remains unprotected and when the preventive action has already been executed and can be considered as protected.

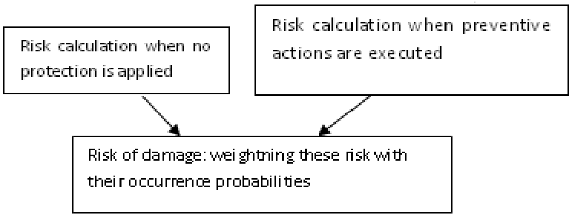

Figure 2. A simple dichotomous weighting of the risk associated to successful/unsuccessful preventive action execution

In reality however, the timing of the preventive action indeed matters. Taking the example of the open air mass event with 1000 participants consider the cases when the alarm for the execution of the preventive action only comes 2 minutes and 20 minutes late. Assume that in the first case 950 people can be brought to safety, but in the latter case only 100 people will be safe. The simplified approach would take both cases equal, resulting in a misleadingly high risk value in this case. This property can be demonstrated with the so-called equivalent risk function [13].

$$R_{eq}(\tau) = N * P(\tau) * L(\tau) \qquad (4)$$

The notion of equivalent risk was proposed to model the issue of timing with a continuous risk function derived from the risk calculation in the standard. The equivalent risk function is specific to each preventive action and describes how the risk would decrease with the progress of action execution. For example in case of an open air mass event this function signifies how the exposure changes as time progresses from the action execution.

Practically speaking it shows that the cost ($L$ in (1)) and the probability of damage ($P$ in (1)) decreases as less and less people can become exposed to lightning hazard. Here $N$ is assumed to be an exogenous property of the area where the object to be protected is located – as it is also defined in the standard. Knowing the process of the preventive action and the changes that occur in $P$ and $L$ during the execution (4) can be calculated both numerically and analytically using the risk calculation methods defined in the standard.

Taking the example of an open air event it is a realistic scenario that people are removed from the event site in case of lightning (or any other) hazard. As described in the previous section expression (3) would also change with time as less and less people are exposed to hazard. Hence for this case as well, the equivalent risk function will decrease after beginning the evacuation of people from the event site.

It is possible to derive an 'average risk' as an estimate for the annual risk of the solution. The average should be calculated by taking an execution time distribution function which shows the probability distribution of the time available between the alarm given by the forecasting system and the actual development of lightning hazard. This may be obtained by using historical lightning data and simulation methods. The continuous weighting results in a single risk value that may be used as an annual risk estimate.

$$R = \int_{0}^{\infty} R_{eq}(\tau) p_{ex}(\tau) d\tau \qquad (5)$$

In this function $R_{eq}$ refers to the equivalent risk function (shown in Fig. 3). In a practical approach this weighting can be calculated using numeric methods and historic data and the equivalent risk function.

By showing the product of the equivalent risk function and the execution time distribution, the characteristics of the solution is clearly seen. In this example the average time available is more than sufficient to execute the preventive action, but those late alarms (especially up to 10 minutes) are mostly contributing to risk – so by further fine tuning of the forecasting system the resulting risk can be significantly decreased (at the expense of more costly actions).

### C. Open air mass event – a practical example

The approaches outlined in this paper can be demonstrated with a common practical example: an open air event which is held only for a given period of time and involves a variable number of participants. In case of such an event the only way to protect the participants is using preventive lightning protection with real time cell observation and evacuating participants to sheltered areas as a preventive action.

Here this example will not be discussed in numerical details, but focus is on the use of notions described in this paper.

For such an event the usual risk calculations would yield very low risk value (depending on the strike density in that time interval) and also by treating the probability of damage and loss as static properties it would miss the actual method of protection - a temporary action.

The preventive action could be described by the following equivalent risk function shape (described by (4)):

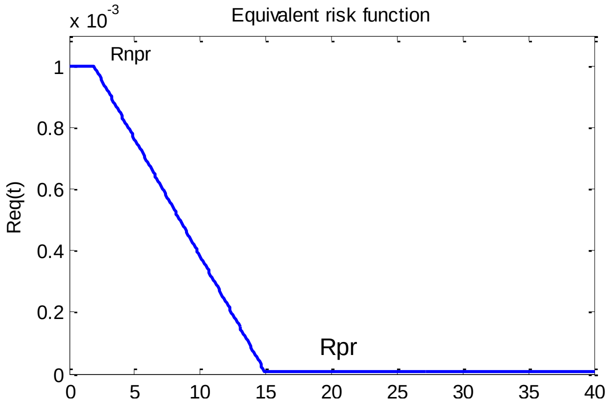

Figure 3. Example of an equivalent risk function

This function practically shows that participants can be evacuated to available shelters in roughly 15 minutes, with the first few minutes being spent on preparations. This figure captures that during the execution of the action there are less and less people exposed to hazard (assuming similar probabilities of damage) over time as described by (4).

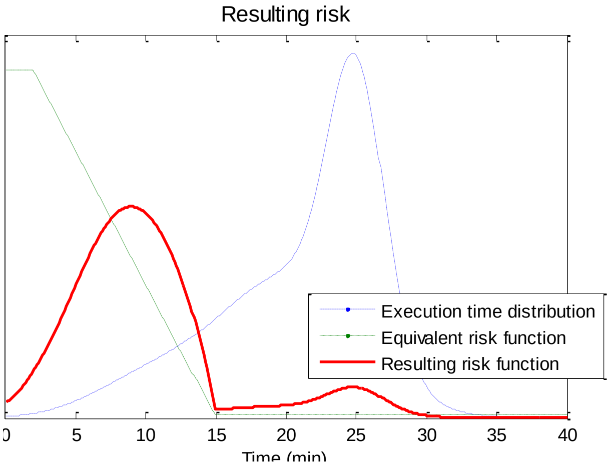

Figure 4. Example of an equivalent risk function

The number of dangerous events is taken as a constant value, obtained by using (2), the probability of damage is also taken as a constant – please note that when calculating (4), it does not include yet the inaccuracy of forecasting.

The uncertainty introduced by the forecasting of lightning hazard is taken into account when calculating (5), considering the equivalent risk function (or risk profile) of the preventive action and the distribution of execution time (time left to execute the action before hazard development).

Figure 4 demonstrates the calculation of (5) for this case with the equivalent risk function shown in Figure 3 and a theoretical execution time distribution – it is an optimistic figure for an alarm timed 25 minutes in advance of the hazard to make sure that late alarms do not come frequently. The resulting risk in Figure 5 only shows the multiplication of these two without the integral – again, the execution time distribution basically serves as a probabilistic weighting function.

## IV. CONCLUSIONS

The current trend regarding the international standard drives the development of the underlying theories and ideas in the direction of simplifications. There are plenty of areas in which the standard contains thorough, yet complicated calculations and descriptions of various properties of the protection and of the object to be protected. A substantial know-how is required alongside the knowledge of the standard to properly design a lightning protection solution. Therefore currently only the experts with scientific background are capable of designing a fully compliant solution. Yet in practice most of the lightning protection systems are designed by specialists, not having the level of qualifications that permit a deep understanding of the standards' concepts. Therefore the simplification of the procedures outlined in the standard is nowadays a mainstream topic of the scientific community.

In terms of the usage of forecasting, it is very important to be cautious. The approach of this paper demonstrates that using forecasting and preventive actions as the tool of protection in the framework of preventive lightning protection (or even using just alarms with fixed timing) is much more complicated than primary or secondary protection and may not be treated using only the standard itself.

In this paper it was briefly shown that the basic concepts on which risk is based on – the object to be protected, the average number of lightning strikes, the probability of damage and the loss – become much more complicated in this case. Here in section III some approaches were introduced regarding estimating the annual risk. However these approaches may be simple, it is required to bring this issue further to the scientific community to gain more understanding of the underlying process and to properly interpret it in the context of the standard.

We can conclude that even though there is a well exposed need for simplifying the standard, using forecasting should not be taken lightly. The standard still has to be improved to adapt this new concept and the complicated planning process [7] means that for this solution even more expertise is required than in the case of primary and secondary protection.

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