Experimental analysis of preventive lightning protection methods

Attila Gulyás
Department of Power Engineering
Budapest University of Technology and Economics
Budapest, Hungary
Gulyas.attila@vet.bme.hu

István Kiss
Department of Power Engineering
Budapest University of Technology and Economics
Budapest, Hungary
Kiss.istvan@vet.bme.hu

Dieter Poelman
Radar and Lightning Detection
Royal Meteorological Institute of Belgium
Brussels, Belgium
Dieter.poelman@meteo.be

István Berta
Department of Power Engineering
Budapest University of Technology and Economics
Budapest, Hungary
Berta.istvan@vet.bme.hu

***Abstract*— In recent decades lightning detection technologies and computation methods have been developing in an unprecedented pace. Present-day observations from lightning location systems (LLS) allow real-time lightning hazard forecasting and provide as such the building blocks for novel and preventive approaches to lightning protection. Preventive lightning protection, a lightning protection method based on lightning hazard forecasting in combination with preventive actions, has been introduced in the literature. This paper approaches preventive lightning protection from a practical aspect by analyzing the efficiency of two forecasting methods: zonal preventive lightning protection and high reliability lightning protection. The analysis is carried out on archived lightning location data and a detailed comparison is given on the efficiency of these methods and their applicability with respect to the international standard.**

Keywords-lightning protection; preventive lightning protection; risk management; preventive action;

I. INTRODUCTION

Conventional lightning protection methods deal with the protection of the object to be protected from the hazardous effects (physical, thermal, electrical) of the lightning strike [1]. However, it is also possible to provide protection by decreasing the exposure of the object to be protected to lightning hazard acting at the right time before hazard develops [2]. Lightning hazard means that an active thunderstorm cell (producing cloud-to-cloud (CC) and/or cloud-to-ground (CG) lightning) approaches the object to be protected. With properly chosen preventive actions it is possible to decrease the risk of damage to adequate levels so that no other lightning protection methods are required. However, in order to do so, it is vital to forecast the formation of the lightning hazard adequately.

The development of the available lightning detection technologies since the late 90's allows real time observation of lightning activity and thus a more accurate forecasting of lightning hazard [3]. This enables protection of objects where conventional protection methods are unfeasible – or further improving the efficiency of conventional lightning protection systems. The combined use of lightning hazard forecasting and preventive actions as a means of lightning protection has been introduced as preventive lightning protection [2].

The preventive actions are executed upon the receipt of an alarm signal from the lightning hazard forecasting system. It is calibrated so that it allows sufficient time to execute the preventive action considering its specific execution time (shown in Fig. 1). Combined use of forecasting and actions means that both the alarming strategy (the forecasting method) and the execution of the preventive action have to be planned together, considering the possibilities and limitations of each component [4].

Besides planning these in accordance to each other it is also vital that this solution conforms to the international standard on lightning protection [5]. Since this method involves using non-standard (non-'static') methods as means for protection the calculations of risk are also a special task.

This paper presents a practical analysis of a preventive lightning protection solution carried out using historic data. This is an important step during the planning of the solution [4], as it gives an initial estimate on the efficiency of the final solution. The steps of the analysis are to 'test' certain forecasting methods using historical data, consider the possible preventive actions to be used (here this will be approached from the side of the risk profiles of these actions), check the corresponding risk values against the international standard and finally to decide on the actual parameters of the solution. The aim of this paper is to go through these steps of analysis and to compare the efficiency of certain forecasting methods.

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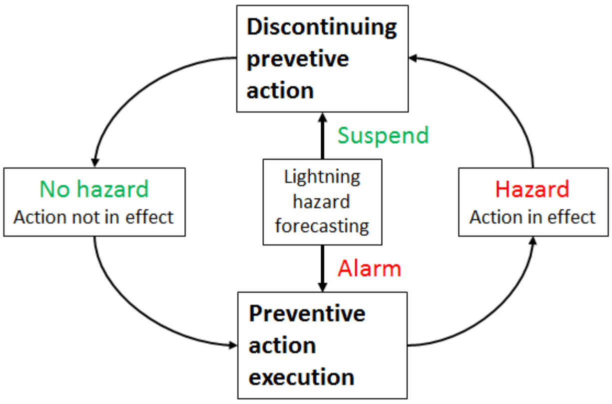

Figure 1. The operation of preventive lightning protection

In section II a brief theoretical overview is given extended with information on the datasets used. Section III outlines the methods used and raw results (including risk calculations as well) and section IV concludes.

II. OVERVIEW

When describing conventional lightning protection methods the most important measure is the annual risk of damage as defined by the international standard [5]. Risk comes from the possible failure of the devices realizing protection – the lightning rod, down-conductor, earthing or the internal protection devices.

In case of preventive lightning protection however the tools of protection are different, they are actions executed at a given time yielding another layer of uncertainty. This is caused by possible late timing of the alarm initiating action execution. Hence, the description of preventive lightning protection differs significantly from conventional methods [6].

A. *Events related to alarming*

The inaccuracy to alarm is described by the event space of preventive lightning protection [7] – here we consider accurate alarms, unnecessary alarms and late alarms. Each of these events describe relations between the lightning hazard development and the transmitted alarm. Lightning hazard here means in this sense that an active thunderstorm cell was observed in a given distance of the object to be protected. This zone (around the object to be protected) is denoted as 'Danger Zone' (DZ). We consider CC lightning also as a part of hazard although it doesn't directly endanger the object to be protected, but it signals that a CG strike may follow in any moment.

Accurate alarms mean that alarming was proper, lightning hazard did develop and the action was executed in time.

Unnecessary alarms are the cases when forecasting suggests that the preventive action should be executed, but finally no lightning hazard develops. Note that these alarms are not fundamentally false as it may happen that the activity of the cell diminishes when approaching the object to be protected or simply changes its direction.

Late alarms are the most important in the terms of protection efficiency. In these cases the preventive action wasn't executed at the time the lightning hazard developed increasing the risk of damage. The 'lateness' of the alarm has to be taken into account as well as it will be presented later.

In case of a good solution the probability of unnecessary and late alarms is kept low, but there is always a compromise between these two. While unnecessary alarms represent excess costs, the late alarms increase the risk of damage. Thus, finding the balance between the cost of the solution and the risk of damage is the key question when planning such a solution.

B. *Lightning hazard forecasting methods*

There were two methods introduced earlier to forecast the development of lightning hazard, zonal preventive lightning protection and high reliability lightning protection [7]. For both methods the lightning hazard development means that the active thunderstorm cell enters the proximity of the object to be protected (the DZ).

Zonal preventive lightning protection (ZPLP) means that another zone is designated, which serves as a boundary for triggering alarms upon incoming strikes. This is denoted as the Warning Zone (WZ). When an active cell enters the Warning zone the alarm is given and the preventive action is executed. It is assumed that the preventive actions are immediately executed – there is no delay between receiving the alarm and starting the execution of the preventive action. Such a solution may be used as well when limited data (only stroke distance) information is available (local detectors) [8].

In case of High Reliability Preventive Lightning Protection (HRPLP) the active thunderstorm cells are monitored real-time within a given distance of the object to be protected. Based on the estimate of their velocity and heading it can be estimated when and if those cells will cause lightning hazard.

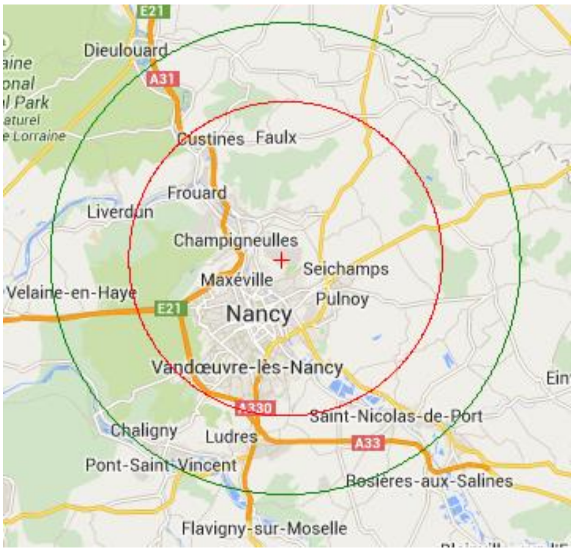

Figure 2. Defining zones around the object to be protected (Green – Warning Zone; Red – Danger Zone)

The input of a HRPLP forecasting may be lightning and/or meteorological data. Since the meteorological data shows the physical extent of the clouds (thus the cells), its use means an advantage in lightning hazard forecasting [9], [10]. In this study however only the lightning data was available to execute our simulations.

C. Preventive lightning protection and risk

As briefly discussed before, calculating the risk of preventive lightning protection is different from standard risk calculation although it is based on the standard. The risk associated with using a given preventive action is calculated using the equivalent risk function [6]. It is a time function of risk describing the risk which assumes stopping the execution of the preventive action at a given time and calculating the annual risk according to the standards.

The annual risk associated with a preventive lightning protection solution can be calculated by probabilistically weighting the equivalent risk function of the preventive action with the distribution of the 'lateness' of the alarm.

Fig. 3 demonstrates the equivalent risk function (in red), and the distribution of alarm 'lateness' (in blue) approximated with a Gaussian distribution.

This figure also shows that in order to obtain a good solution (with low annual risk) perfect forecasting is not required (one that never produces late alarms). The late alarms may be 'allowed' to a certain extent if they do not pose a high risk (the lightning hazard develops only when the preventive action is almost fully executed). Thus this gives room to compromise between late and unnecessary alarms.

D. Risk profiles of preventive actions, calculating risk

Preventive actions themselves are actions which are executed in order to decrease the risk of damage due to lightning strike at the object to be protected. The action's execution is assumed to be started instantly upon the receipt of an alarm. If there is any delay due to preparations or so, then that is also to be considered as a part of the action.

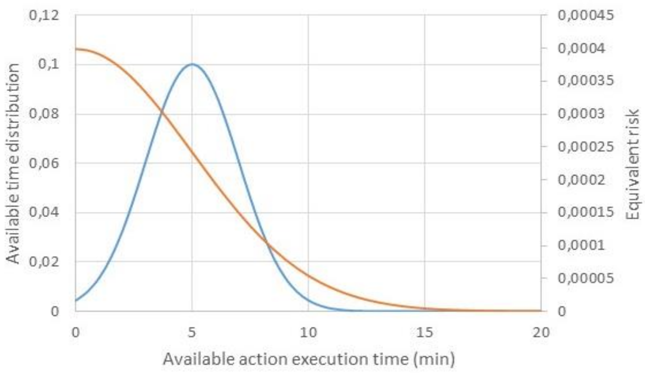

Figure 3. Approximating annual risk

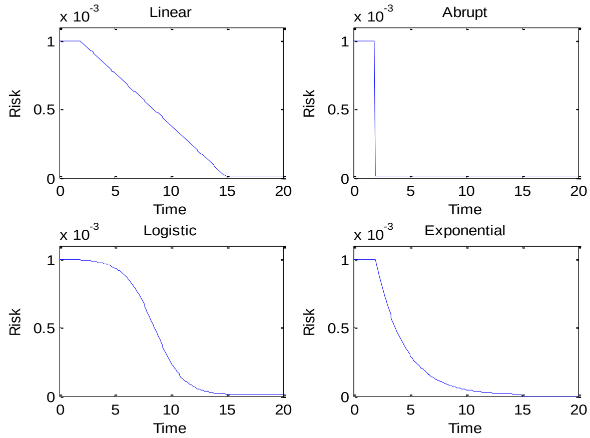

Figure 4. Typical risk profiles (equivalent risk functions)

The course of the execution of the action can be described by how the risk is being decreased as a function of time. This is the equivalent risk function $R_e(t)$, or the so-called 'risk profile' of a preventive action (typical risk profiles are shown in Fig 4.).

A given point of this function can be calculated (assume it is at t_1) by starting the action execution and stopping it at t_1 and calculating the corresponding risk value according to the international standard (as if it were left like that for a year). For example in case of a live line maintenance (LLM) [11] this means starting removing the worker's maintenance cabin from the cable, stopping it at t_1 (assuming that the lifter is still semi-retracted) and calculating the risk of damage according to the international standard under those conditions.

There are various risk profiles possible for a preventive action.

- Flat (or 'abrupt') risk profile: the risk only decreases after the action has been executed
- Linear risk profile: the risk decreases linearly as the execution progresses
- Logistic curve: the risk decreases significantly at one point of execution – e.g. when in LLM the worker gets to a safe distance from the power line.
- Exponential risk profile: the risk decreases quickly during the initial stage of the execution.

Calculation of the risk with the risk profile of the preventive action is a basically a probabilistic weighting of the equivalent risk function with the 'occurrence' of a given risk value (the distribution of 'lateness' of the alarms) [6]:

$$R = \int_{0}^{t_{ex}} R_{eq}(\tau) p_{ex}(\tau) d\tau + R_{pr} \int_{t_{ex}}^{\infty} p_{ex}(\tau) d\tau \qquad (1)$$

where:

$R_{eq}(t)$ – the equivalent risk function (R_{pr} is the constant part of it, the 'remaining risk' even when the action was executed)

$p_{ex}(t)$ – the distribution of the time left for action execution

t_{ex} – the time required to execute the preventive action

Practically, Eq. (1) is split into two parts. The first term corresponds to late alarms for the cases when the time left to execute the action is shorter than required. In this case the equivalent risk function is weighted with the time distribution. The second term corresponds to those cases when the execution was finished in time – this is the 'normal', accepted risk.

In order to use this formula for the approximation of risk when using historic data a high case number is required to approach a continuous distribution. Since only a lower case number was available in this study only a short qualitative analysis is done.

III. Methodology and Results

A. Methodology

The main method of this work was a simulation using archived data spanning a wide geographic area (France-Belgium-Netherlands) obtained in 2012 August provided by the Royal Meteorological Institute of Belgium. As an object to be protected an arbitrary point on the map was selected and the various forecasting methods (ZPLP and HRPLP) were executed.

The goals of the simulation were the following:

- Provide a time distribution of when the alarms would be given before lightning hazard developed
- Approximate the event space (probabilities for the events defined in section II)

For these purposes we assumed a DZ of 10 km (based on [12] also 2, 5, 10 km or even bigger values could be used) and a simple preventive action requiring 5 minutes – the equivalent risk function was not fixed. In the previous section a specific emphasis was given to take into account both forecasting and preventive action at the same time during the planning phase of the solution.

To be able to analyze ZPLP in a more complex setting it was simulated with different WZ-s (5 and 10 km outside the DZ). Taking the WZ radius and the action execution one may assume that a radius of 5km and 10km enables proper forecasting of cells propagating with 60 km/h and a 120km/h speed, respectively.

In case of HRPLP this does not apply as here cell's location is forecasted for the timespan of the action execution. Considering the possible inaccuracies in the forecasting of speed the safety factor of 1.1 was used for the DZ radius when calculating the cell propagation (so the DZ was taken to be 11 km in this case).

The object to be protected used in our test is shown in Fig. 2 (as a source for the map, Google maps was used in the tests). The choice fell on this area as in the available data this was one of the stormiest regions.

B. Obtaining results

The dataset available contained the detected CC/CG strokes from 2012.08.01-2012.08.31. On the performance of the systems used please see [3], [13]. The time resolution of this data corresponds to the raw measurements, but for HRPLP the data was grouped to 5 minute blocks.

Due to the short timespan covered by the data 5 points were selected as object to be protected around the initially designated point (Nancy Aerodrome). The simulation was ran on each of these points for HRPLP and ZPLP (assuming 5 and 10 km wide WZs).

In case of both methods the outcome of the benchmark is a discrete approximate to the probabilistic distribution of time left to execute the preventive action once the alarm was given. Also there were some cases when the forecasting methods simply fail to warn in time – when thunderstorms develop close to the object to be protected in the DZ. For producing warnings for these cases other forecasting solutions could be used in practice, mainly based on electric field or corona measurements [14]–[17], but they are not in the scope of this paper.

The analysis itself consists of running the forecasting algorithms (ZPLP or HRPLP) on the input dataset directly. For both methods the output of the test run would be the alarms suggested by the given forecasting methods and the time when the lightning hazard actually develops.

For ZPLP this means that a CC or CG stroke was detected in the DZ signaling the presence of an active cell in the zone. In case of HRPLP hazard is assumed to develop once an approximated cell (elliptic approximation was used) was found in the DZ. Due to this difference the base of comparison for these two methods will be done based on general performance and not by reaction to individual cells.

C. Results

In the investigated timespan a total of 56 hazardous events were identified in the ZPLP algorithms and 45 in case of HRPLP. This difference can be explained by the difference in determining lightning hazard. Based on the timing of the alarm the event space in Table I. was calculated for the three methods. Due to the lower number of alarms, the values are given as relative frequencies as percentages rather than probabilities.

TABLE I. The Event Space of Different Methods

Event space	**Forecasting method**		
	ZPLP 5*	***ZPLP 10****	***HRPLP***
Accurate alarm	30.33%	33.90%	42.39%
Late alarm	32.5%	17.43%	6.5%
Unnecessary alarm	37%	48.62%	51.1%
Total number of events:	89	109	92

*. ZPLP 5 and ZPLP 10 denotes the WZ radius

In this table the alarms with remaining time below 280 seconds were considered as late alarms (due to the sizable DZ radius this approximation holds). The following apparent features can be seen from this data:

- ZPLP always produces more late alarms than HRPLP
- HRPLP produces the most unnecessary alarms (and accurate alarms)
- ZPLP methods produce similar accurate alarms
- Increasing WZ size improves the late alarm rate, but also increases the number of unnecessary alarms.

The data in this table only gives a high level overview of the methods' performance. For an in-depth analysis it is required to investigate the timings of the alarms.

Fig. 5 shows that HRPLP provides the most accurate alarms – in the 250-300 second region all the values are above 285 seconds almost reaching the required 300 second execution time. Both ZPLP methods produce a significant portion of completely late alarms, when the action execution begins only once hazard has already developed. This is probably due to the size of the WZ, as fast cells may pass through the WZ without producing a stroke which would trigger the alarm.

Calculating the risk with these values can only be done numerically, but as it requires a higher number of cases than currently available, only a short analysis is given. The focus here is on determining which risk profiles are adequate for a given forecasting method.

In general we may consider the abrupt and the exponential risk profiles as the two extremes (see Fig. 4). The abrupt function is the worst case as until the action is executed completely, the risk does not decrease at all – so all late alarms are to be considered. In case of actions with exponential risk profile those late alarms which are only a bit late (compared to the total action execution time) do not have a serious effect as the associated risk values are very low.

Considering this, Fig. 5 suggests that in case of ZPLP methods a preventive action with very steep exponential risk profile would yield appropriate risk. On the other hand HRPLP is much more flexible in these terms and actions with less optimal risk profiles can be permitted.

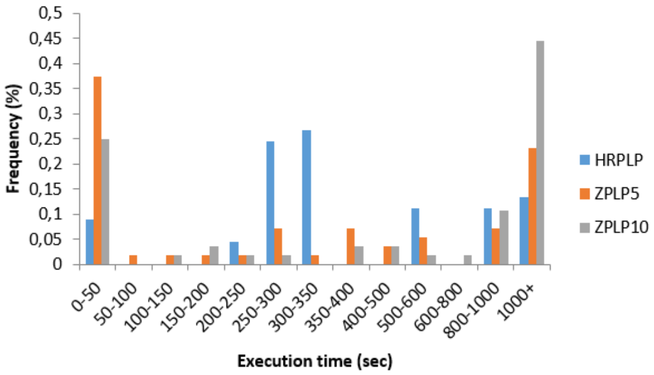

Figure 5. Distribution of the execution time

This also shows that upon selecting the preventive actions the available forecasting methods are to be considered as well.

IV. CONCLUSION AND DISCUSSION

In this paper a practical analysis of preventive lightning protection was shown using a real dataset. First a brief general description was provided about preventive lightning protection focusing mainly on the forecasting methods and its relation to risk was discussed. Then a practical analysis was carried out using a detailed lightning dataset recorded in 2012 spanning a wide geographic area. The analysis was twofold. It focused first on the raw performance of the different forecasting methods, then a short analysis on the risk profiles was given.

The analysis of the forecasting systems has uncovered that while ZPLP performs as it was expected earlier [18], the much more sophisticated algorithm used in HRPLP does not have a huge advantage when only considering its event space. It has only a 10% advantage on providing accurate alarms. HRPLP excels in terms of the late alarms, where it is clearly better than the other methods.

In case of each method a considerable ratio of unnecessary alarms was found, which is caused by the changes in cell propagation and in case of ZPLP the protection method itself. In some cases this may be neglected, especially if PLP is used to protect human lives.

Since this analysis only used the lightning data, the accuracy found in this analysis is lower than the case when other meteorological data is used. Radar data further improves the performance of HRPLP as the propagation speed and bearing of a cell can be determined much more accurately. In that case a considerable improvement of this method can be expected.

It is also important to have sufficient data when the preventive solution is planned. Although for this work the data was sufficient to compare the performance of the different forecasting methods, it did not allow the complete approximation of annual risk, which is a key part of planning. Neither was in the scope of this paper a thorough theoretical analysis (based on probabilistic efficiency calculations).

The condition for having sufficient data is to be able to draw up a probabilistic distribution on the time available to execute the preventive actions. From this data we may assume that it is indeed required to have data from several years to conduct such an analysis.

Finally, a very important aspect not discussed here is the financial aspect of using preventive methods. Besides the late alarms the unnecessary alarms or the accurate, but unnecessarily early alarms decrease the efficiency of the preventive solutions. Fig. 5 shows clearly that in some cases the alarm was given very soon to execute the preventive action, thus if the costs of the preventive actions are high this may also be an issue (a good example for this would be an airport where suspending of refueling or take-off and landing yields immense costs).

As mentioned earlier the purpose of this paper was not to give a complete analysis of the planning process of a preventive solution, but rather to provide a practical example to it. The forecasting efficiency, annual risk approximation and a cost efficiency analysis are all required to design an adequate solution. Despite complex planning process, the advantage of preventive lightning protection is that it may provide protection to people and goods also in cases when conventional lightning protection cannot.

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