Comparison of forecasting methods in preventive lightning protection – a case study

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Abstract: Recently a new approach was introduced in lightning protection incorporating the use of forecasting tools and preventive actions into one lightning protection system, the preventive lightning protection. The key feature of this protection system is that the hazard forecasting methods are planned according to the available preventive actions. The appropriate use of forecasting is very important in the terms of protection efficiency (and also cost effectiveness). This paper introduces three forecasting methods (zonal PLP, high reliability PLP, and fuzzy forecasting) and gives a comparison of the methods through a specific case study. The case study also gives a good opportunity to introduce the calculation involved in the forecasting methods.

Zonal PLP means that there are certain zones defined around the object to be protected which serve as a hazard evaluation for the forecasting system. The advantage of this method lies in its simplicity, but it may result in many unnecessary alarms, thus decreased cost effectiveness.

High reliability PLP on the other hand relies on individual thunderstorm cell monitoring, thus is more accurate. Due to the constant monitoring it requires much more resources. However by using the systems currently available, this method may be realized easily in real-time.

Fuzzy PLP is a novel approach to forecasting. It is close to High reliability PLP in terms of real time monitoring, but this method involves the use of a fuzzy expert system. The expert system has the same input data as High reliability PLP, but it utilizes special fuzzy functions to decide on the alarming.

The case study introduced in this paper addresses an important problem in lightning protection, the problem of refuelling airplanes. The object to be protected in the study is an airport, which may be endangered by a thunderstorm cell. In the paper besides the comparison of the forecasting methods, an overview is given of the methods and preventive lightning protection itself.

Keywords: Lightning protection, preventive lightning protection, zonal PLP, high reliability PLP, fuzzy PLP.

I. Introduction

With the rapid development of meteorological radars and lightning detection systems real-time information may be gathered on the progression of thunderstorms. This information (also referred to as 'nowcasting') may be used to forecast lightning hazard, thus is a useful tool in realizing preventive lightning protection.

The preventive lightning protection method means avoiding damage of a lightning strike with special preventive actions. The preventive actions can be of various types, and the primary goal of preventive lightning protection is to decrease the risk of damage due to lightning for the duration of the thunderstorm. The preventive action shall be initiated before the beginning of the lightning activity and shall be discontinued after the end of the thunderstorm. [1]

The timing of the preventive action is crucial for adequate protection and cost efficiency. Thus the hazard forecasting method is in a focal point of the development of preventive lightning protection.

In this paper three forecasting methods are described in details and compared using a case study. The second section includes the description of these methods (namely zonal preventive protection – ZPLP; high reliability preventive lightning protection – HRPLP; fuzzy preventive lightning protection FPLP). These methods utilize different algorithms to evaluate the data obtained from lightning detection systems and meteorological radars. Section three introduces the case study and the properties of each forecasting methods. The results of the case study are given in section 4 and section 5 concludes.

II. The forecasting methods in preventive lightning protection

The existence of forecasting is a prerequisite to realize preventive lightning protection. As Fig 1 shows the preventive actions – the method of protection – are executed following an alarm given by the hazard forecasting (or detection) system.
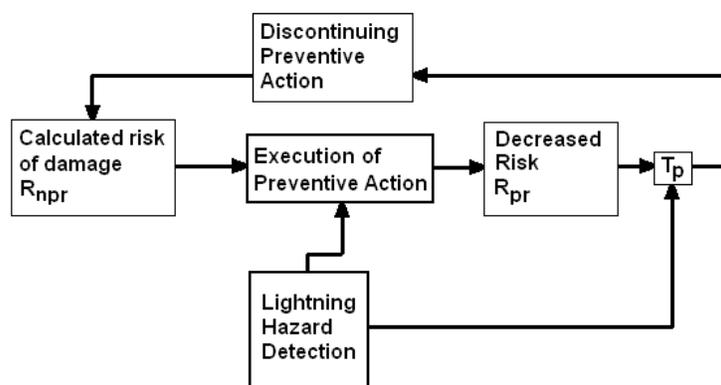
Figure 1.: The operation of preventive lightning protection

The same hazard detection system is used when deciding for the suspension of the preventive action. This may be important as a question of cost effectiveness, but does not influence the protection efficiency, thus it's not in the scope of this paper.

In preventive lightning hazard denotes the case when the object to be protected is endangered by direct or nearby lightning strikes. Accordingly a zone may be designated around the object to be protected where the presence of an active thunderstorm cell (a cell with electrostatic activity – either CC, IC, CG or intra-cloud lightning activity) endangers the object to be protected. This zone is denoted as the 'Danger Zone' (DZ), since a presence of a thunderstorm cell in this area means lightning hazard. The radius of this zone around the object to be protected varies depending on the size of the object to be protected and its sensitivity to secondary effects [2]. The size of the DZ is the same regardless of the forecasting method.

There are three approaches to the forecasting methods in preventive lightning protection. Zonal preventive lightning protection utilizes zones for hazard forecasting. It is the simplest and cheapest solution. High reliability and fuzzy preventive lightning protection are using constant monitoring and hazard evaluation for triggering preventive action execution. The latter two methods provide of course more effective protection, but yield much more costs.

Zonal Preventive Lightning Protection (ZPLP)

The simplest solution for hazard forecasting is the zonal forecasting method. With this method another zone is defined besides the DZ denoted as the Warning Zone (WZ). Whenever an active thunderstorm cell enters this area the alarm shall be given to trigger the execution of the preventive action.
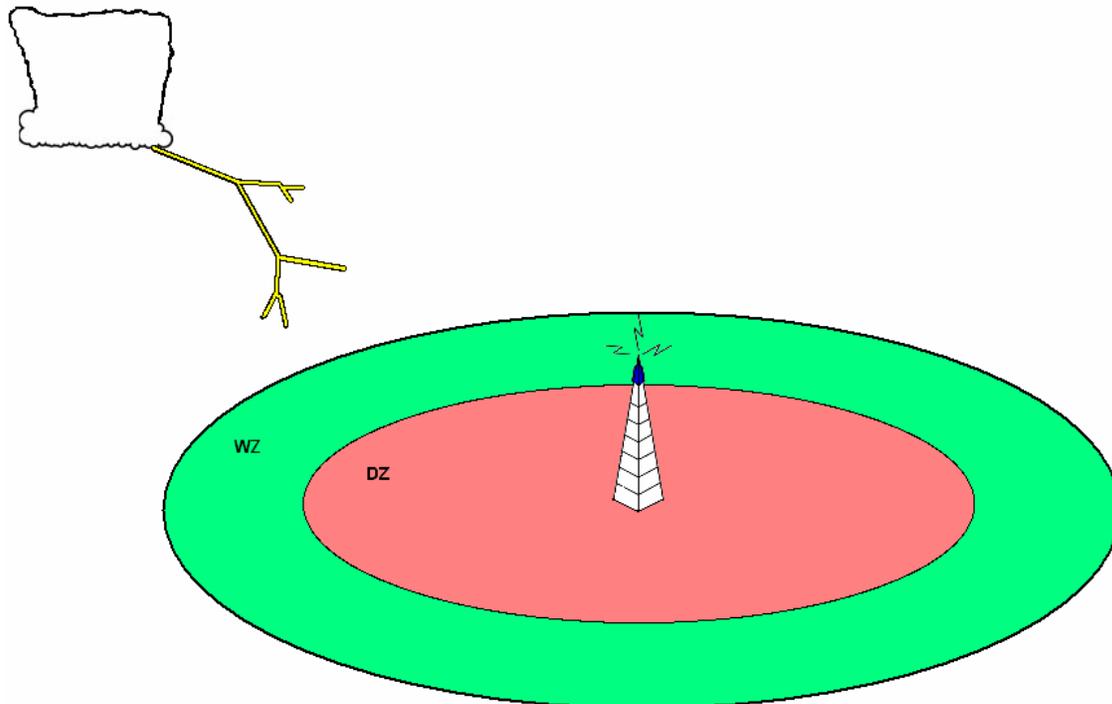
Figure 2.: The DZ and WZ in ZPLP

The size of the WZ shall be chosen according to the average velocity of the thunderstorm cells (determined using empirical data) and the time requirements of the preventive action.

$$r_{WZ} = r_{DZ} + t_{act} v_{storm} \tag{1}$$

The execution time in (1) denotes the time required from starting the execution of the preventive action until the object to be protected is considered to be protected. The progression velocity of the thunderstorm cell is to be taken into account as well. However since the WZ is designated as a result of the planning process (it's constant), a suitable progression velocity of the thunderstorm cell is selected. A given WZ radius with a specific progression velocity assures the protection of the object to be protected, if the thunderstorm cell progresses slower than the value which was used in (1).

In some cases the alarm may not come in time depending on the speed of the thunderstorm cell and the formation of an active cell inside the WZ or the DZ. In the former case the thunderstorm cell progresses faster than assumed in (1). Formation of thunderstorm cells may be forecasted using local detectors [3], but it's not in the scope of the current paper.

High reliability preventive lightning protection (HRPLP)

In high reliability preventive lightning protection the concept of a WZ is entirely omitted, because this method concentrates on forecasting the hazard for individual thunderstorm cells. The concept of a DZ is still used in this solution of course. An area around the object to be protected is observed constantly and thunderstorm cells entering it or forming inside are monitored. The following information is gathered.

- Distance from the DZ
- Propagation direction
- Propagation velocity
- Size and shape

The last three properties of the thunderstorm clouds were approximated in ZPLP using empirical data. In this solution however these properties are constantly monitored and the preventive action is only carried out, when these properties fulfill the following criterions.

- The thunderstorm cell's path leads into the DZ
- The thunderstorm cell is close enough to the DZ

The first criterion is denoted as the direction criterion further on and the second as the distance criterion. Both of these criterions can be checked using the data from meteorological radar system and lightning detection networks [4].

The evaluation of the direction criterion means checking if the propagation path will cross the DZ. When this criterion is fulfilled, the distance criterion is to be calculated.
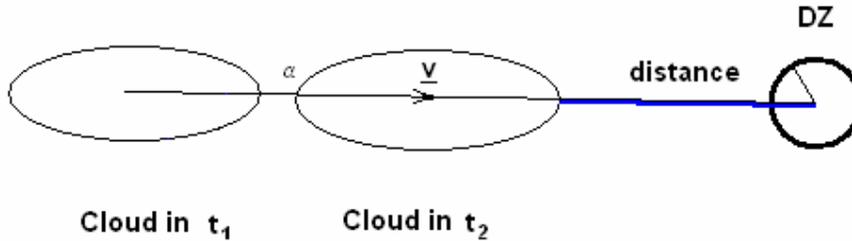
Figure 3.: the operation of HRPLP and calculating the distance of a thunderstorm cell

Fulfilling the distance criterion means that the thunderstorm cell is closer to the DZ than the so called 'critical distance'. If the thunderstorm cloud gets closer to the DZ than the critical distance, then the preventive action is to be carried out immediately.

$$d_{crit} = r_{DZ} + (t_{act} + t_{samp}) v_{storm}$$
(2)

As seen in the expression the critical distance depends on the speed of the individual thunderstorm cell. The execution time of the preventive action and the sampling period is also to be taken into account to avoid late alarms. This may be interpreted as a 'changing WZ', but this notion is wrong in the meaning that the WZ applies for all of the thunderstorm cells, while the critical distance is unique for each one.

Fuzzy preventive lightning protection (FPLP)

A novel approach in protection against electrostatic hazards is the use of expert systems based on fuzzy logic [5]. By applying fuzzy logic to lightning protection the uncertainties in risk calculations may be accounted for [6,7] and it may be applied in preventive lightning protection as well [8].
The application of fuzzy logic is realized by using a so called 'fuzzy interference system' (FIS). The FIS is an expert system which capable of approximating a function between input and output quantities. In preventive lightning protection the alarming decision may be made using a FIS system. Moreover using a FIS system in alarming is capable of handling such objects to be protected which may not be described using the international standards [9]. The open air mass performances are a perfect example, since in that case the 'object to be protected' is people at endangered locations. The number of these people may vary with time along with some of their other properties, which all influence the time requirements of the preventive action and also its cost. Applying a FIS system for such a complex task is a good solution in preventive lightning protection [10].
In FPLP the active thunderstorm cells are to be monitored the same way as in HRPLP. The decision making algorithm is different in these cases though. While in HRPLP the distance and direction criterion are to be evaluated, FPLP is capable of giving more sophisticated and detailed information.

As the first step to realize FPLP the input quantities are to be determined (the output quantity is an alarming decision – may take several values besides alarm/do not alarm). Then the so called 'membership functions' are to be determined, which are an interpretation to a given value of the input parameters. Using the values of the membership functions then a rulebase is created which determines the output quantities – the alarming decision in this case. The membership functions and the rulebase is different for each application, but general planning considerations are not in the scope of this paper.
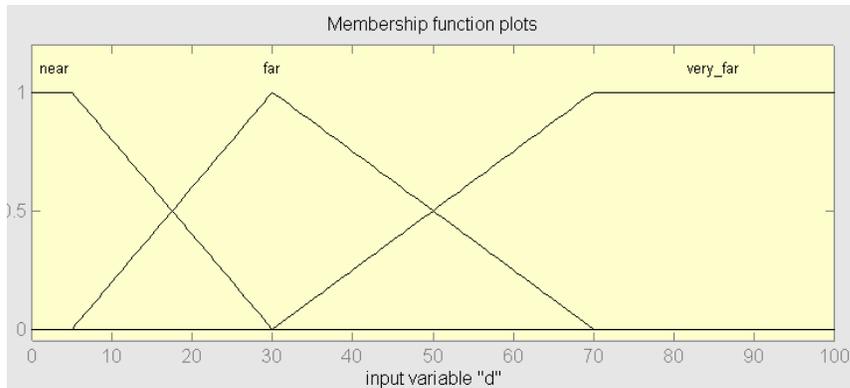
Figure 4.: a membership function (input: probability that the thunderstorm cell enters the DZ)
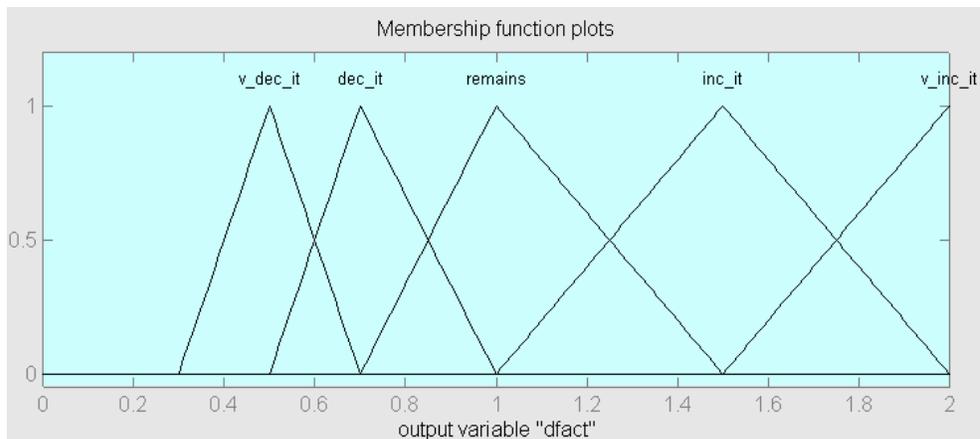
Figure 5.: the output of the FIS system

Fig. 4-5. shows certain functions used in the FIS system. In our case the FIS is used to modify the actual predicted time of alarm. It is made in the following way. Based on the incoming information (detected lightning density, radar pictures, etc.) the border of active thunderstorm cells are determined. Now the distance between the DZ and this border is determined (D_act) Doing this calculation periodically (in each sampling period) the speed of the active cell (cells) can be determined. The product of this speed and the time of activating the preventive action gives a critical distance: the alarm has to be given, when D_act reaches D_critical. Using the FIS this critical distance is modified by a factor that is determined by the output membership

functions. Thus distance D_FIS can be determined. Alarm has to be given when D_FIS meets D_act. Also with the use of the membership function the decision maker may be informed about the level of the hazard as well.

Due to the capabilities of the FIS system complex tasks in preventive lightning protection may be used. This includes the application of PLP in case of special preventive actions – actions which have properties changing over time [10].

III. The case study of Lexington airport – performances of ZPLP, HRPLP and FPLP

In this section a case study is shown using existing empirical data. The object to be protected in our case study is Lexington airport (Kentucky, USA) during a refueling operation.

Figure 6.: Lexington airport
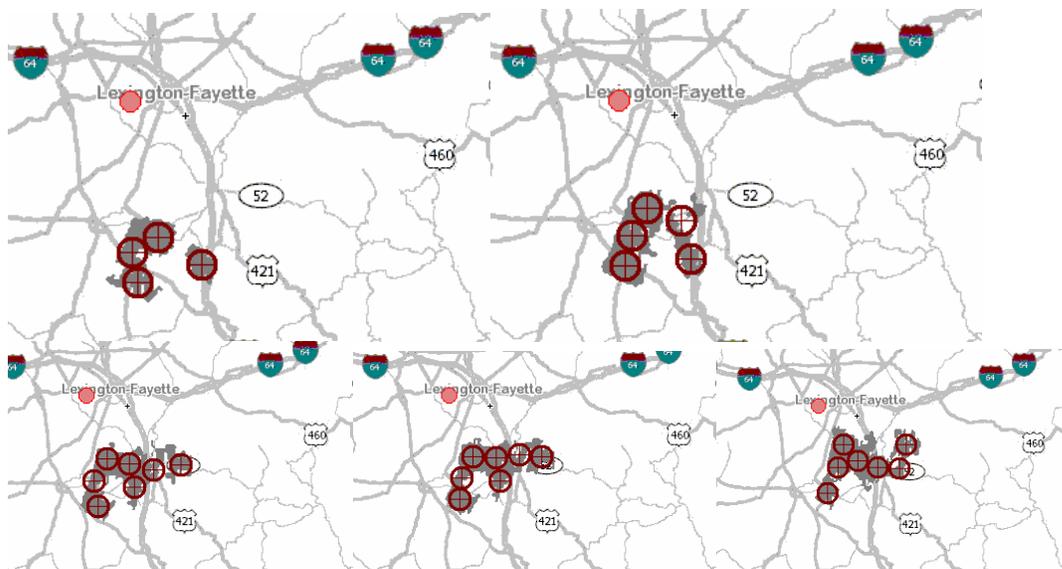
Figure 7.: Lexington airport and the approaching thunderstorm cell (first 5 samples out of 15)

The investigated situation is shown in Fig 6-7. The data was recorded from 16.04.2008 (410PM), with 5 minute sampling periods. The DZ (5 km radius as per current US regulation) airport is designated in a solid red circle in the upper left corner, while the rapidly developing thunderstorm cell is designated with the solid grey area. Also note that the cloud has been modeled using a circular cloud model for HRPLP and FPLP. This was used to take account for the inaccuracies of the lightning detection system.

The preventive action in our case study is the suspension of the refueling operation. For the sake of simplicity 5 minutes was assumed for the time requirement of action execution. 5 minutes after the execution the action the airport is to be considered protected. A complex risk calculation and approximation of this case study is not in the scope of our paper, but it's feasible using recently proposed methods [11].

Applying ZPLP

In ZPLP a WZ is required to provide a condition to give an alarm. In our case taking into account the time requirement of the action and using 240 km/h as an upper limit in the velocity of the thunderstorm cell (to provide high protection efficiency), a WZ radius of 25km was calculated using (1). The DZ radius was set to 5 km as in all of the solutions, just as the radius of the circles in the circular cloud model (see below).

Applying HRPLP

The thunderstorm cell was approximated with a circular cloud model. For the sake of simplicity a very simple approach was used: the circular cloud model consisted of circles with a 5 km radius. Of course there may be more optimal solutions, since several methods exist to approximate various shapes with circles [12-15]. The implementation of these methods is quite complex and it has to be kept in mind, that to take into account the inaccuracies of lightning detection systems and to finally determine the probability of hazard development (to evaluate the direction criterion) a stable circular model has to be used. The simplest way of such an approach is the use of circles with equal radii.

Applying FPLP

Fig. 8.shows the membership functions in the FIS system for each sampling period (1-15). The leftmost column shows the distance of the cloud and the object to be protected, the middle column is the function showing the speed (changes). The output is shown at the column at the right. Also see Fig 4-5 for the actual distance membership function and the output function.

d | dvdt | dfact

(d axis: 0 — 50 — 100; dvdt axis: -150 — 0 — 150; dfact axis: 0 — 1.08 — 2)

The results

The following table summarizes the alarming decision for each solution. Although fig 7. contains the first 5 sampling periods (25 minutes), data was gathered for 70 minutes. Each sample consists of velocity (veloc) and distance (dist) information on the numbered circles (1-24). The distance is calculated from the centre point of a circle to the object to be protected. It means that for example in case of ZPLP a distance of 30 km should trigger an alarm.

Circles	Param	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0 min	veloc																								
	dist	66	55	51	65																				
5 min	veloc	72	87	126	24																				
	dist	60	49	40	63	49																			
10 min	veloc	78	85	96	153	121																			
	dist	55	42	33	51	40	50	58																	
15 min	veloc	42	35	22	40	47	92	49																	
	dist	51	41	32	49	39	45	55																	
20 min	veloc	66	113	121	140	43	105	120																	
	dist	46	34	24	45	35	54	51																	
25 min	veloc	0	30	54	99	54	175	195																	
	dist		31	21	41	32	44	55	53																
30 min	veloc		157	148	139	99	204	38	144																
	dist		39	26	39	36	47	51	64	52															
35 min	veloc		150	42	52	132	78	52	30	116															
	dist		31	25	41	38	40	47	67	52	55														

40 min	veloc	44	49	67	22	70	70	34	85	46											
	dist	28	24	37	36	38	46	64	45	51	56	47									
45 min	veloc	25	30	38	52	62	43	52	13	97	73	135									
	dist	28	26	37	35	40	46	67	46	57	57	49									
50 min	veloc	40	42	114	46	102	38		8	84	17										
	dist	26	23	36	32	37	43		57	50	47	27	44								
55 min	veloc			17		60	133		12	8	36	118									
	dist			35		40	38		58	50	49	37	56								
60 min	veloc			102		90	48		42	46	48	47									
	dist			35		35	37		53	49	40		59								
65 min	veloc			285		191	137		67	0	136	70									
	dist			19		19	25		55	0	39	64	40	26	42	29	26	38	30		
70 min	veloc			13		48			60	0	57	57	32	51	60	80	90	48	34		
	dist			20		20			59	0	41	68	38	23	44	34	30	36	27	48	48

Table I.: The distance and speed of the thunderstorm cloud (v [kmph]; d [km]) in the rest of the sampling periods

The red cells in Table I indicate that if ZPLP is applied using the parameters given above, then an alarm would've been given, while the orange cells denote when the alarms would've been given by HRPLP as well. Note though, that in the 70th minute HRPLP would not trigger an alarm, the direction condition would be fulfilled in this sampling period as well. This means that the thunderstorm cell is still closing on the object to be protected, but also as it's seen in the table the speed of the thunderstorm cell decreased.

Fig. 9. Illustrates the time function of the closest distance between the border of thunderstorm cells and the danger zone (D_act), the critical distance D_critical (the alarm has to be given if D_critical reaches D_act) and the diagram of modified values of D_critical determined by the fuzzy inference system (D_FIS). Comparing the diagrams, it can be seen, that without the fuzzy system an unnecessary alarm can be given. Here it is necessary to remark, that in other cases FIS can bring the moment of giving an alarm earlier, see [8] for details.

Fig. 9: time functions of D_act, D_critical and D_FIS

Although this is not a part of the analysis, the thunderstorm cell does not endanger the airport in the end, but heads northwards. This simple analysis yields in an alarm from the monitoring system after 65 minutes from the start. At this time no part of the thunderstorm cell is in the DZ. The minimum distance is 19.1kms. In this case if the thunderstorm cloud heads straight towards the airport with a velocity larger than 54.6 km/h may endanger the refueling operation.

So in this case study, an alarm would've been given, but it would've been an unnecessary alarm. When using HRPLP the time of alarm would've been 65 minutes from the sighting, but with ZPLP this time would be 45 minutes earlier. It also would've been an unnecessary alarm, but it would've resulted in much higher costs decreasing cost effectiveness. By using FPLP no alarm would've been given using the modified D_CRIT function as an output of the FIS system. This yields a cost effective solution.

Note though that the performance of ZPLP is very sensitive to its parameters. In this case the WZ was chosen to be 25km. With a smaller WZ (15 km, providing protection for cells propagating with 120 km/h; or 20 km providing protection for cells propagating with 180 km/h) cost efficiency may be increased on the expense of protection efficiency.

IV. Conclusion

Our paper shortly described the forecasting methods of PLP. Three forecasting methods were introduced, the ZPLP, HRPLP and FPLP methods. The methods were also compared in a simple case study based on existing empirical data. As the empirical data showed, that both HRPLP and FPLP outperformed ZPLP (as it was expected). In the protection point of each of these methods would've provided adequate protection for the operation, but ZPLP did it the least cost effective way. The other methods are considerably more expensive than ZPLP, but in the long run they may prove a better choice (since the suspension of refueling may have high costs) in the current example.

This case study also showed that the use of novel systems – the FIS system – the unnecessary alarm may be omitted to further increase the cost effectiveness of preventive lightning protection. By using either of these solutions an accurate hazard forecasting system is required. It may consist of local detectors (in case of ZPLP and FPLP only), it may be a lightning detection network, or a mixed system including both types of detection. If any of these solutions are available then preventive lightning protection is a feasible solution.

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