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HIGH RELIABILITY PREVENTIVE LIGHTNING PROTECTION

Attila Gulyás, Dr. István Kiss
Budapest, University of Technology and Economics
Department of Power Engineering

1. INTRODUCTION

Recently a new approach was introduced in lightning protection emphasizing the importance of possible preventive actions and the usage of available monitoring equipment and detailed data in timing the execution of this preventive action. This approach was denoted as preventive lightning protection (Gulyás et. al. 2006), and it differs from the previous preventive solution in focusing on each case individually.

Some areas of practice – especially protection of human lives, non-stationary objects, or protection of extremely sensitive equipment – require special solutions, making preventive lightning protection a useful tool in realizing protection.

Preventive lightning protection however has its limitations. It offers protection using static zones for alarming, which means in some cases it is either not cost efficient, or the alarm is not given in time. These are the drawbacks of this method, so improving it can lead to a much better solution of this issue using a different approach.

In Section 2 of this paper a short review on preventive lightning protection and its uses is given. Some practical examples and the corresponding efficiency calculations are also shown. High reliability preventive lightning protection, an improvement in preventive lightning protection is introduced in Section 3. Finally Section 4 concludes giving a short summary of the paper.

Its theoretical background is discussed along with the first steps in the efficiency calculations.

Along with the theoretical background of the theories short examples are shown, and the efficiency of the preventive solution is discussed.

2. PREVENTIVE LIGHTNING PROTECTION

2.1 Background

Nowadays primary and secondary lightning protection is applied for protection against the damage due to the primary and secondary effects of lightning. These protection methods include the risk assessment process as well as the exact planning and installation of the different protection devices. These devices include both primary and secondary protection devices.

In some cases however these solutions are not cost effective, as these devices yield some costs, which depend basically on the quality and quantity of the installed devices.

Also there are some cases when not even these devices can protect the living. The most important purpose of lightning protection is the protection of the living against the effects of lightning, yet there's no protection method aimed on directly protecting the living. The protection of people is realized with the protection of the buildings, and installations.

If people are exposed to the effects of lightning and are not near, or inside a protected area during the thunderstorm, they're endangered. Primary and secondary protection can't be realized in these cases.

This is because the people are not "stationary objects" one can protect with any kind of device. (For example at open air events, lightning protection can't be realized cost effectively (Németh et. al. 2008a).) A dynamic method is needed for their protection.

2.2 The definition and operation of preventive lightning protection

Dynamic in this case means that the protection is not always in effect, it is dynamic in time unlike the installation of certain devices. These protection solutions are preventive measures, or preventive actions.

Preventive lightning protection means avoiding damage with preventive actions of various types by decreasing the risk of damage to the object to be protected only for the duration of the thunderstorm. (Gulyás et. al. 2006).

The figure below shows the operation of preventive lightning protection. As shown, it is dynamic in time, and it emphasizes proper risk assessment upon planning.

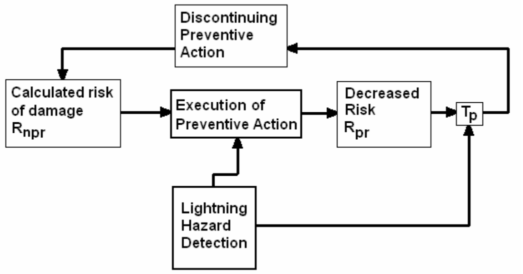

Figure 1. Operation of preventive lightning protection

Explaining Figure 1 shortly; the state when no hazard is present is denoted with a certain risk value (it is calculated as the other risk values in lightning protection) R_{npr}, which is a value representing the "unprotected" state of the object. When the lightning hazard detection gives the signal that hazard is about to develop, then the preventive action is executed (it takes some amount of time to execute it, thus the alarm has to be given earlier enough). It results in the risk of damage to the object to be protected decreasing to the value of R_{pr}. It remains in effect for the duration of the thunderstorm T_p and then it's discontinued, since no hazard is present. The risk of damage is "increased" again to R_{npr} – in reality there should be absolutely no risk of damage due to lightning strike, because the thunderstorm is already far enough. (For further details of this distance, see this section below.)

Using these different risk values only emphasizes that the "state" of the object to be protected changes due to the execution of the preventive action. However if the alarm somehow is not given in time then the R_{npr} value has a very significant meaning, showing that the object is still endangered!

The key features of preventive lightning protection are the following:

- information gathering
- forecasting
- preventive action

The first step in realizing preventive lightning protection is the gathering of the required information. This practically means that information is needed regarding the object to be protected – should it be a special object, or a crowd of people – and the available forecasting methods (meteorological, and lightning detection data).

Various information is required to plan and evaluate the preventive actions, and to choose the used forecasting method. (The planning process can be found in Gulyás et. al. 2007b.)

Further details of preventive lightning protection were published in different articles (Gulyás et. al. 2007a, Gulyás et. al. 2007b, Gulyás et. al. 2007c, Németh et. al. 2007a), these are not discussed in this paper.

The key difference of this method from either primary or secondary protection is that it utilizes not specific protection devices, but focuses on selecting the most appropriate preventive action, and applying it at the right time.

Preventive lightning protection uses so called Danger Zones, and Warning Zones. Earlier works on similar topics (Soulage et. al 2004, Loujou et. al. 2007) concentrate mostly on the usage of forecasting, but preventive lightning protection is focused on the preventive actions rather than the forecasting. Thus a different approach is used when defining the elements of a zonal protection.

The Danger Zone (further on denoted as DZ) is the area around the object to be protected – including its own area – where an active thunderstorm cell means hazard (primary or secondary). Practically when the thunderstorm cell penetrates into this area, the preventive action shall already be carried out.

The Warning Zone is the zone where once a thunderstorm cloud is detected, the preventive action shall be carried out. Signaling can be realized with an alarm system, or automatic operation can be implemented if possible. Since preventive lightning protection mostly serves as a protection method for people being at endangered places rather than sophisticated equipment – exceptions follow – the signaling is mostly carried out by alarming. Multiple WZs can also be used as described in Németh et. al. 2007a, Németh. et. al. 2007b, and Gulyás et. al. 2008 forthcoming.

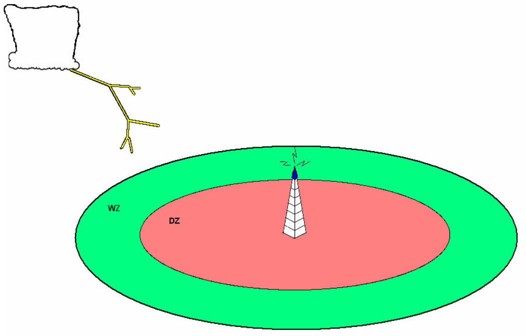

Figure 2. DZ (red) and WZ (green) of an antennae tower

Using the DZ and WZ for the explanations: once the thunderstorm cloud enters the WZ, the preventive action is to be carried out, so when the thunderstorm cloud enters the DZ, the object to be protected is already protected by the preventive action carried out.

2.3 Practical examples

There are numerous practical examples already working, but mostly these applications weren't planned using the preventive lightning protection framework. Thus mostly they are applications of preventive measures rather than actual implementations of preventive lightning protection.

One of these examples is the protection of maintenance workers at the Ostankino TV tower in Moscow (Gorin et. al. 2002). There are corona antennas installed on the tower and in case of increased atmospheric activity, the flowing current increases, and before the actual hazard develops, the workers are moved to safety.

The protection efficiency and cost efficiency (these are discussed later) of this solutions however are still in question, as they can be calculated only empirically.

Another solution is one realized at NASA launch sites (NASA 2006). There are field mills used in a network providing field data around the launch site. From the electrical activity, the activity of the thunderstorm can be approximated (Gunn 1965).

This solution is neither discussed in the scope of preventive lightning protection, but in this case cost efficiency is out of question, and the protection efficiency is maximized.

Nowadays live line maintenance (LLM) is gaining importance in the field of power line maintenance. When doing LLM the workers are transported to the power line, thus they are exposed to certain hazard of primary and secondary effects. Lighting strike to a power line section may have fatal consequences (as there have been, see Németh et. al. 2008b) even if it is kilometers away from the worksite! In Hungary preventive lightning protection is being applied as the protection in LLM.

In this solution the cost efficiency of the protection is very good, since the forecasting is quite accurate, and the protection efficiency is not in question either. The exact definition of these concepts is shown later on. They were mostly used in the common sense in this section.

2.4 Efficiency of preventive lightning protection

The efficiency of preventive lightning protection consists of its protection efficiency and its cost effectiveness. During the planning process this is an optimization problem.

Cost efficiency means that if the preventive action was carried out, then hazard did develop later on (thus protection was necessary). When a lot of the alarms were unnecessary, then also some costs could've been saved, the cost efficiency was low.

Protection efficiency means that the object to be protected was protected by the preventive action. If the actions were carried out when the hazard was already developed, then protection efficiency is high. If there were many late alarms, then protection efficiency is low. This does not mean, that damage was done to the object to be protected. It only means, that the risk of damage to the object to be protected was the "original" R_{npr} value (see Figure 1.). This concept differs significantly from the protection efficiency used in primary and secondary lightning protection.

The actual calculations used in planning protection are aimed at approximating the different efficiency parameters of the solution. In discussing efficiency, the so called "event space approach" is used. It is based on describing which events may occur.

The active thunderstorm cells can be classified hazardous or non-hazardous to the object to be protected.

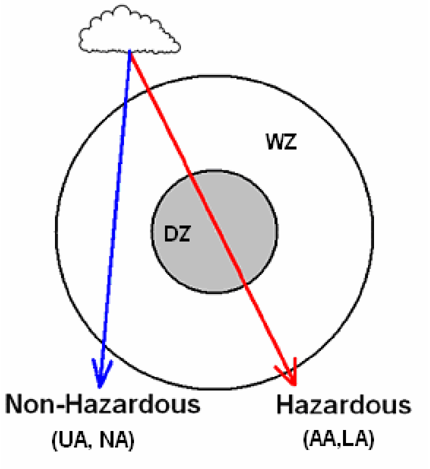

Figure 3. The possible events depending on thunderstorm propagation

There are four events regarding the alarm:

- Accurate alarm, the cloud moves over the DZ, and is detected in time, corresponding probability: p_{aa}
- Inaccurate alarm, the cloud moves over the DZ, but the alarm is not given in time, or the cloud develops above the DZ, corresponding probability: p_{la}
- Accurate alarm, the cloud does not move over the DZ, but an alarm is given by lightning detection, since the thunderstorm touched the WZ, corresponding probability: p_{ua}
- Inaccurate alarm, the cloud does not move over the DZ, but touches the WZ, and no alarm is given because of the lightning detections inaccuracy, corresponding probability: p_{na}

These events form the event space, we suppose, that they cover each possibility of alarming. However one more comment is still necessary. It is quite practical, as shown later, to distinguish between the major cases, when a thundercloud does get over (or propagates over) the DZ, and when it doesn't. The former is denoted by *Hazardous*, and the latter is denoted as *Non-Hazardous* thundercloud. The probabilities, or in this case more like their distribution shall be denoted as p_{haz} and p_{nhaz}.

	Storm is touching the DZ (hazardous)	
	Yes	**No**
Storm is detected (in time)	P_{aa} *(correct)*	P_{ua} *(incorrect)*
Storm is not detected (in time)	P_{la} *(incorrect)*	P_{na} *(correct)*

Table 1. The event space of preventive lightning protection

Table 1 summarizes the possible events with the according probabilities and the operation of the lightning detection system (correct/incorrect).

For the probabilities defined in this section, the followings hold.

$$p_{haz} + p_{nhaz} = 1 \qquad (1)$$

$$p_{haz} = p_{aa} + p_{la} \qquad (2)$$

$$p_{nhaz} = p_{ua} + p_{nal} \qquad (3)$$

These probabilities can be calculated empirically or theoretically. In the planning process (Gulyás et. al. 2007b) the theoretical calculation is the first to be done. The empirical calculation is required to check the theoretical calculations. They are to be updated upon the evaluation of the protection. The calculation of the empirical distributions follow a simple pattern thus giving the possibility of making these calculations based on present data.

$$p_{aa} = \frac{N_{detected}}{N_{all}} \qquad (4)$$

This can be applied to all of the probabilities. More than this, some of these events can exactly be described with simple ratios. The UA (unnecessary alarms) for example means the ratio of the thunderstorms passing through the WZ without touching the DZ, and all of the thunderstorms passing through the WZ. Note that the event space consists only of the thunderstorms detected by a lightning detection system. We assume that all of the thunderstorms are detected.

The event space parameters are calculated using a probabilistic approach (Gulyás et. al. 2007a) giving theoretical values. These values shall be based on some empirical properties (information gathering) and give guideline to the comparison of the different solutions, and the overall efficiency of the solutions. The discussion of these theoretical calculations is not in the scope of this paper.

2.5 Drawbacks of preventive lightning protecttion

As preventive lightning protection is a dynamic method, it is crucial to give alarms in time to have the preventive action executed at the time the hazard develops.

There are some problems with forecasting when the clouds don't propagate towards the DZ when entering the WZ (an unnecessary alarm), or develop in the WZ, thus a late alarm is produced.

These properties are already discussed in the description of the event space, and correspond to the decrease of the cost efficiency, and the protection efficiency.

Other works in the discussion of the forecasting equipment give empirical data to the different forecasting efficiencies of the systems using times rather than zones (Loujou 2007), and they also clearly show that this dynamic approach faces problems especially when thunderstorm clouds develop close, or above the DZ.

Also cost efficiency is decreased, when the preventive action is carried out too early (in effect a thunderstorm cell with low propagation speed enters the WZ), and protection efficiency is decreased, when the preventive action is not carried out in time (a cell with a too high propagation speed enters the WZ).

To account for these effects an improvement of this method is required incorporating a constant monitoring and forecasting of the lightning hazard rather than using static zones to determine if the alarm shall be given.

3. HIGH RELIABILITY PREVENTIVE LIGHTNING PROTECTION

3.1 Definition and operation of high reliability preventive lightning protection

Preventive lightning protection using a constant WZ can be realized and evaluated using the event space approach. If more detailed meteorological and lightning information (VHF, LF) is available then a solution with much higher reliability can be realized, though its cost may be considerably higher. We denote this method further on as High Reliability Preventive Lightning Protection.

There are some specific cases when the static zones mean decrease to the protection or cost efficiency as mentioned earlier. The problem at those cases is that either the propagation direction of the thunderstorm cell is not towards the DZ, or the propagation speed is either too low, or too high yielding a too early, or late alarm.

The individual properties of the different thunderstorm cells are disregarded when using preventive lightning protection with static WZs.

High reliability preventive protection uses continuous monitoring of the thunderstorm cell propagation parameters, thus making individual alarming decisions for each thunderstorm cell.

The propagation parameters to be monitored are the following for each thunderstorm cell:

- propagation direction
- propagation velocity

Monitoring these parameters the criterions for giving an alarm can be summarized with the following two criterions.

- direction condition
- distance condition

The direction condition means that the thunderstorm cloud is heading towards the DZ (and thus the object to be protected). In this case the alarm shall only be given if the thunderstorm cell is close enough to have the preventive action carried out, still far enough to have enough time for the execution of the action. The latter one is denoted as the distance condition.

Summarizing it, if a thunderstorm cell is heading towards the DZ and is close enough, the alarm should be given, and the preventive action is to be executed.

The difference from preventive lightning protection is that this protection method focuses on the individual thunderstorm cells in forecasting rather than just focusing on giving alarm when a thunderstorm cell enters a static area (WZ).

For the implementation of this method constant monitoring of the thunderstorm cells is required along with calculations (shown later). Thus it is far more costly than ordinary preventive lightning protection, when only the area of the WZ is to be monitored, and the alarm is given, when a thunderstorm cell is detected in the given area. These real-time calculations in high reliability preventive lightning protection can be automated.

3.2 Theory of high reliability preventive lightning protection

The goal of this section is to introduce the event space approach (used in preventive lightning protection) into high reliability preventive lightning protection, to make the two methods comparable with each other.

Before discussing the event space model in this case, it's important to define the operation parameters in the theory.

The operation – as described in the previous section – is based on continuous monitoring of each thunderstorm cell, and determining its heading, and propagation velocity.

This can be described by an appropriate $\underline{v}$ vector, which has the direction of the propagation, and a length proportional to the propagation velocity. Thus the direction and distance condition is calculated real time using this vector (which is also recalculated in real time).

The calculation of the vector is based on taking samples of the thunderstorm cell's position in certain time intervals. The cloud is approximated in theory with a circular cloud model – just as it was in preventive lightning protection (Gulyás et. al. 2007a, Gulyás et. al. 2007b, Gulyás et. al. 2008).

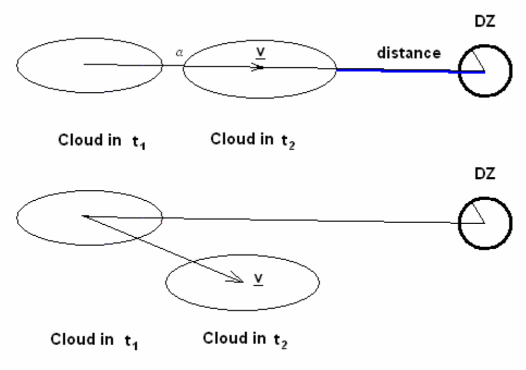

Figure 4. Calculation of the $\underline{v}$ vector

In Figure 4 the calculation of vector $\underline{v}$ is shown. In this figure the cloud can be of any shape (as in reality), and it shows that $\underline{v}$ is calculated taking into account the center point of the geometrical shape a cloud has. (Note that thunderstorm cells can be divided into sections, which are then approximated with circles. In this case the calculation of multiple vectors is necessary.)

The direction condition is determined using the actual vector direction, and the distance condition is calculated by projecting the vector to the points of the perimeter of the cloud. Lengthening it shows if it crosses the DZ, and its length shows the distance of the cloud and the DZ.

Of course one should take the shortest distance as the actual distance between the cloud and the DZ. The distance condition is fulfilled, when the distance is smaller than the critical distance calculated the following way:

$$d_{crit} = r_{DZ} + t_{act} v_{st} \qquad (5)$$

In this expression r_{DZ} denotes the radius of the DZ, t_{act} denotes the time required to execute the preventive action, and v_{storm} is the velocity of the thunderstorm cell.

This expression is similar to that used in preventive lightning protection.

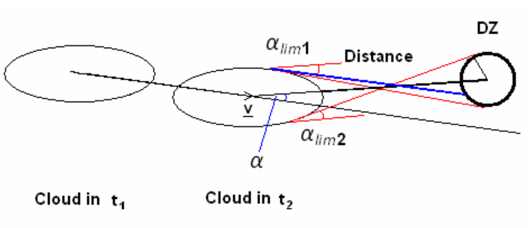

Figure 5. Calculation of the direction condition

Figure 5 shows the calculation of the direction and distance condition as discussed above. The direction condition is fulfilled if the angle of $\underline{v}$ and the baseline between the centre point of the DZ and the cloud is smaller than the given limits (α_{lim1} and α_{lim2} in Figure 5.).

The event space approach is used in high reliability preventive lightning protection, making it comparable with preventive lightning protection. The event space is the following.

	Alarm was given in time	Alarm wasn't given in time
Thunderstorm cell endangers the object to be protected	Accurate alarm - p_{aa}	Late alarm (inaccuracy) - p_{la}
Thunderstorm cell does not endanger the object to be protected	Unnecessary alarm (inaccuracy in data) - p_{ua}	-

Table 2. The event space of high reliability preventive lightning protection

As Table 2 describes, nearly the same events are defined as there were in preventive lightning protection. The event "no alarm" had no significant meaning in preventive lightning protection, and thanks to the different method, it does not even occur in high reliability preventive lightning protection.

The most significant difference between the two methods is that the event space parameters change with time.

The position of the thunderstorm cell is obtained in a time interval (denoted from now on as sampling period), and with the new information, the vector $\underline{v}$ changes, and shall be recalculated.

Theoretically if the detection is accurate, then only the accurate alarms and late alarms could occur. Late alarms would occur if the thunderstorm cell develops near the DZ.

But practically the points which are used upon the calculation of $\underline{v}$ aren't always calculated accurately.

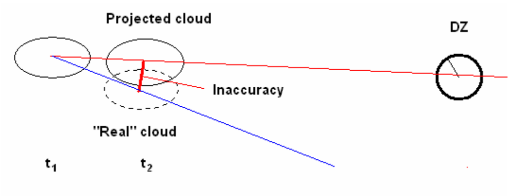

Figure 6. Miscalculation of $\underline{v}$

Figure 6 shows the effect of the miscalculation of the end point of $\underline{v}$. It may yield in either unnecessary alarms decreasing cost effectiveness, or late alarms decreasing protection efficiency.

The event space parameters thus can be only used to compare the individual solutions, when one has an idea about the accuracy of the detection. Further on it is assumed that the accuracy of detection can be measured with a circle having a radius of r_{acc} around the calculated center point of the cloud from which the vector $\underline{v}$ is calculated.

The next calculation is only an outline of the calculations. The calculation of all of the event space parameters requires complex numerical methods, which are not in the scope of this paper. The next calculation shows taking into account the miscalculation of the direction condition only.

The circular cloud model is used in the next calculation, and it is also assumed that the starting point of $\underline{v}$ was determined accurately, and that the direction condition is fulfilled.

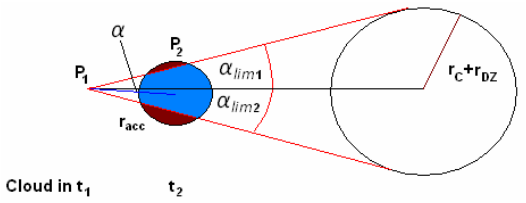

Figure 7. Calculation of the event space parameters (simplified)

The position of the cloud is calculated in t_1 and t_2 giving the two points (P_1 and P_2) producing vector $\underline{v}$. It is assumed that P_1 was determined accurately, but P_2 is in the circle with the radius of r_{acc}. The angle of $\underline{v}$ and the line connecting the center point of the DZ and P_1 is denoted with α.

The two angles indicated in Figure 7. are not the same as those shown in Figure 5. They mean the same condition, but still are different, because the approach discussed using Figure 7. includes some simplifications. The latter angles are also the limits, but they can be calculated from P_1.

As it is shown in Figure 7, if P_2 is in the blue portion of the circle, then the direction condition is fulfilled, and the alarm shall be given (if it wasn't already given!).

If P_2 is in the red area of the circle, then giving the alarm would lead to an unnecessary alarm (or if it was given then it was unnecessary.

If we assume that the distribution of P_2 is flat along the circle, than the probability of an unnecessary alarm is easily calculated taking into account the inaccuracy of the detection.

The method of the calculation is a simple geometrical probability calculation.

$$p_{ua} = \frac{T_{c1}}{r_a^2} \qquad (6)$$

In this expression T_{c1} and T_{c2} denotes the areas where if P_2 falls, the alarm is unnecessary. The calculation of these areas is quite complicated, and this shows why numerical methods are more productive.

$$T_{c1} = r_{acc}^2 \pi \cos^{-1} \frac{|v| \sin(\alpha_{lim1} - \alpha)}{r_{acc}} - \\ - \sqrt{r_{acc}^2 - (|v| \sin(\alpha_{lim1} - \alpha))^2} * \\ * (r + \sqrt{r_{acc}^2 - (|v| \sin(\alpha_{lim1} - \alpha))^2})$$

(7)

$$T_{c2} = r_{acc}^2 \pi \cos^{-1} \frac{|v| \cos(\alpha_{lim2} - \alpha) \tan \alpha_{lim2}}{r_{acc}} - \\ - \sqrt{r_{acc}^2 - (|v| \cos(\alpha_{lim2} - \alpha) \tan \alpha_{lim2})^2} * \\ * (r + \sqrt{r_{acc}^2 - (|v| \cos(\alpha_{lim2} - \alpha) \tan \alpha_{lim2})^2})$$

(8)

There are some much simpler approximation methods to the event space parameters, but they only hold with certain simplifications, thus have only limited usage. With the computing capabilities nowadays available, the numerical solution is much easier.

When introducing the concept that even P_1 was not calculated correctly (which is closer to reality), the expressions get even more complicated, as (7-8) do not hold anymore. Instead, they are to be calculated to each possible P_1 locations. Summarizing the expression in one simpler form giving a guideline for the calculation:

$$p_{ua} = \frac{1}{r_{acc}^2 \pi} \int (T_{c1}(P_1) + T_{c2}(P_1)) \, dP_1 \qquad (9)$$

But this expression also only applies if the circular model is used. Formulas for various shapes can be given but are not in the scope of this paper. (In (9) the integral by P_1 is calculated in a circular area around the original P_1, just as in case of P_2.)

4. Conclusions

This paper introduced high reliability preventive lightning protection along with giving a short theoretical summary to the concept of preventive lightning protection.

The dynamic solution of lightning protection, preventive lightning protection was described, focusing solely on the theoretical approaches and giving only short description of the practical examples.

The drawbacks of that method were shown, and its improved version, high reliability preventive lightning protection was introduced. It is an even more dynamic method than preventive lightning protection, but yields better protection, and requires more complicated calculations to evaluate – which shall be mostly numerical calculations opposed to the calculations of preventive lightning protection.

These two methods are entirely based on the availability of real time lightning data, and meteorological data. They differ from the other forecasting based methods proposed in focusing on the preventive action and planning the forecasting according to it. Both methods are the most accurate and effective, if total lightning data (Loujou et. al. 2007) is available.

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