PROTECTION OF OVERHEAD LINES WITH METAL-OXIDE ARRESTERS

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Abstract – **The paper is focused on the lightning protection of overhead lines using Metal Oxide Arresters (MOA). Among many different possibilities to equip a line with arresters, the case of an overhead line without earth wire was studied, using the ATP code. Considering both the lighting stroke on the tower and on the phase conductor, the outage number reduction for the entire line is presented for different distributions of protected towers along the line. The influence of tower foot resistance is also shortly presented. The main conclusion derived from this study is that the flashover probability decrease is not linear dependent on the share of the protected tower.**

Keywords: *lightning, partial protection, overhead lines without earth wire, flashover likelihood.*

1. INTRODUCTION

MOA utilization to improve the lightning behavior of overhead lines becomes, in the last decades, a spread enough method [1]. Lines equipping with arresters is favorable both for the new designed lines and for those in operation. If the tower foot resistances are too high, the earth wire efficiency strong decreases, but the arresters presence may compensate this effect. Also, the arresters presence may become extremely efficient in the zones with high frequency of lightning phenomena or at the higher towers like that used for crossing rivers, roads or other lines.

For the new designed lines, the advantages of MOA utilization can be better exploited, for example by eliminating the earth wires, completely or partially. More than that, considering the temporary and switching overvoltages decreasing as consequence of arrester presence, a line compactization possibility may result. Adding the outage number reduction of the protected line, these three positive effects may justify the arresters cost.

There are some differences concerning the MOA protection effect on the lines by comparison with its operation in substations. Thus, in substations, the arresters are connected directly between the phase conductors and the earth grid and installed on its own supports. As consequence, the same earth grid potential is applied to all three phases' insulators of an equipment or busbar system.

On the line, the arresters are mounted on the upper side of the towers, in parallels with insulator strings, what means that the arresters earth connection is realized through the tower column. The lightning current, which passes through the the tower, determines a distribution of potential along it and different potentials at the tower arm ends where the insulator strings are fixed. This distribution is influenced both by tower inductivity and foot resistance.

The protection effect is real for a limited distance from the arrester, around 100-150 m, along the current path. That distance is sufficient for a substation but is not in the case of an overhead line because the distance between towers is greater than that.

The line can be entirely protected only if all the towers are protected with MOA on all phases. Such a solution was never applied because the costs are too high.

There are a lot of possibilities to install MOA on the line: on all the phases but at a limited number of towers; only on one or two phases at every tower or at some towers.

The solution of protection with MOA for one or two phases was studied Zanetta L.C. a.o. [2] for the case of an overhead line with horizontal disposal the three phases, but having only one earth wire asymmetrically arranged. Thus, one of the phase conductors was more exposed to lightning strokes.

Another application was to equip with MOA only the upper phase of a line without earth wire [3]. Such protected, this phase took over the function of an earth wire without the risk of insulation flashover for it.

Some of the possibilities to protect the overhead lines with MOA were studied by the authors too. For example, in [4] the influence of impulse front time and tower foot resistance on the critical current were analyzed for a line without earth wire and equipped with MOA on one or two phases.

The influence of MOA parameters on the critical current amplitude as the thermal stress for the line arresters were examined in [5]. The main result was that the line arresters residual voltage influences in an insignificant measure both critical current amplitude and thermal stress.

The object of this paper is to analyze the behavior of partially protected lines, with MOA on all the three phases but for different shares of the protected towers. Because the earth wire absence thanks to MOA presence represents an important economic advantage, this type of line was considered.

2. OVERHEAD LINE MODEL

The present study was carried out for a single circuit 110 kV line without earth wire and with a phase conductor's disposal in the corners of a triangle with horizontal base.

For the line, the traveling waves ATP model was adopted [5]. The line model is organized in three sections: the middle section with 10 spans of 200 m each and 11 towers and two side sections of 20 km length. These side sections are necessary to avoid the influence of the reflected waves from the two ends of the line.

The lines towers were modeled as mixed circuits: inductivities for the upper side and o line with distributed parameters for the column. The non-linear resistance of MOA was represented as a broken line. Because the insulation flashover level depends on the front duration of the applied voltage, the time-voltage characteristic of the insulator strings was taken into account. Such a curve, determined especially for a 110 kV insulator string was not available so was estimated according to the method proposed in [6].

Thus, if U_{50} is the minimum impulse flashover voltage according the distance between string ends, the time-voltage equation is

$$u(t) = U_{50}\sqrt{1+\frac{k}{t}}\ , \tag{1}$$

where

$$k = \left[\left(\frac{U_0}{U_{50}}\right)^2 - 1\right]T_0\ . \tag{2}$$

U_0 is the flashover voltage at the moment $T_0 = 2$ µs; those value depends on the length of the insulator string. For example, if the insulator has 7 cape-pin units, then U_{50} = 650 kV and l = 1.2 m. The resulting values are U_0 = 797 kV and k = 1.007. The time-voltage has the shape in figure1.

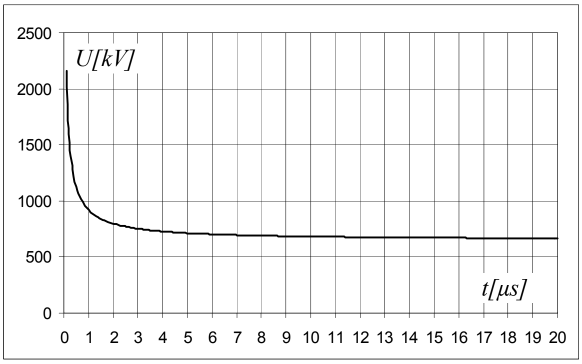

Figure 1: Voltage-time characteristic of the insulator string

The impulse current was generated by a current source and injected in the tower top or in the upper conductor at midspan.

3. LIGHTNING STROKE ON THE TOWER

If arresters are installed at a single tower on all the three phases, the insulator flashover is avoided at that tower, but it will happen at the next tower, but for a greater amplitude of the lightning current than when the arresters are missing. If more towers are so equipped, the insulation flashover will appear at the first unprotected one, and the critical current will be so greater so much protected towers exists between the hit tower and the first unprotected one. This way, the critical current may increase until the flashover likelihood will become so much reduced to be negligible. Table 1 presents some simulation results for such situations. Tower no. 6 is situated in the middle of the line model; the others tower are the next both sides.

MOA on R, S, T phases at towers no.:	Lightning stroke on the tower no.:	Critical current amplitude [kA]	Insulation flashover at tower/phase
without MOA	6	21,25	6/R
6	6	33,9	5/ R
	5	21,25	
5,6,7	6	76,3	4/R
	5	33,9	
	4	21,25	
4,5,6,7,8	6	157	3/R
	5	76,3	
	4	33,9	
	3	21,25	

Table 1: Lightning stroke on the tower top. Critical current amplitudes for MOA on all phases at some towers

If the lightning strikes a tower protected with MOA on all three phases and the earth wire is missing, a fraction from the impulse current which flows through the tower is derived through the arresters to all the phase conductors. Each conductor will acquire a potential that is equal to the tower arm potential subtracted with the residual voltage of the arrester. Because the tower arm potential is not the same for all the three phases, the conductor potentials are not equal, too. This conductor potential determines an insulation direct flashover at the first unprotected tower.

If the lightning strikes an unprotected tower, the arresters on the neighboring tower, if any, have an insignificant influence on the critical current, because there is no path for the impulse current from the stroked tower to the conductors. If a back flashover happens at the stroked tower, a fraction of the lightning current will flow through the arrester on the affected phase to the protected tower and other back flashover can appear at that tower. That is not important for the line outage probability because the first flashover is sufficient to disconnect it.

When the lightning strikes the tower, the insulation flashover happens only on the upper phase (phase R) because the tower arm potential for this phase is greater than for the others.

The results in Table 1 show that the flashover probability becomes negligible if at least two protected towers exist between the protected stroked tower and the first unprotected one.

The efficiency of line partial protection with MOA installed on all three phases at some towers can be evaluated knowing the critical current change comparatively with the values for the same line, without MOA (Table 1).

Thus, if one notes with 1 p.u. the flashover probability for the completely unprotected line, this probability decreases to:

- 0.7 p.u. if the unprotected tower is the next from the protected stroked tower;
- 0.21 p.u. if another protected tower exists until the first unprotected one;
- 0.02 p.u. if two protected towers separate the stroked protected tower from an unprotected one.

Figure 2 shows, in p.u., the diminution of flashover probability as consequence of lightning strokes on the line towers, for different situations regarding the line protection with MOA. The flags on the curves indicate the number of consecutive protected towers, while on the horizontal axis is marked the number of unprotected towers what exist between two groups of protected ones. All the possibilities of lightning stroke on towers were considered, that means those for what the flashover probability at the unprotected towers are different.

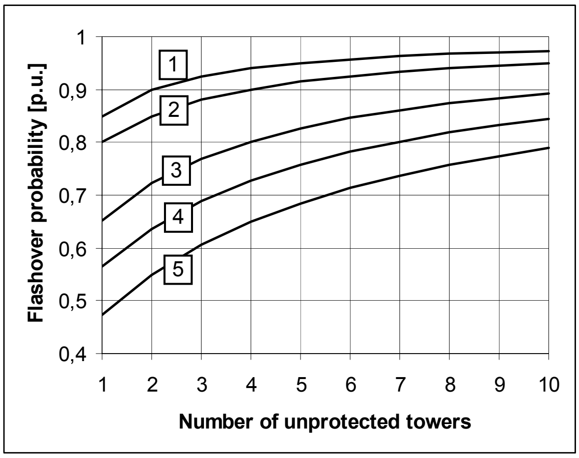

Figure 2: Flashover probability reduction by MOA when the lightning strikes the tower

According with the quantity of protected and unprotected towers in fig.2, the share of protected towers for the entire line length in presented in fig.3.

One may observe that the same flashover probability diminution can be obtained for different modes of line equipping with arresters. For example, to acquire a flashover probability of 70% in comparison with the unprotected line, three possibilities to install the MOA can be used:

a) Groups of 3 protected towers, followed by groups of 2 unprotected ones that mean a share of 60% protected towers;

b) Groups of 4 protected towers, followed by groups of 4 unprotected ones, that means a share of 50% protected towers;

c) Groups of 5 protected towers, followed by groups of 6 unprotected ones that mean a share of 45% protected towers.

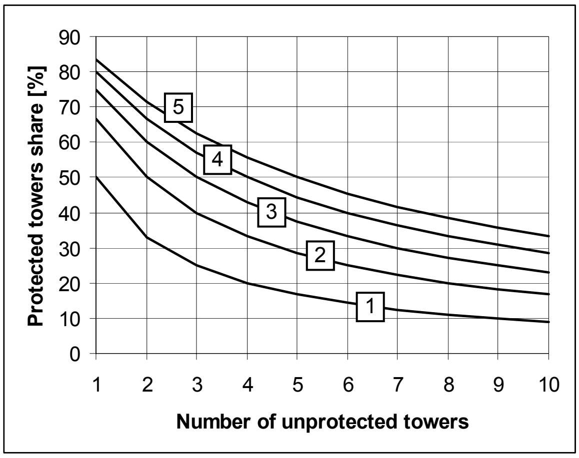

Figure 3: Protected towers share in the line

The diminution of the flashover probability is greater as the share of protected towers increases. However, this diminution is not so important as one expect even if the number of unprotected towers is very small. The curves in fig.2 will reach 0 flashover probability only when the unprotected towers groups have 0 member.

4. LIGHTNING STROKE IN PHASE CONDUCTORS

When the lightning hit a phase conductor, the lightning current propagates on the line in both directions and the conductor potential increases until the flashover condition is fulfilled. The corresponding current amplitude is much smaller than that induces a back flashover when the lightning strikes the tower.

If some MOA exist on the line, a fraction of the impulse current flows towards towers, through arrester non-linear resistances, thus the critical current amplitude increases by comparison with an unprotected line.

The results of a set of simulations for the case of lightning stroke on the upper phase (R) are shown in Table 2. All the line towers unmentioned in the first column of this table are unprotected.
The insulation flashover happens on the stroked phase at the nearest unprotected tower from the impact point. If, both sides from the impact point, the line towers are protected with arresters, the amplitude of the critical current increases as much as more protected towers exists until an unprotected one.

MOA on R, S, T phases at towers no.:	Lightning stroke between the towers no.:	Critical current amplitude [kA]	Insulation flashover at tower/phase
without MOA	6-7	3,25	6/R
6	6-7	3,7	5/R
6,7	6-7	19,2	5/R
	5-6	3,75	
5,6,7	5-6	18.9	4/R
	4-5	3.75	
5,6,7,8	6-7	46,2	4/R
	5-6	19.1	
	4-5	3,75	

Table 2: Lightning stroke on the upper phase conductor. Critical current amplitudes for MOA on all phases at some towers

If the quantity of protected towers is not the same both sides from the impact point, the critical current amplitude will correspond to the smaller distance until the first unprotected tower. The contribution of the greater number of arresters on the opposite side of the lightning impact point has a very little importance on the critical current amplitude.

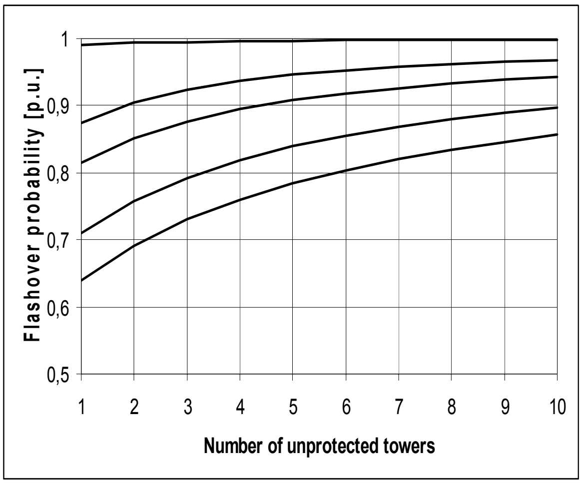

Figure 4: Flashover probability reduction by MOA when the lightning strikes a phase conductor

Using the same method to evaluate the insulation flash-over probability cut depending on the MOA distribution along the line, as for the lightning stroke on the tower, one obtain the curves in figure 4. The significance of variables and curves flag in figure 2 and figure 4 are the same.
A comparison between curves in figure 2 and figure 4 shows that for the same distribution of arresters on the line, the flashover probability cut is smaller for the lightning stroke on the phase conductor than on the tower top.

5. OVERALL LINE PROTECTION EFFICIENCY

The entire number of lightning strokes on the overhead line is divided between towers and conductors depending on the ratio of the span length to the tower height. Because the arrester efficiency is not the same when the lightning strikes the tower or the conductors, the strokes distribution between those must be taken into account. As greater is the span length as smaller will be the MOA influence on the line outage number owing to the greater number of lightning strokes on the conductors. Thus, for the 110 kV line some 70% of the lightning strokes reach the towers and 30% reach the conductors. As consequence, the overall reduction of the flashover probability is that shown in figure 5.

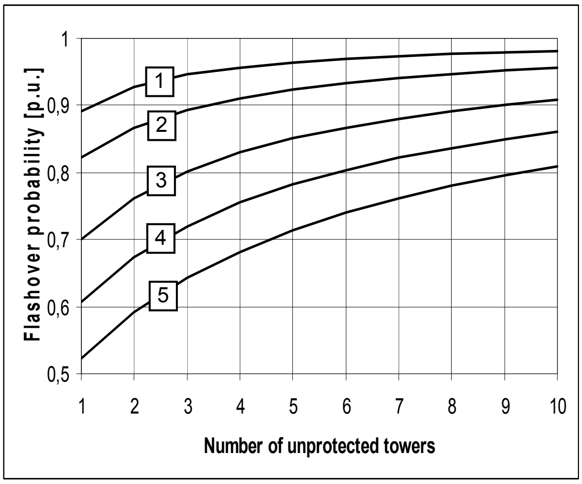

Figure 5: Overall effectiveness of line protection with MOA

These results are not too encouraging to adopt the method of line equipping with MOA instead of earth wire. From the number of possibilities used in this study, the greatest protection efficiency, that means a flashover probability cut to almost 50%, can be obtained when between groups of five protected towers exists only one unprotected one. In other words, an arresters share of 83 % can reduce the line outage number to half comparatively with the same unprotected line.
Because the non-linear dependence between these factors, a subsequent growing of the arrester share

with 17% will reduce at zero the line outages number. Such reasoning has the shortcoming to be limited to a singular aspect, namely the technical consequence of line outage probability was obtained for a particular set of parameters concerning the impulse current shape and tower foot resistance.

The choice of a solution to protect an overhead line with arresters must consider the economical aspect too, that means the supplemental costs and the reduction of some costs by comparison with the unprotected line. The supplemental costs refer mainly to the arresters stand alone and its armatures. The costs cut-off derive from the line outage number decrease as from tower dimensions reduction as consequence either of earth wire elimination or of internal overvoltages diminution.

This study has more a theoretical importance concerning the way to evaluate the efficiency of the arresters mounted on an overhead line to protect it against lightning. The presented results were obtained for an impulse front duration of 2 μs front and 20 Ω for the tower foot resistance.

Such an analysis can be extended to a set of these parameters values. Figure 6 shows an example of possible results obtained for the same line as above in the case of lightning stroke on the single protected tower. As reference, to represent the flashover probability in p.u. values, were considered the critical current amplitudes for the same line without any arrester, but for the same values of the impulse front time and tower foot resistance.

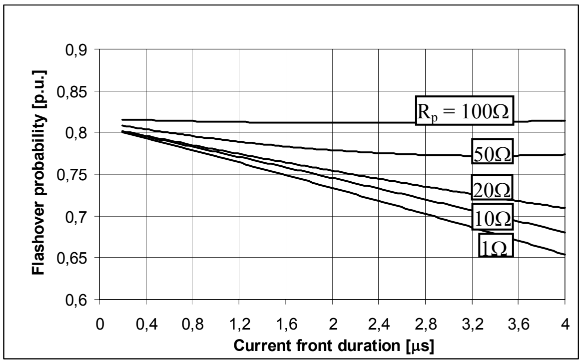

Figure 6: Influence of some factors on the insulation flashover probability.

The information in figure 6 is sufficient to evaluate the overall efficiency of line protection with arresters only for the case when the group of protected towers consists in a single tower.

However, one may observe that as the tower foot resistance greater is, the lightning current shape has a smaller importance for the change of the flashover probability. The impulse front duration increasing induces a flashover probability reducing and a growing for the critical current amplitude. Also, the influence of changes in tower earth resistance is more important for longer impulse front time. For shorter impulse front time, prevails the effect of tower inductivity, that opposes to the impulse current flow as much as greater is its front slope.

6. CONCLUSIONS

The analysis presented in this paper refers to MOA efficiency on an overhead line without earth wire, separately for the lightning stroke on the towers or on the phase conductors. Different distributions of protected towers on all the three phases were considered.

The main conclusions are:

- the arrester efficiency is greater if the lightning strikes on towers than on phase conductors;
- although the insulation flashover does not happen at a protected tower, it will happen at an unprotected ones, so the outage number reduction is smaller than the share of the protected towers in the line;
- the substitution of the earth wire with line arresters seems to be not so favorable as expected, at least when the tower foot resistances are in the normalized limits.

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