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LIGHTNING PERFORMANCE OF HIGH VOLTAGE TRANSMISSION LINES PROTECTED BY SURGE ARRESTERS: A SIMULATION FOR THE HELLENIC TRANSMISSION NETWORK

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Abstract - Lightning strikes to overhead transmission lines are a usual reason for unscheduled supply interruptions in the modern power systems. In an effort to maintain failure rates in a low level, providing high power quality and avoiding damages and disturbances, plenty of lightning performance estimation studies have been conducted and several design methodologies have been proposed. The protection of overhead transmission lines is achieved using shield wires and surge arresters. Surge arresters should be insulators at any voltage below the protected voltage, and good conductors at any voltage above, to pass the energy of the lightning strike to ground. In this work an analysis of the lightning performance of 150kV transmission lines of the Hellenic interconnected system is presented, using Simulink and data collected by the Hellenic Public Power Corporation S.A. The lines are divided into regions each of them has different keraunik level, length and tower footing resistance. All the lines are protected with shield wires and in the current simulation surge arresters are implemented on every tower or in a given step. The installation of surge arresters improves the lightning performance of the line. The simulation results are compared with real recorded failure rates, provided by the Hellenic Public Power Corporation S.A., and show that shield wires combined with surge arresters in every tower is the best protection against lightning overvoltages. By increasing the tower footing resistance, the lightning failure rate becomes greater, especially when the line is protected only with shield wire. Additionally, smaller arresters intervals decrease the failure rate. The results of the current work could be useful for the maintenance and the design of transmission lines in the Hellenic System.

1 INTRODUCTION

Protecting overhead transmission lines against lightning strokes is one of the most important tasks to safeguard electric power systems, since lightning is a usual cause of faults in overhead lines. The protection of the lines is achieved using shield wires and surge arresters. Shield wires are grounded conductors placed above phases, to intercept lightning strokes, so they cannot directly strike to phase conductors. In order to avoid backflashover, low tower footing resistance is demanded. Surge arresters installation improves the lightning performance of the lines, reducing the outage rate. A surge arrester presents a momentary path to earth, which removes the superfluous charge from the line. The most common types of arresters are the open spark gaps, the SiC arresters with spark gaps and the Metal Oxide surge arresters without gaps. The last type, which is composed of non linear resistors of metal oxide, mainly ZnO without spark gaps, is today the most common used [1].

The last decades several methodologies and software tools have been presented in the technical literature in order to evaluate the lightning performance of high voltage transmission lines. These are extended from analogue computer methods [2], Monte Carlo techniques [3], traveling wave methods [4] and simulation software tools [5, 6] (e.g. EMTP, PSCAD, Pspice, Simulink, etc.) to more modern and sophisticated methods such as artificial neural networks (ANN) [7], which have been effectively implemented the last years in almost every power systems' problem [8-10]. In this work an analysis of the lightning performance of 150 kV transmission lines of the Hellenic interconnected system is presented, using Simulink & MATLAB and recorded data collected from the Hellenic Public Power Corporation S.A. The obtained results show clearly that the use of surge arresters can reduce significantly the lightning faults and their use can improve the lightning performance of them.

2 TRANSMISSION LINES AND ELECTROGEOMETRICAL MODEL

When lightning hits a phase conductor of a transmission line, the total lightning current (I) is divided, and half of the current will go in each direction. This stroke is confronted with the characteristic impedance (Z) and the resulting voltage is $1/2 \cdot I \cdot Z$. When lightning strikes the tower structure or overhead shield wire, the lightning discharge current, flowing through the tower and tower footing resistance, produces potential differences across the line insulation. If the line insulation strength is exceeded, flashover occurs, i.e. a backflashover. Since the tower voltage is highly depended on the tower resistance, it follows that footing resistance is an extremely important factor in determining lightning performance [11].

Fig. 1 shows a typical tower of a 150 kV transmission line of the Hellenic system and Table 1 gives the characteristics of the line that are examined in the current work.

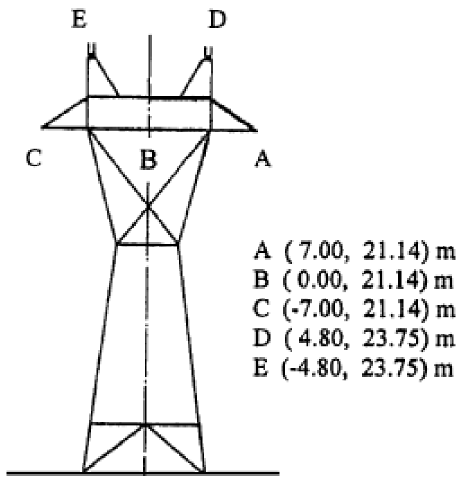

Fig.1 - Typical tower of a 150kV transmission line of the Hellenic system

Table 1: Line characteristics of the analysed transmission lines

No.	Line	Voltage (kV)	Length (km)	No. of Towers	Insulation Level (kV)	Conductor Dimensions (ACSR MCM)	No. of Circuits
1	Volos - Lafkos	150	35	90	750	336.4	1
2	Ioannina - Kalpaki	150	28	86	750	336.4	1
3	Pyrgos - Megalopoli	150	70	179	750	336.4	1
4	Aktio-Argostoli	150	81	224	750	336.4	1

The termination point of a lightning stroke to a transmission line can be either a shielding wire, phase conductor, tower or even ground. The electrogeometrical model using the concept of striking distance has got the ability to determine the termination point. In general, the striking distance *r* in m is given by the equation:

$$r = A \quad I^b \qquad (1)$$

where:

A and *b* are constants dependent on the termination point and

I is the prospective stroke current in kA.

Although there are several versions of electrogeometrical model, where each one uses different values for the constants *A* and *b*, all of them consider the following three concepts: a) strokes arrive vertically, b) the lightning leader develops unaffected by the existence of grounded objects until it arrives within striking distance from the grounded object and c) the striking distance is related to the current of the return stroke. In this study the electrogeometrical model proposed by IEEE Working Group [12] was used in the calculations.

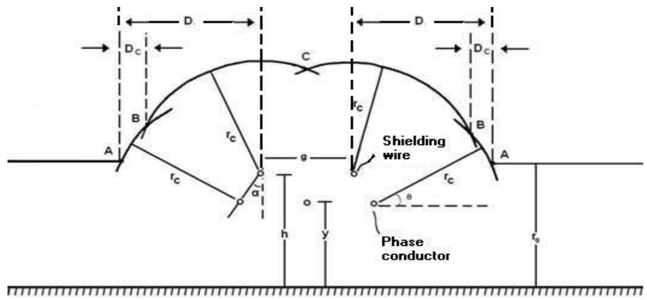

Fig. 2 - Electrogeometrical model: representation of shielding wires and phase conductors

The probabilities $h_A(I_P)$ and $h_B(I_P)$ that the lightning strikes a phase conductor or the overhead ground correspondingly, can be estimated for each value of the peak current I_P using equations (2) and (3):

$$h_A(I_p) = \frac{D_C}{D} \quad (2)$$

$$h_B(I_p) = \frac{D - D_C}{D} \quad (3)$$

where:
D_c is the shielding failure exposure distance shown in Fig. 2 and
D is the vertical distance between the shielding wire and the intersection point A.

3 SURGE ARRESTERS

Surge arresters (or lightning arresters or surge diverters) are installed on transmission lines between phase and earth in order to improve the lightning performance and reduce the failure rate. Surge arresters are semiconductors with non-linear resistance from a few Ω to several MΩ. Several different types of arresters are available (e.g. gapped silicon carbide, gapped or non-gapped metal-oxide) and all perform in a similar manner: they function as high impedances at normal operating voltages and become low impedances during surge conditions. Even though a great number of arresters which are gapped arresters with resistors made of silicon-carbide (SiC) are still in use, the arresters installed today are almost all metal-oxide (MO) arresters without gaps, something which means arresters with resistors made of metal-oxide [13]. An ideal lightning arrester should: (i) conduct electric current at a certain voltage above the rated voltage; (ii) hold the voltage with little change for the duration of overvoltage; and (iii) substantially cease conduction at very nearly the same voltage at which conduction started [14].

The main characteristics of a surge arrester are [15]:

- maximum continuous operating voltage (MCOV), which must be greater than the maximum network operating voltage with a safety margin of 5 %;
- rated voltage, which must be1.25 x MCOV;
- protection level;
- capacity to withstand the energy of transient overvoltages

The lightning energy E (in Joules) absorbed by an arrester is computed by the relation:

$$E = \int_{t_o}^{t} u(t) \cdot i(t) dt \quad (4)$$

where:
$u(t)$ is the residual voltage of the arrester in kV and
$i(t)$ is the value of the discharge current through the arrester in kA.

When the absorbed energy by the arresters exceeds their maximum acceptable level of energy, then they will fail (damage). Assuming that surge arresters are the last protection measure of a transmission line, an arrester failure is considered as a line fault. The arresters' failure rate is given as [16-20]:

$$FR = N_g L \left[\int_{T_t}^{\infty} \left\{ \int_{I_A(T_t)}^{\infty} f(I_P) \cdot h_A(I_P) dI_P \right\} g(T_t) dT_t + \int_{T_t}^{\infty} \left\{ \int_{I_B(T_t)}^{\infty} f(I_P) \cdot h_B(I_P) dI_P \right\} g(T_t) dT_t \right] \quad (5)$$

where:

$I_A(T_t)$ is the minimum stroke peak current in kA required to damage the arrester, when lightning hits on a phase conductor, depending on each time-to-half value,

$I_B(T_t)$ is the minimum stroke peak current in kA required to damage the arrester, when lightning hits on the overhead ground wire, depending on each time-to-half value,

$f(I_P)$ is the probability density function of the lightning current peak value,

$g(T_t)$ is the probability density function of the time-to-half value of the lightning current,

FR is the arrester total failure rate,

N_g is the ground flash density in flashes per km^2 per year and

L is the line length in km.

4 EXAMINED LINES AND COMPUTATIONS

The Hellenic electrical transmission network runs at the same time through plain regions, mountainous regions and coastlines, so the estimation of lightning performance is significant in order to take the appropriate decision during the design and maintenance of the lines. In Table 2 are given the parameters of the analyzed transmission lines. The lines are divided into regions due their different characteristics through their length. None of these lines is protected with surge arresters in fact, and purpose of this work is to examine the improvement of the lighting performance of these lines after arresters implementation.

Table 2: Line design parameters of the analysed transmission lines

Line	Region	Towers	R (Tower footing resistance in Ω)	N_g (Average ground flash density 1997-2002)
Volos - Lafkos	I	1-17	9.8	1.38
	II	18-40	5.1	2.07
	III	41-90	10.4	3.24
Ioannina - Kalpaki	I	1-40	4.2	4.04
	II	41-86	25.8	3.16
Pyrgos - Megalopoli	I	1-66	6.2	2.74
	II	67-124	10.8	2.08
	III	125-179	14.5	2.57
Aktio-Argostoli	I	1 - 55	4.8	3.54
	II	56 - 137	64.9	3.25
	III	138 - 224	126.3	2.77

There are numerous widespread commercial software tools used for power systems simulation, such EMTP, PSCAD, Simulink, etc, which give a graphical representation and transient analysis of the systems. In the current work Simulink was used, which additionally has programming advantages [21].

The waveform of the lightning surge has been produced by a double exponential wave. The time to crest value is constant at 2μs, since its influence is negligible in comparison with the time-to-half value, which is varied. The frequency distributions and the parameters of the lightning current are based on the measurements performed by Berger in Monte San Salvatore [22].

The transmission lines were represented by a distributed parameter line model, which is based on the Bergeron's travelling wave method used by the EMTP and represents wave propagation phenomena and line end reflections efficiently. The surge impedance values are 400Ω for phases and 700Ω for ground wires. The towers are represented as distributed parameters lines 200Ω. Fig.3 represents an equivalent circuit for a one phase conductor.

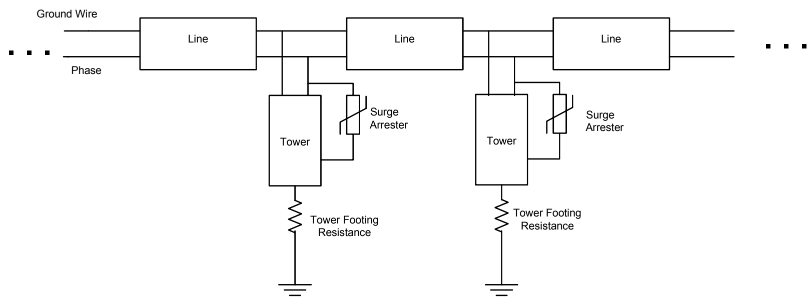

Fig.3 - Equivalent circuit for one phase conductor

In the case of lightning stroke on ground wire, the flow of the lightning current to earth causes an increase on the potential of the metal structure, which when reaches the critical flashover voltage a backflashover occurs. The dielectric strength of the insulator was represented as a voltage-controlled switch (Fig.4). When the voltage U exceeds the critical flashover voltage the switch closes.

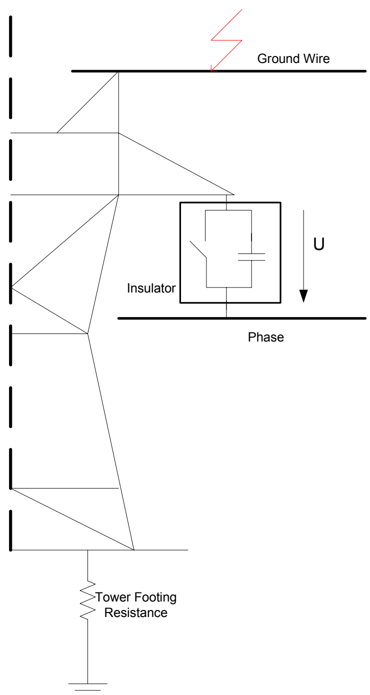

Fig.4 – Insulator string representation

The arresters that are used in this simulation have a rated voltage of 144kV, nominal discharge current 10kA, discharge energy class 3 and withstand energy capability 8kJ/kV MCOV. Arresters with these characteristics are used by the Hellenic Public Power Corporation S.A. for the substation protection. It must be mentioned that the Hellenic Public Power Corporation S.A. does not use arresters for line protection. In the simulation surge arresters are installed on all phases and are examined three cases: Case 1 arresters on every tower, Case 2 arresters on every second tower and Case 3 arresters on every third tower.

The waveforms of the arresters' terminal voltage and the current flowing through them – taken by Simulink simulation – are used in order to calculate the energy dissipated by the arresters, which when exceeds the arresters energy capability, fault is occurred. The arresters failure rate is computed using Eq. (5); in order to find the minimum stroke currents for each time-to-half value $I_A(T_t)$ and $I_B(T_t)$, which required for the arresters' failure, an arithmetic method programmed in Matlab is used [17]. Considering a stroke on phase or on ground wires, for each time-to-half value is calculated the lighting current that damages the arresters, with a time-to-half range 10μs to 1000μs and step 1μsec.

5 RESULTS AND DISCUSSION

In table 3 are presented the recorded transmission lines' lightning failures in comparison with the obtained surge arrester failure rates for each one of the analyzed cases, considering arresters failures as line faults. The results show that the use of surge arresters improves the lightning performance of the lines and reduces the line outages.

Table 3: Field observation data versus obtained results for years 1997-2002

Line	Region	Average recorded failure rate without arresters*	Computed Failure Rate for Case 1	Computed Failure Rate for Case 2	Computed Failure Rate for Case 3
Volos - Lafkos	I	0.1	0.051	0.060	0.072
	II	0.6	0.082	0.104	0.109
	III	0.9	0.385	0.453	0.523
	Total	**1.6**	**0.519**	**0.617**	**0.704**
Ioannina - Kalpaki	I	0.5	0.102	0.163	0.197
	II	1.0	0.449	0.527	0.570
	Total	**1.5**	**0.551**	**0.690**	**0.767**
Pyrgos - Megalopoli	I	1.0	0.279	0.345	0.376
	II	1.7	0.412	0.478	0.532
	III	2.4	0.582	0.721	0.803
	Total	**5.1**	**1.273**	**1.544**	**1.711**
Aktio - Argostoli	I	0.5	0.256	0.304	0.331
	II	2.4	1.690	1.842	2.032
	III	3.9	2.562	2.638	2.758
	Total	**6.8**	**4.508**	**4.784**	**5.121**

The graphic representation of the results in Fig.5 gives a sense of the expected improvement of the lightning performance of each line. The lightning performance of the lines and the computation of the outage rate were determined for different arresters location and for regions with different tower footing resistances and ground flash densities. Surge arresters installation on every tower gives the best protection, especially for regions with high tower footing resistance. When tower resistance is low enough, arresters protect sufficiently the lines, even if are installed on every three towers.

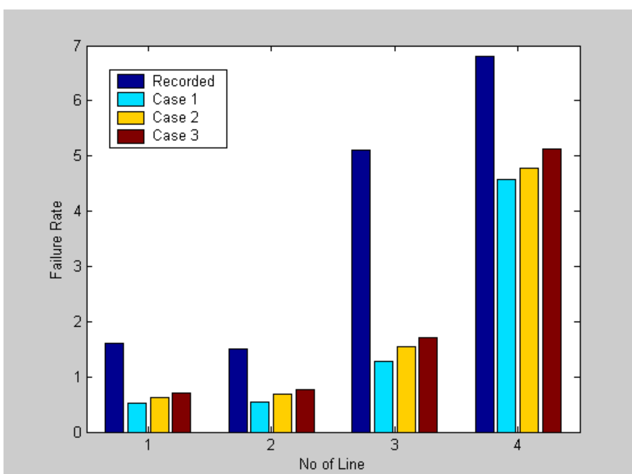

Fig. 5 – The obtained results in comparison with the recorded faults for all the lines for each case

Fig.6 shows the failure probability of the arresters vs. the tower footing resistance for all the examined lines and for all the cases. Increasing tower footing resistance leads to increasing of arresters failure probability, while arresters failure rate depends also on line length and ground flash density. It is also observed that smaller interval decreases the arresters failure rate. This is also obvious in Fig.6 where for each tower footing resistance the failure probability is higher as the interval increases. Thus, for regions with high tower footing resistance arresters installation, probably with higher withstand capability, on every tower is suggested.

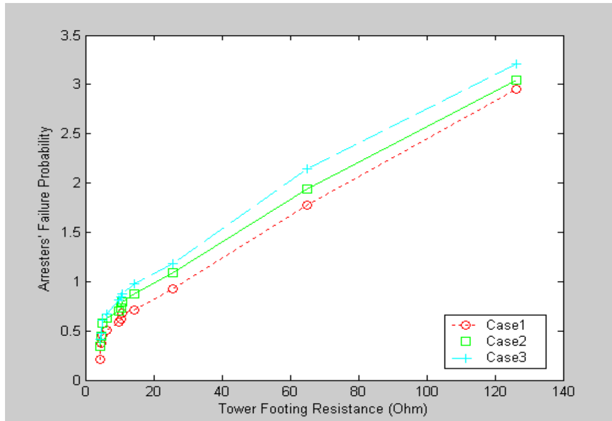

Fig.6 – Tower Footing Resistance vs. Arresters' Failure Probability

6 CONCLUSIONS

The application of surge arresters in overhead transmission lines contributes to the improvement of their lightning performance and to the failures' reduction. In this paper the lighting performance of four lines, using arresters for lightning protection, of the Hellenic transmission system were simulated and the results were compared with real recorded faults. During the design of new lines, which will use surge arresters for lightning protection, or the installation of surge arresters on existent lines, must be decided the arresters interval and their energy capability, taking into account for each region of the lines the tower footing resistance, which is the dominant parameter, and the ground flash density. For lines with very low tower footing resistance, arresters on every three towers seem to be almost the same effective, as if they were installed on every one or two towers, reducing a lot the number of failures. For lines with high soil resistivity arresters with higher withstand capability should be installed on every tower, in order to achieve better results. In any case, the criteria are not only technical but financial too, since the installation and maintenance cost and the expected benefit have to be estimated for the optimum and most economic line design.

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