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Assessment of surge arrester failure rate and application studies in Hellenic high voltage transmission lines

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ABSTRACT

The use of transmission line surge arresters to improve the lightning performance of transmission lines is becoming more common. Especially in areas with high soil resistivity and ground flash density, surge arresters constitute the most effective protection mean. In this paper a methodology for assessing the surge arrester failure rate based on the electrogeometrical model is presented. Critical currents that exceed arresters rated energy stress were estimated by the use of a simulation tool. The methodology is applied on operating Hellenic transmission lines of 150 kV. Several case studies are analyzed by installing surge arresters on different intervals, in relation to the region's tower footing resistance and the ground flash density. The obtained results are compared with real records of outage rate showing the effectiveness of the surge arresters in the reduction of the recorded failure rate. The presented methodology can be proved valuable to the studies of electric power systems designers intending in a more effective lightning protection, reducing the operational costs and providing continuity of service.

1. Introduction

Lightning strikes are the main reason for outages in overhead transmission lines. In an effort to maintain high power quality and to avoid damages and disturbances, overhead ground wires and surge arresters are used for the transmission lines' protection.

Numerous different methodologies have been presented in the technical literature in an effort to assess the lightning performance and improve the lightning protection of transmission lines. These methodologies are extended from the use of analogue computer methods [1], Monte-Carlo simulation techniques [2] and travelling wave methods [3], to the use of electrogeometrical models [4,5], simulation software [6,7] and artificial neural networks [8,9]. Although there are many papers dealing with this subject, only a few consider the presence of protection devices such as surge arresters [10–15]. The reason is obvious since the use of surge arresters is not a common practice in all electric utilities. Even in countries such as the USA and Japan where surge arresters have installed since the 1980s [16,17], these are not utilized broadly by all USA or Japanese electric utilities.

In the current work the contribution of surge arresters in the lightning protection of transmission lines is studied. A methodology is presented for the computation of the transmission lines' lightning failures including the failure probability and the failure rate of the surge arresters. Considering that a surge arrester is the last protection mean in a transmission line, an arrester failure as well as backflashover and shielding failures were considered as transmission line faults. The proposed methodology, which is based on the electrogeometrical model, uses also a simulation tool in order to estimate the critical currents that exceed arresters rated energy stress. The methodology is applied on six operating Hellenic transmission lines of 150 kV, of known outage rate, considering surge arresters for every 1, 2 or 3 towers. It must be mentioned that none of the Hellenic transmission lines, either the 150 kV or 400 kV, is equipped with surge arresters. The obtained results show clearly that the use of surge arresters reduces significantly the lightning faults and their use can improve the lightning performance of them.

2. Lightning parameters

The lightning parameters, which have been used in this study, are based on the measurements performed by Berger in Monte San Salvatore [18]. In order to simulate lightning strokes, lightning parameters such as the peak value of lightning current and the steepness, are randomly selected from the statistical distributions, using the well known Monte-Carlo statistical technique [2] and the methodology presented in detail in [19]. According to the Lightning and Insulator Subcommittee of the T&D Committee [20],

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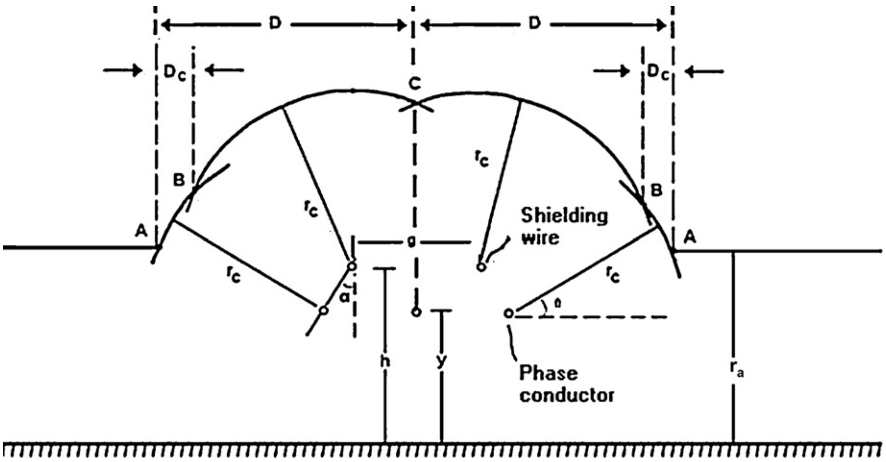

Fig. 1. Electrogeometrical model: representation of ground wires and phase conductors.

90% of the lightning strokes are considered negative while 10% of the lightning strokes are considered positive, something which has also adopted for the calculations of this study.

3. Electrogeometrical model

The termination point of a lightning stroke to a transmission line can be either a ground 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:

$$r = AI^b \tag{1}$$

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 [5] was used in the calculations.

The fractions of lightning strikes $h_A(I_P)$ and $h_B(I_P)$ that will terminate, respectively, on a phase conductor or on an overhead ground wire, can be estimated for each value of the peak current I_P using Eqs. (2) and (3):

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

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

where D_C is the shielding failure exposure distance shown in Fig. 1 and D is the vertical distance between the intersection point C and the intersection point A (Fig. 1).

4. Surge arresters

Surge arresters are designed to be insulators for nominal operating voltage, conducting at most a few milliamperes of current and good conductors when the voltage of the line exceeds design specifications to pass the energy of the lightning strike to the ground.

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 [21]. The distinctive feature of a metal-oxide arrester is its extremely non-linear V–I characteristic, rendering unnecessary the disconnection of the resistors from the line through serial spark gaps, as it is found in the arresters with SiC resistors.

The most significant technical characteristics of surge arresters according to the IEC 60099-4 are [21,22]:

(a) Continuous operating voltage (U_c). Designated rms value of power frequency voltage that may be applied continuously between the terminals of the arrester. MCOV of the arrester must be higher than the maximum continuous operating voltage of the system.
(b) Rated voltage. Maximum permissible rms value of power frequency voltage between arrester terminals at which is designed to operate correctly under temporary overvoltages.
(c) Discharge current. Impulse current which flows through the arrester.
(d) Residual voltage (U_{res}). Peak value of the voltage that appears between arrester terminals when a discharge current is injected.
(e) Rated discharge current. Peak value of lightning current impulse, which is used to classify an arrester.
(f) Lightning impulse protective level. Voltage that drops across the arrester when the rated discharge current flows through the arrester.
(g) Energy absorption capability. Maximum level of energy injected into the arrester at which it can still cool back down to its normal operating temperature. Standards do not define energy capability of an arrester. In IEC exists the term line discharge class, but since this in not enough information, various manufacturers present thermal energy absorption capability in kJ/kV (U_c), defined as the maximum permissible energy that an arrester may be subjected to two impulses according to IEC clause 8.5.5 [22], without damage and without loss of thermal stability [23,21].

5. Failure probability and failure rate of a surge arrester

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

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

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 arrester energy absorption exceeds its withstand capability, the arrester is damaged (failure). Considering the energy required to cause damage to an arrester (4), the failure probability of an arrester is calculated by Eqs. (5)–(7) [13,24–26]:

$$P_A = \int_{T_r}^{\infty} \left\{ \int_{I_A(T_t)}^{\infty} f(I_p) \cdot h_A(I_P) dI_p \right\} g(T_t) dT_t \tag{5}$$

$$P_B = \int_{T_r}^{\infty} \left\{ \int_{I_B(T_t)}^{\infty} f(I_p) \cdot h_B(I_P) dI_p \right\} g(T_t) dT_t \tag{6}$$

$$P_T = P_A + P_B \tag{7}$$

$$A_T = N_L \cdot l \cdot P_T \tag{8}$$

where P_A is the probability that an arrester fails due to lightning stroke on a phase conductor, P_B is the probability that an arrester fails due to lightning stroke on the overhead ground wire, $I_A(T_t)$ 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, T_r is the rise time of the incident waveform, P_T is the total failure probability of an arrester, A_T is the arrester total failure rate in failures per year per line, N_L is the number of lightning flashes to a line per 100 km per year, equal to: $(N_g/10)(28\, h_t^{0.6} + g)$, h_t is the tower height in m, g is the horizontal spacing in m, between the ground wires, N_g is the ground flash density in flashes per km^2 per year and l is the line length in km.

A lightning strike to a phase conductor, to a tower or to an overhead ground wire can cause arrester failure. For direct strikes to phase conductors, low tower footing resistance results in higher energy through the arrester; for strikes on towers or on ground wires, high resistances increase the arresters failure probability. The probability of failure due to strike on phases is small, so backflashover is the dominant case for the determination of the arresters' failure rate. Thus, the arrester discharge current $i(t)$ and the energy E depend on the tower footing resistance value, with the lightning peak current (that allows the arrester to reach its energy absorption capability) to decrease as the tower footing resistance increases.

The stroke peak current for each time-to-half value T_t (depending on the exceeded required energy for the arrester failure), can be calculated analytically or using an appropriate simulation tool [11–13,24–26]. In this work MATLAB & Simulink were used [27], where the transmission lines were represented by a distributed parameter line model, which is based on the Bergeron's travelling wave method [28] used by the EMTP [29] and represents wave propagation phenomena and line end reflections efficiently. The surge impedance values are 400 Ω for phases and 700 Ω for ground wires. The towers are represented as distributed parameters lines equal to 200 Ω. The dielectric strength of the insulator was represented as a voltage-controlled switch. When the voltage U exceeds the critical flashover voltage the switch closes. For the evaluation of the flashover of the insulator strings, the v–t curve is used recommended by IEEE [31]: $V_D = (400 + (710/t^{0.75}))\, W$, where V_D is the flashover voltage, t is the time to flashover and W is the insulators string length. The tower footing resistance is modeled as a lumped resistance. As far concerning the arresters it was used the element provided by Simulink, due to the difficulties and the limitations in order to use one of the existing models [30,31].

As far concerning the estimation of the ground flash density, a new method was used based on the optical transient density [27]. The ground flash density is estimated simple and with accuracy using NASA satellite's observations of average optical flash density for the geographical region of Hellas [33,34] and the nominal relation of 4:1 between optical transient density and ground flash density as it is proposed in [32]. It must be noticed the great advantage of this method, since NASA's databases contain not only annual but also seasonal and monthly observation data.

6. Shielding and backflashover failure rate

Shielding failure rate N_{SF} is associated to a required minimum current $I_{\min}$ to cause a line insulation flashover [35,36]. N_{SF} in failures per year per line is defined as follows:

$$N_{SF} = \frac{2N_g l}{10} \int_{I_{\min}}^{I_{\max}} D_C f(I) dI \tag{9}$$

where $f(I)$ is the probability density function for the current, D_C is the shielding failure exposure distance shown in Fig. 1, $I_{\max}$ is the maximum lightning current in kA that the ground wire will allow to strike the phase conductor due to the placement of the ground wire, $I_{\min}$ is the minimum current equal to $2U_a/Z_{surge}$ [35], U_a is the insulation level of the transmission line in kV and Z_{surge} is the conductor line surge impedance.

Backflashover failure rate is estimated for transmission lines, with or without ground wires, according to the method developed by the members of High Voltage Laboratory of National Technical University of Athens, and is presented in detail in [19,36,37,38,39]. N_{BF} in failures per year per line is defined as follows:

$$N_{BF} = N_L \cdot l \cdot \int_{(I_{peak})_{\min}}^{(I_{peak})_{\max}} \int_{(di/dt)_{\min}}^{(di/dt)_{\max}} P(\delta) dI_{peak}\, d(di/dt) \tag{10}$$

where $P(\delta)$ is the probability distribution function of the random variable δ, which is a function of the two random variables I_{peak} and di/dt as shown in the following relation:

$$\delta\left(I_{peak}, \frac{\mathrm{d}i}{\mathrm{d}t}\right) = R\frac{I_{peak}}{2} - 0.85U_a + L\frac{di}{dt} \tag{11}$$

with δ greater than zero when there is a backflashover, R is the tower footing resistance in Ω, L is the total equivalent inductance of the system (tower and grounding system's inductance) in μH, calculated according to the simplified method presented in [5], di/dt is a random variable denoting the lightning steepness in kA/μs and I_{peak} is a random variable denoting the peak lightning current in kA.

7. Total lightning failure of transmission lines

The total lightning failure of a transmission line in failures per year per line is the summation of any arrester failure, shielding failure and failure due to backflashover. Thus:

$$N_{TOTAL} = A_T + N_{SF} + N_{BF} \tag{12}$$

8. Application of the proposed methodology

The methodology presented in this paper has been applied and tested on six 150 kV operating transmission lines of the Hellenic

Table 1
Line characteristics of the analyzed transmission lines.

No.	Line	Voltage (kV)	Length (km)	No. of towers	Insulation level (kV)	Conductor dimensions (ACSR MCM)	No. of circuits
1	Ioannina-Kalpaki	150	28	86	750	336.4	1
2	Igoumenitsa-Sagiada	150	18	44	750	336.4	1
3	Kilkis-Serres	150	58	162	750	336.4	1
4	Arachthos-Igoumenitsa	150	76	239	750	336.4	1
5	Megalopoli-Sparti	150	64	173	750	336.4	1
6	Aktio-Argostoli	150	81	224	750	336.4	1

Table 2
Line design parameters of the analyzed transmission lines.

Line	Region	Towers	R (tower footing resistance in Ω)	N_g (average ground flash density 1995–2000)
Ioannina-Kalpaki	I	1–40	4.2	3.824
	II	41–86	25.8	3.140
Igoumenitsa-Sagiada	I	1–29	57.5	4.353
	II	30–44	14.9	2.599
Kilkis-Serres	I	1–46	2.0	3.284
	II	47–106	4.4	2.114
	III	107–162	1.8	2.646
Arachthos-Igoumenitsa	I	1–80	5.2	3.540
	II	81–163	13.0	4.188
	III	164–239	45.4	2.950
Megalopoli-Sparti	I	1–45	5.1	3.700
	II	46–75	39.7	3.430
	III	76–173	11.2	3.381
Aktio-Argostoli	I	1–55	4.8	3.540
	II	56–137	64.9	3.248
	III	138–224	126.3	2.773

Table 3
Technical characteristics of the used surge arresters.

Continuous operating voltage (U_c)	$108 < U_c < 115$ kV (rms)
Rated voltage	144 kV (rms)
Rated discharge current	10 kA
Residual voltage	<330 kV (max) for 5 kA <350 kV (max) for 10 kA <390 kV (max) for 20 kA
Discharge energy class	3
Energy capability	8 kJ/kV

interconnected system. These lines, were carefully selected among others, due to: (a) their high failure rates during lightning thunderstorms [39], (b) their consistent construction for at least 90% of their length, (c) their sufficient length and their sufficient time in service in order to present a reasonable exposure to lightning and (d) the significant different characteristics, such as the ground flash density and the tower footing resistance, which exist through their length, since they run at the same time through a plain region, a coastline and/or a mountainous region.

Table 1 presents the Hellenic high voltage transmission lines and their characteristics, which have been used in this study [39]. Table 2 presents the same lines divided into regions, showing clearly the significant different values of ground flash density [36] and tower footing resistance that exist in each one of them [39]. It must be mentioned that none of the operating Hellenic transmission lines, either the 150 kV or 400 kV, is equipped with surge arresters. Therefore the application of the proposed methodology in these particular lines was a very challenging work.

The technical characteristics of the surge arresters used in the analysis of the transmission lines are shown in Table 3. Using MATLAB & Simulink three different case studies were analyzed. In the first case, surge arresters were installed on all the towers of each one region of the transmission lines and for each one of the three phases. In the second and third case studies the surge arresters interval for each one of the analyzed lines and for each one region was set to every second and every third tower, respectively, for each one of the three phases. In the boundary of two regions of a transmission line, where the tower footing resistance varies significantly (e.g. regions I and II of the transmission line Igoumenitsa-Sagiada) or the ground flash density presents significant differences (e.g. regions II and III of the transmission line Arachthos-Igoumenitsa) the surge arresters were installed on both towers, which were near to the boundary, independently from the surge arrester interval.

It must be mentioned that in this study lightning flashes were considered to strike only the towers in which surge arresters were installed. Although this is not what really happens in the transmission lines (flashover can also occur on a tower without arrester either due to on them or due to lightning strike on neighbouring towers equipped with arresters), this is the worst case for the surge arresters, which is the main issue of this study.

9. Results and discussion

In Table 4 are presented the field observation data, i.e., actual recorded transmission lines' lightning failures, the estimated using the proposed methodology transmission lines' failure rate without the use of arresters and the obtained failure rate of the examined transmission lines for each one of the three analyzed cases, i.e., surge arresters are installed on every single, second or third tower.

In general, the use of surge arresters on transmission lines certainly reduces the backflashovers and the shielding failures. However, in the total transmission line faults must also be included the arrester damages, since arresters consist equipment of the line and they need repair or replacement after their failure. Additionally, a damaged arrester is not effective any more and can create new problems if it continues to remain on the line. In the current work, considering the arresters failures as line faults, the failure rates after the arresters installation are compared with real failure records and the estimated failures. The implementation of surge arresters

Table 4
Field observation data versus obtained results for years 1995–2000.

Line	Region	Average field observation failure rate[a]	Failure rate without arresters	Failure rate for Case 1[b]	Failure rate for Case 2[c]	Failure rate for Case 3[d]
Ioannina-Kalpaki	I	0.5	0.462	0.102	0.255	0.374
	II	1.0	0.974	0.449	0.776	0.790
	Total	1.5	1.436	0.551	1.031	1.164
Igoumenitsa-Sagiada	I	2.2	2.305	0.786	1.668	1.870
	II	0.6	0.648	0.121	0.304	0.410
	Total	2.8	2.953	0.907	1.972	2.280
Kilkis-Serres	I	0.9	0.955	0.063	0.218	0.356
	II	1.9	1.884	0.147	0.513	0.705
	III	0.7	0.724	0.049	0.255	0.436
	Total	3.5	3.563	0.259	0.986	1.497
Arachthos-Igoumenitsa	I	0.6	0.613	0.425	0.761	0.813
	II	1.5	1.540	0.769	1.288	1.740
	III	3.1	3.207	1.005	1.890	2.487
	Total	5.2	5.360	2.199	3.939	5.040
Megalopoli-Sparti	I	0.5	0.461	0.277	0.424	0.400
	II	0.9	0.836	0.439	0.723	0.898
	III	2.3	2.199	0.753	1.332	1.815
	Total	3.7	3.496	1.469	2.479	3.113
Aktio-Argostoli	I	0.0	0.008	0.256	0.329	0.389
	II	2.1	2.053	1.690	1.971	2.093
	III	3.7	3.672	2.562	2.977	3.366
	Total	5.8	5.733	4.508	5.277	5.848

[a] Average field observation failure rate means recorded lightning failures (actual data).

[b] Case 1: The surge arresters are installed on every single tower.

[c] Case 2: The surge arresters are installed on every second tower.

[d] Case 3: The surge arresters are installed on every third tower.

improves the lightning performance of the line, especially when they are installed on every single or second tower. For arresters installed every third tower, the reduction of the line failure rate is not great enough and is possible for regions with high tower footing resistance the total failure rate to increase (e.g. Aktio-Argostoli).

Fig. 2 shows the surge arresters failure probability in relation to the tower footing resistances, for all the lines, which have the same structural characteristics, for each one of the three analyzed case studies, since the arresters failure probability depends only on tower footing resistance for a given interval. As it was expected, low resistance, corresponds to lower arresters' failure probability, with the failure rate to be depended on the ground flash density and the line length. In any case the tower footing resistance must be low enough, in order to minimize the surge arresters failure probabilities and the transmission line lightning failures.

Fig. 3 shows the relationship between the installation interval and arresters failure probabilities for the line Igoumenitsa-Sagiada. It is observed that smaller interval decreases the arresters failure rate. This is also obvious in Fig. 1, where for a given tower footing resistance the surge arrester's failure probability is higher as the interval increases. Thus, for regions with high tower footing resistance (e.g. Aktio-Argostoli) arresters installation on every tower is suggested.

Fig. 4 shows the percentage failure reduction for all the analyzed lines in each one of the three examined case studies, using the equation:

$$F.R.R.\,(\%) = \frac{F.R._{o} - F.R._{i}}{F.R._{0}} \cdot 100\% \tag{13}$$

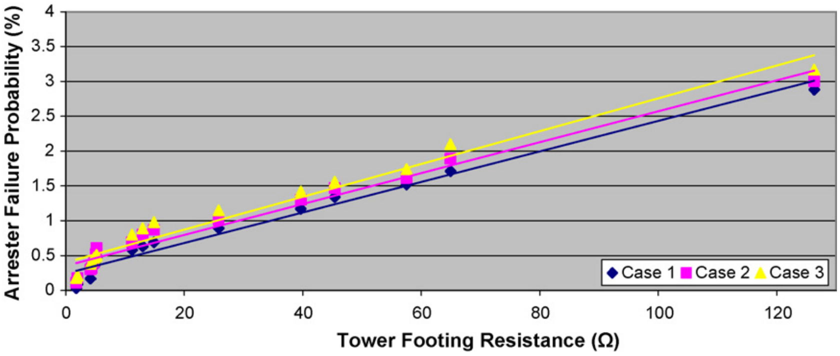

Fig. 2. The variation of surge arresters failure probability with tower footing resistance for each one of the three analyzed case studies.

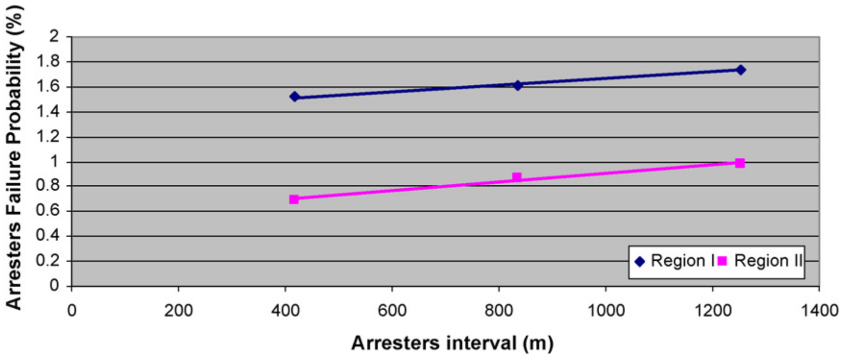

Fig. 3. The variation of surge arresters failure probability with the arresters interval for the transmission line Igoumenitsa-Sagiada.

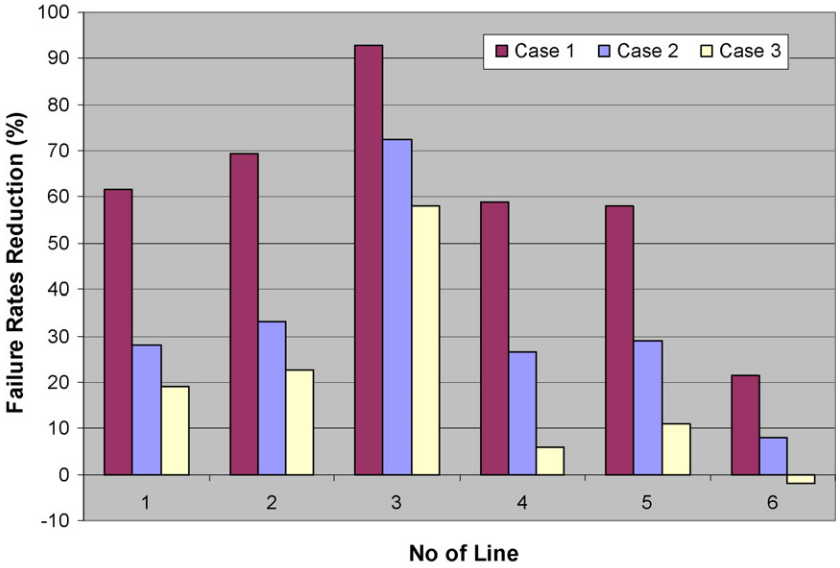

Fig. 4. The obtained failure rates reduction for all the analyzed lines for each one of the three analyzed case studies.

where *F.R.R.* is the failure rate reduction, $F.R._o$ is the failure rate without surge arresters, *i* is equal to 1, 2 or 3 denoting the three examined case studies and $F.R._i$ is the failure rate with installed surge arresters for the examined case study.

In lines with low tower footing resistance (e.g. Kilkis-Serres) the obtained failure rate after surge arresters installation on every tower is approximately ten times lower than the failure rate without arresters. In lines with high values of resistance (e.g. Aktio-Argostoli) the application of surge arresters reduces the failure rate, but the reduction is not so impressive. Solution for these lines, which have more failures due to lightning strikes, could be the use of arresters with higher energy capability.

Based on the above analysis, it is clear that the application of surge arresters in overhead high voltage transmission lines can contribute to the improvement of their lightning performance and to their failures' reduction. Electrical engineer designers must pay special attention to the surge arresters' interval and to their energy capability, which are related to the tower footing, resistance (dominant parameter) and the ground flash density. For lines with very low tower footing resistance, surge arresters on every three towers seems 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 transmission 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 economical too, since the installation and maintenance cost and the expected benefits have to be estimated for the optimum and most economic transmission line design.

10. Conclusions

The paper describes in detail a methodology, which assesses the lightning performance of high voltage transmission lines protected with surge arresters. The total transmission lines' failure rate is assessed including also in the lines' faults the surge arresters' failures. The proposed methodology has been applied on six operating Hellenic transmission lines of 150 kV, of known outage rate, which present significant different line characteristics through their length, i.e., ground flash density and tower footing resistance. Three different case studies were analyzed by installing surge arresters at three different intervals, i.e., arresters were installed on every tower, on every second tower and on every third tower. The results have shown that the transmission lines with arresters present a better lightning performance compared to the lines without surge arresters. For surge arrester installed every third tower, with the lines presenting high tower footing resistances, the reduction of the total line failure rate (backflashovers, shielding failures and arresters failures) is not significant. Results have also shown that the arrester failure probability decreases, when the tower footing resistance and the arresters' interval decreases and the failure rate is dependent on the ground flash density and the transmission line's length. The proposed methodology can be used by electric utilities as a useful tool for the design and lightning protection of electric power systems and especially for lines, which have significant different characteristics through their length, reducing the operational costs and providing continuity of service.

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