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INTRODUCTION

Journal of Energy special issue: Papers from International CIGRÉ Colloquium “Application of line surge arresters in power distribution and transmission systems”

Welcome to this special issue, which is based on selected papers presented at the International CIGRÉ Colloquium “Application of line surge arresters in power distribution and transmission systems”, held in Cavtat, Croatia, on May 25th–29th, 2008.

The International CIGRÉ Colloquium was organized by the Study Committees C4 (System Technical Performance) in cooperation with the Croatian National Committee and SCs A3 (High Voltage Equipment) and B2 (Overhead Lines). The goal of the Colloquium was to examine the various aspects of line arrester application (LSA) from system aspects to apparatus aspects. Ten main topics were covered in the four Colloquium sessions. The Colloquium extended over four days, organised in half-day sessions. Participants from manufacturers and utilities, along with those from universities and research centres, gave their presentations and took part in discussions. Three invited lectures were held, 38 papers were submitted and the Colloquium was attended by 90 participants from 24 countries.

The Colloquium covered many relevant issues on LSAs and provided the opportunity for all to discuss various aspects of LSA application. The ongoing improvement of surge arrester technology on the one side, and the requirement of higher reliability of much higher utilised transmission lines on the other, lead to an increasing use of LSAs for nearly all system voltage levels worldwide.

The main use of LSAs is to improve transmission line lightning performance or to avoid double circuit outages, but also other purposes for LSA installation have been reported:

- reduction of required insulation level and line compaction;
- reduction of the visual impact of overhead transmission line systems;
- replacement of ground wires to increase the capability of lines to cope with ice storms;
- overvoltage control in the vicinity of HV substations;
- improvement of lightning performance of different voltage level lines (by the installation of the LSA on the lower level insulation circuits only);
- line upgrading;
- security of the population;
- live line working.

Experience has shown that the use of LSAs for the improvement of line lightning performance is more efficient than conventional methods (installation of the unbalanced insulation on the double-circuit line, reducing tower footing resistance, etc.). Many LSAs are in service today and substantial service experience has been accumulated, which indicates that:

- the installation of LSAs have shown a good effectiveness in all reported cases;
- mechanical aspects of LSA installations have turned out to be a dominant root cause of in-service failures;
- only few cases of LSA failures caused by the inappropriate electrical features have been reported.

The important facts about LSAs that can be expected in the future are:

- the LSA design concepts will be further developed and the application of LSAs will grow;
- further development of computational models, procedures and computer programs will help to determine the optimal number, location and rating of LSAs to improve the reliability and availability of a transmission system;
- further development of monitoring systems for LSAs will enable their online monitoring and better control in service.

From the 38 papers presented at Colloquium, 16 papers were accepted for publication in Journal of Energy after having undergone the peer-review process. We would like to thank the authors for their contributions and the reviewers who dedicated their valuable time in selecting and reviewing these papers. It was very challenging to collect a balanced overview of the entire Colloquium, but we believe that the papers which were selected represent some of the best research about application of LSAs in power distribution and transmission systems. We hope this special issue will provide a valuable insight into LSA application, as well as a pleasant and inspiring reading.

Guest Editors
Ivo Uglešić
Božidar Filipović-Grčić

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INSTALLATION OF LSA ON A 400 KV DOUBLE-CIRCUIT LINE IN RUSSIA

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SUMMARY

Necessary information for making decisions regarding installation of LSA in a double circuit 400 kV line running between substation Vyborgskaya in Russia and substations Yullikyalya and Kyumi in Finland are discussed. Lightning discharge energy requirements for LSA have been calculated and the risk for single- and double-circuit lightning related faults with and without arresters has been estimated as a function of tower footing resistance. The decisions regarding ultimate number and location of arresters along the line are described and the type and technical data of the arresters selected are given. Furthermore the measuring system used to monitor lightning surges through the arresters is presented as well as the experience from the installation and the 3 years of service.

KEYWORDS

Line surge arresters, Lightning protection, Arrester energy requirements, Arrester monitoring

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1. INTRODUCTION

Application of line surge arresters in northern countries has historically been a quite rare occurrence due to the relatively low ground flash density in these countries. On the other hand, prevailing poor grounding conditions could make it difficult and very costly to ensure sufficiently low tower footing resistances to avoid too frequent flashovers even at a low ground flash density. In addition, the expectations from buyers of electrical power are changing and what previously may have been an acceptable outage rate is now no longer tolerable. This becomes particularly the case when consumers and network owners become aware of what could be achieved with modern surge arresters applied on the lines. Of course, this in turn puts very high demands on the reliability of the arresters themselves, both mechanically and electrically, in order not to introduce new reasons for outages due to arrester malfunctions. The report describes the installation of LSA on a 67 km long 400kV line in Russia, of which 42 km is double-circuit. The line constitutes an important connection link between Russia and Finland, which is why a low outage rate is extremely important and double-circuit faults in particular must be avoided. The line runs between substation Vyborgskaya in Russia and substations Yullikyalya and Kyumi in Finland. Previous experience shows roughly 4 faults per year for the line with 2 faults in average per circuit. Target rate was set at maximum 0.5 fault per 100km and year. Tower footing resistances along the line are very high at many locations. The installation in 2004 was preceded by a careful analysis of possible arrester stresses with respect to lightning energy as well as analysis of necessary number of arresters to achieve the target reduction of outage rate.

2. ARRESTER ENERGY CONSIDERATIONS

When installing a great number of arresters along a transmission line it is vital to ensure that the current and energy capability of the arresters is sufficiently high so that the arrester failure rate does not exceed the target outage rate. Both shielding penetration and strokes to shield wires and towers must be considered.

2.1. Calculation model

A line section with 17 double circuit towers with one 400 kV circuit positioned on each side of the towers was modelled in the EMTP. An average span length of 350 m was used between the towers. Both the circuits were modelled with their 2 conductor phase bundles as well as the two overhead shield wires. Across each phase insulator voltage controlled switches were used to model flashover. Polymer-housed surge arresters with rated voltage of 360 kV were assumed to be connected to all 3 phases in one of the circuits. The electrical data for the arresters is given in Table 1. The model of the arresters comprised the non-linear voltage-current characteristics for 8/20 μs current impulses and a compensation circuit in series to model the arrester response to steeper surges. Connection leads and length of arresters were accounted for by inductances.

Table 1. Electrical data for 420 kV line surge arrester.

Rated voltage kVrms	IEC line discharge class	Lightning discharge capability as per IEC [8] (Annex N)	Protective level in kVpeak at lightning current with wave shape 8/20 μs			
		kJ	5kA	10kA	20kA	40kA
360	3	1440	804	846	931	1046

2.2. Lightning strokes to towers or shield wires

The value of ground flash density, Ng, was not accurately known for the area. Two values of Ng were therefore used, 2.9 and 1 respectively, which were considered to well cover the actual range. For Ng=2.9 the number of flashes per km of line per year was calculated to 0.9 and for Ng=1 the corresponding figure was 0.3; adopting the methods outlined by CIGRE [1]. The intended number of arresters to be installed along the line was around 100, which meant that approximately 12 km of the line would be protected by LSA. To estimate the risk for the arresters to be overloaded the MTBS

(Mean Time Between Surge) for the line arresters could be calculated for lightning surges of different probability of occurrence from the equation [5, 6]:

$$MTBS = \frac{1}{(p \times N)}$$

where N is the number of flashes per year to the line section with arresters and p the probability that a lightning flash has a total charge and current exceeding a particular value.

Furthermore, the total flash charge was selected to cover multiple strokes. Three probability values were selected equal to 0.002, 0.005 and 0.01 respectively. From the statistical distribution of total charge of negative flashes [2, 4] these probabilities correspond to total flash charges of 134.1, 101.2 and 78.6 As respectively. Corresponding current amplitudes with the same probability of occurrence were calculated as per [1] to 190.1, 158.2 and 136 kA respectively. Current impulses with the required value of charge and amplitude were constructed. Front time and steepness for the impulses were calculated as median values for the statistical distributions based on the current amplitude. The 3 current impulses were injected in the tower top of the centre tower of the modelled line section. The calculations were performed with tower footing resistance of 600 and 170 ohms which covered the range of tower footing resistance where LSA were intended to be used. Five towers on each side of the centre tower were given the same tower footing resistance as the centre tower. The non-linear performance of the tower footing resistance taking into account soil ionization was modelled for the centre tower. The result is given in Table 2 where corresponding figures for the MTBS are given for Ng =2.9 and 1 and for a total line section of 12 km with LSA. For other values of Ng the MTBS could be recalculated accordingly. As seen from Table 2 the coupling factor as well as the instantaneous value of the power frequency affects the amount of arrester energy.

Table 2. Arrester energies and MTBS for lightning strokes to towers or shield wires.

Current impulse "probability"	MTBS Ng=2.9	MTBS Ng=1	Tower footing resistance	Arrester energy in kJ: Top phase,R		Middle phase,S		Bottom phase,T	
				Phase angle R-phase		Phase angle R-phase		Phase angle R-phase	
	years	years	(Ω)	30^{o}	210^{o}	30^{o}	210^{o}	30^{o}	210^{o}
0.002	46	139	600	168	56	151	165	87	240
0.005	19	56	600	148	30	141	114	78	194
0.01	9	28	600	119	18	107	84	56	159
0.002	46	139	170	128	16	105	83	57	161
0.005	19	56	170	105	9	83	57	43	129
0.01	9	28	170	77	5	59	43	26	104

Table 3. Arrester energy due to shielding failures.
*) No flashovers in unprotected system.

Tower footing resistance centre tower	Tower footing resistance adjacent towers	LSA in adjacent towers	Arrester energy
ohm	ohm		kJ
600	600	Yes	207
170	170	Yes	231
100	100	Yes	246
20	20	Yes	289
20	600	Yes	314
20	600	No*)	983

2.3. Shielding penetration within the protected section

Applying classical electrogeometrical theory yields that the line is effectively shielded with a low probability for shielding failures. However, for Ng=2.9 a shielding penetration rate of 0.175 per 100 km per year to one of the two circuits is estimated. Maximum current for shielding penetration is calculated to 22.5 kA. Taking into account the entire line length with double circuit of 42 km this yields 0.07 shielding failures per year. Selecting a MTBS of 25 years results in a surge probability of 1/(25*0.07) = 0.57. From [2, 4] corresponding flash charge is calculated to 6.3 As. An impulse with charge 6.3 As and amplitude 22.5 kA and with front steepness and front time calculated as median values for the statistical distributions based on current amplitude was constructed. The current impulse was injected in the top phase in the centre tower of the line section model. The tower footing resistance of the centre tower and adjacent towers was varied. The result of the calculations is shown in Table 3. For shielding penetration the most severe case is with the arrester in a tower with low footing impedance in contrast to the case for strokes to tower structure or shield wires for which the highest arrester stress is obtained for highest footing impedance. Note that the tower footing resistance of 20 ohms is selected as an extreme case since LSA, in general, are not considered to be installed in towers with such low values of tower footing resistance.

2.4. Summary of energy stresses

The energy stresses calculated for the LSA in the double-circuit line were well below the lightning discharge capability of 1.44 MJ for the selected arrester type. For lightning strokes to towers or shield wires the arrester energy is low even taking into account strokes with very low probability and MTBS in the range of the technical lifetime of the arresters. For shielding failures a significant energy may be obtained. However, compared with the capability of the selected arrester the safety margin is considered sufficient.

3. CALCULATION OF RISK OF INSULATION FLASHOVER WITH AND WITHOUT ARRESTERS

A number of computer calculations were performed to investigate the risk of flashover of line insulators during lightning events. Cases with and without arresters in all 3 phases of one of the circuits were considered. To model the lightning overvoltage withstand of the line insulators, flashover models based on voltage-time curves were used, assuming a LIWL of 1490 kV. The same model of a line section and towers as in paragraph 2.1 was used. The tower-footing resistance was varied from 20 to 600 ohms. A lightning stroke was injected in the top of the centre tower of the modelled line section. The lightning current was modelled as a double-exponential impulse with a concave front, with varying values of amplitude and maximum steepness. The amplitude and steepness of the current impulses were varied in such a way that limiting curves could be established as shown in the examples in Figure 1. In total 108 current impulses with different amplitudes and steepness were applied for each case in order to cover the whole statistical distribution of lightning strokes. In addition the phase angle of the power-frequency voltage was varied in steps of 30 electrical degrees. In total 1296 calculations were made for each value of tower-footing resistance. Combined values of stroke current amplitude and steepness above the limiting curve will cause flashover of a line insulator. The corresponding risk of flashover can be estimated by taking into account the statistical distribution of stroke current amplitudes and steepness and applying the method described in [9]. Furthermore the average value is taken for the 12 calculations with different phase angles. The result of the risk calculations is shown in Figure 2.

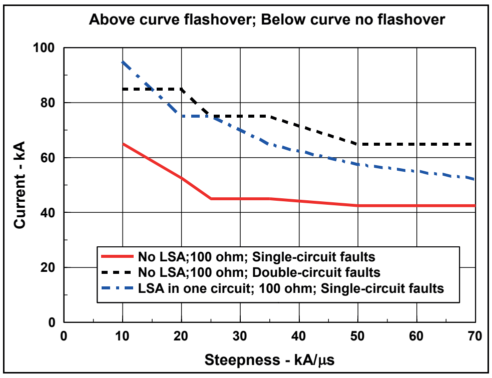

Figure 1. Limiting curves for the case with 100 ohm tower footing resistance

The total number of flashovers at a tower with a particular footing impedance is estimated as the number of lightning strokes per km line per year times the span length times 0.6 [3] times risk of flashover per lightning stroke as per Figure 2. For the complete transmission line the total risk is calculated as the sum of the risk at each tower. If arresters are located in one of the circuits at a tower the risk for double-circuit faults is practically eliminated; only the risk for single-circuit faults in the unprotected circuit remains. By making the calculations in a spreadsheet format, the most efficient solution for locating a specific number of arresters could easily be determined. For instance all towers with footing resistance above a selected value, e.g. 250 ohms, could be equipped with arresters. The efficiency in using a particular number of arresters could be exemplified in Figure 3. Arresters in this case are located at the towers with highest footing impedances. With LSA in all phases in one circuit single-circuit faults only occur in the unprotected system.

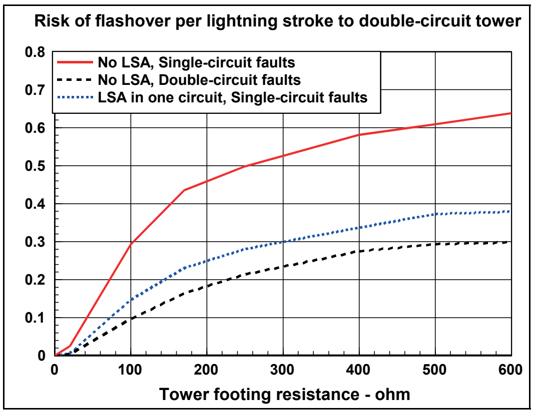

Figure 2. Risk of flashover per lightning stroke as function of tower footing resistance.

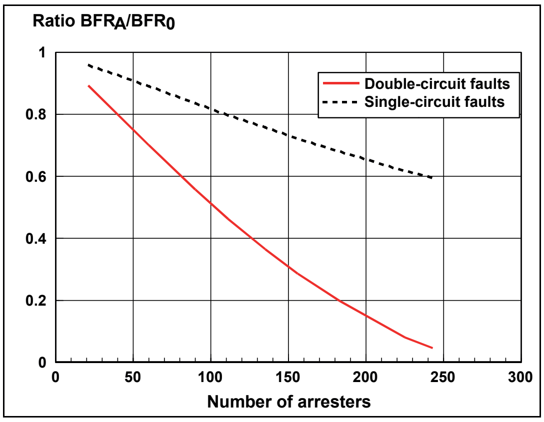

Figure 3. Relative improvement with LSA for Ng=1. BFR_A is backflashover rate with LSA and BFR_0 is backflashover rate without LSA.

3.1. Installation strategy – number of towers

Based on the calculations it was decided to install a total number of 102 surge arresters in one of the two circuits (Linke 2) on 41 selected towers and an additional 6 arresters in the other circuit (Linke 1) on two towers identified as "trouble towers" (Figure 5) with respect to lightning related faults. The locations of the arresters were assessed to optimize their effect on total outage rate; selected basically on magnitude of tower-footing resistance and experience from earlier lightning incidences. Arresters were ultimately installed in all 3 phases on the Linke 2 circuit at 27 selected towers, whilst 13 towers had only one or two phases of the Linke 2 circuit protected by arresters and two specific towers had both Linke 1 and Linke 2 circuits protected.

4. MECHANICAL CONSIDERATIONS AND INSTALLATION PRACTICE

In addition to electrical concerns the mechanical strength of the arresters and installation hardware must match requirements to avoid mechanically related failures as well. Furthermore, considering the installation height of the arresters a possible overloading should not result in dangerous bursting of hard arrester pieces.

Figure 4. Installation of LSA

The arresters were hung on the conductors close to the towers and easily installed by hand with the aid of rope winches and internal-combustion engine drive (Figure 4). The hardware was selected from standard, readily available equipment and by employing a moment-free coupling the mechanical forces could be reduced greatly. A disconnecting device was fitted in series with the arresters. Installation examples are shown in Figures 5 and 6. The high tensile strength of the arresters allows for applying a patented solution with weights under the arresters in order to limit swing during heavy wind. However, after review this was not considered necessary in this case.

The arresters themselves have the ZnO blocks housed in series-connected "modules", which are of an open-cage design formed of fibreglass loops placed on yokes at each end, together with special fibres wound around the module. This arrangement prevents any large pieces from bursting out of the cage through the housing at severe short-circuit conditions. This is particularly important in this case with the arresters located in high towers. The assembly is furthermore kept under heavy compression to maintain good contact between the ZnO blocks up to the specified short-term cantilever load, which for this application with suspended mounting assists equally against permanent tension load. Where deemed necessary – notably at the line connection and disconnecting device – special configurations were used to minimize mechanical stress on joints.

Figure 5. "Trouble tower" with arresters. installed in both circuits and in all 6 phases.

Figure 6. 400 kV line arrester in bottom phase.

5. MONITORING AND FIELD EXPERIENCE

Modern day gapless surge arresters are intended to be maintenance-free and therefore, by design, do not explicitly need to be monitored. Nonetheless, there is a natural interest from the user to know the kind of surges an arrester has been exposed to and thereby make a judgement on the effectiveness of the arresters in protecting insulation and what, if any, damage the surge may have caused to the arrester itself. In a substation environment, this may be a key factor in ensuring desired continuity of supply whereby early detection of arrester deterioration can permit removal of suspect arresters before the situation becomes acute and an unplanned circuit breaker lock-out occurs. Monitoring of both surge magnitude and resistive leakage current through the arresters provides vital data to the maintenance engineer at the substation.

LSA fitted with a disconnecting device do not pose the same degree of risk to system stability. In the rare event of an arrester overload, the disconnecting device will quickly and effectively remove the arrester from the circuit and an auto-reclose operation will re-establish power; if indeed a breaker trip occurs at all. Monitoring of leakage current on LSA is therefore predominantly of academic interest since, even if deterioration was detected, the outage time and cost of lost supply to replace the arrester before overload would be much greater than simply allowing it to overload and replacing it in due course during routine line maintenance. This is, of course, presuming the design is such that it can overload safely and in a controlled manner as described above. Of more practical interest to the engineer is the monitoring of surges through individual LSA along the line. During the system study phase, towers were selected for fitting with LSA in order to reduce the overall outage rate of the line as identified by a statistical representation of where lightning has struck in the past and where backflashovers may most likely occur. It is desirable to have some means of validating the selection as made, together with a way of determining if the improvement in outage rate has been due to the arresters or simply a coincidently less lightning activity in the region of the line.

The arresters were equipped with surge monitors (sensors) placed in series with the arresters at the connection point of the ground conductor in order to record number of arrester operations. Surges are grouped into the appropriate category based on current amplitude. Since it is impossible to approach the LSA to obtain a reading visually, the measured data stored in the sensors is transferred to hand held transceivers at ground level via radio communication and thereafter further on to a PC for statistical analysis. Due to the quite large distance between transceiver and sensor in this particular case with very high towers, an external hand-held antenna was used to improve the communication (Figure 7). The monitors were checked regularly and the latest attempt was in late autumn of 2007. Radio communication with all sensors was established, but few surge counts were registered. Notably, one of the “trouble towers” had been struck. The result was supported by information of relatively low lightning activity in the area during the subsequent years after installation of LSA and no outages have been reported in the arrester protected circuit nor in the unprotected. No mechanical problems have been reported either, validating the arrester and hardware selection as well as installation arrangement.

Figure 7. Communication between arrester sensors and hand-held transceiver (external antenna used).

6. CONCLUSIONS

The conclusions drawn from the project can be summarized as follows:

- Line surge arresters offer a robust, efficient and cost-effective alternative for minimising or even eliminating outages due to lightning surges along important transmission lines also in countries with low ground flash density.
- The energy requirements for LSA were mainly determined by the acceptable arrester failure risk during shielding failure.
- The energy requirement for LSA was well met by arresters of IEC line discharge class 3.
- Double-circuit line outages could be eliminated by proper use of LSA on one of the circuits.
- Mechanical strength is often a function of ZnO block size and hence energy capability. Since the mechanical demands may be decisive in many cases, a higher-energy rated arrester is automatically obtained which provides additional safety margin.
- Installation procedure and hardware must be carefully selected to minimize mechanical stress on arresters and disconnectors. The disconnecting device is often mechanically weak. Hence, the conductor connecting the arrester to ground or phase must be sufficiently long to ensure that the arrester and/or the insulator can swing unrestricted. Otherwise there is a risk that the disconnecting device may break off and appear to have electrically disconnected at a subsequent field inspection.

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Application of ANN and Genetic Algorithm for Evaluation the Optimum Location of Arresters on Power Networks due to the Switching Overvoltages

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SUMMARY

Switching surges are of primary importance in insulation co-ordination of EHV lines, as well as in designing insulation of apparatuses. The magnitude and shape of the switching overvoltages vary with the system parameters, network configuration and the point-on-wave where the switching operation takes place. This paper presents an artificial neural network (ANN) based approach to estimate the peak value of overvoltages and the global risk of failure generated by switching transients during line energizing or re-energizing in different nodes of a power network. Then a genetic algorithm (GA) based method is developed to find the best position of surge arresters on power networks so as to minimize the global risk of the network.

KEYWORDS

Switching surges - Artificial neural network (ANN) - Genetic algorithm (GA) - Surge arrester - Risk analysis - EMTP/ATP Draw.

1 INTRODUCTION

The insulation level of HV and EHV systems is largely determined by the magnitude of switching overvoltages. Switching surges are a transient overvoltage in which a slow front, short duration, and oscillatory is generated [1]. The objective of simulating switching overvoltages in a power system network is to help for a proper insulation co-ordination as well as for designing the insulation level for different equipment and components of the system. This would lead to minimize damage and interruption to service as a consequence of transient overvoltages. For long EHV lines, pre-insertion resistors (PRI) traditionally are used to limit switching overvoltages. In recent years some trends have been to find alternatives to PRI by active use of arresters or by controlled switching [2,3]. This paper presents an ANN application for estimation the failure risk of power networks under switching transients. Then a method based on GA is developed in order to find the optimum location of surge arresters on a power network to minimize the global risk of insulation in the network. Results of the studies are presented for a sample EHV network of Iranian grid to illustrate the proposed approach.

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2 RISK OF FAILURE

The failure risk of a network component due to switching transient presents the probability that the switching surge exceeds the withstand voltage. It is assumed that the probability of disruptive discharge of insulation is given by a normal cumulative probability function:

$$P(V)=\frac{1}{\sigma.\sqrt{2\pi}}\int_{-\infty}^{V}\exp[-\frac{(V-V_{50\%})^2}{2\sigma^2}].dV \qquad (1)$$

where *P(V)* is the probability of disruptive discharge; $V_{50\%}$ is the voltage under which the insulation has a 50% probability to flashover or to withstand and σ is the standard deviation. While we do not have a known function in order to obtain the statistical distribution of switching overvoltages, there is the statistical switching capability of EMTP/ATP which allows us to generate the statistical distribution of switching overvoltages in the network nodes. It is assumed that the switching overvoltages distribution is the normal density function:

$$f(V)=\frac{1}{\sigma.\sqrt{2\pi}}.\exp[-\frac{(V-V_{50\%})^2}{2\sigma^2}] \qquad (2)$$

where *f(V)* is the probability density of overvoltage occurrence; $V_{50\%}$ is the overvoltage for which the probability density of occurrence is 50% and σ is the standard deviation. The failure risk of each interesting network node is calculated by taking the distribution of applied overvoltages together with the distribution of its withstand voltage level and is expressed as [4]:

$$R=\frac{1}{2}\int_{E_0}^{E_m} f(V).P(V).dV \qquad (3)$$

where *R* is the failure risk, *f(V)* the probability density of overvoltage occurrence and *P(V)* is the probability of disruptive discharge. E_0 is the minimum and E_m is the maximum voltage that may be occurred in the system. On any transmission line there are *n* towers that may lead to flashover by switching operations. Essentially all of these towers are nodes where fault may occur. However, only some of these nodes are selected to place arresters, i.e. interesting nodes. There are two possibilities to define global risk of the network. One may only consider the interesting nodes and define the global risk of the network, R_{global}, by:

$$R_{global}=\frac{1}{\sum_{j=1}^{m} t_j}.\sum_{j=1}^{m} t_j.R(j) \qquad (4)$$

where *R(j)* is the risk of each interesting node, t_j relative weight of each node correspond to the most important node considering the economical criteria, and *m* is the number of interesting nodes. But this function does not represent the real failure risk of switching in the network, because there are many other nodes that may lead to flashover and should be considered. The other criterion can be the switching surge flashover rate of line having *n* towers [5]:

$$SSFOR=\frac{1}{2}\int_{E_0}^{E_m}\left[1-\prod_{i=1}^{n}(1-P_i)\right].f_s(V).dV \qquad (5)$$

where *SSFOR* is switching surge flashover rate of overhead line per switching operation, E_0 and E_m are as defined previously, P_i is the probability of flashover at tower *i* for specified switching overvoltage and $f_s(V)$ is density function of overvoltages at open end of the line. If voltage profile along the line be flat, then all P_i in (5) are equal. Then, to prepare global risk of the network, one can use the average flashover rate of all lines in the network, so:

$$R_{global}=\frac{1}{N}\sum_{i=1}^{N} SSFOR_i \qquad (6)$$

where R_{global} is flashover rate per switching operation per line, i.e. global risk of the network, $SSFOR_i$ is the switching surge flashover rate of line *i*, and *N* is number of lines in the network.

3 ANN DESIGN, TRAINING AND TESTING

For an existing system the main factors which affect the peak value of switching overvoltages are switching angle, line length, source strength and shunt reactor. It should be mentioned that a single parameter often cannot be regarded independently from the other important influencing factors. This forbids the derivation of precise generalized rule or simple formula applicable to all cases [6]. Also depending on the surge arrester's location on the network, distribution of overvoltages will be different. Then for any power system, different location of arresters will lead to different values of overvolages and global risk of the network. An ANN can help us to estimate the peak value of switching overvoltages and to evaluate the global risk of the network for each position set of arresters. An ANN is programmed by presenting it with training set of input/output patterns. ANN can learn the relationship between the inputs and outputs. The ANN in this work has the feed forward Multilayer Perceptron (MLP) architecture. A MLP trained with the back propagation algorithm may be viewed as a practical vehicle for performing a nonlinear input/output mapping of a general nature. The MLP architecture proposed in this work, Fig. 1, is composed of single hidden layer and output layer. It is capable of solving difficult and complex problems [7].

The inputs of the proposed ANN are arrays with cell numbers equal to the interesting nodes of the power network. Cells number can take the value of zero or one according to existence or nonexistence of arrester in each relative node. The ANN outputs are peak value of switching overvoltages and/or global risk of the network correspond to each position set of arresters. Supervised training of ANN is a usual training paradigm for MLP architecture. Fig.2 shows the supervised learning of ANN for which the input is given to EMTP to get the peak values of overvoltages then calculate global risk of the network and the same data is used to train the ANN. Error is calculated by the difference of EMTP output and ANN output. This error issued to adjust the weight of connection [8].

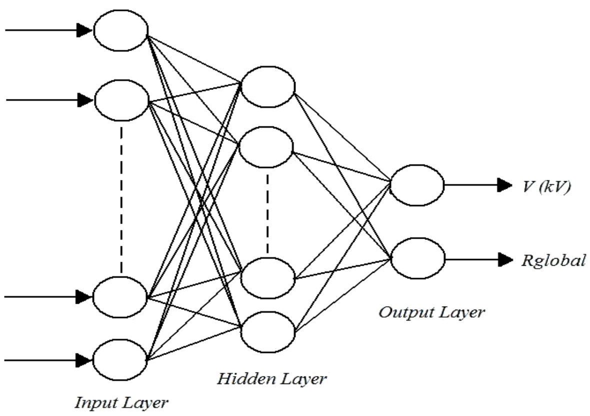

Fig. 1. Proposed MLP-based architecture.

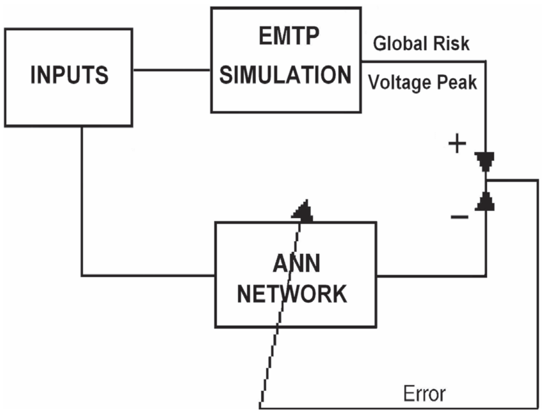

Fig. 2. Supervised learning of ANN.

4 OPTIMIZATION OF SURGE ARRESTERS' LOCATION IN THE NETWORK

The optimization method in this work is based on genetic algorithm (GA) to find the optimum location of arresters which provide minimum value of global risk of power network. Eqn. 6 is the goal function that should be minimized. GA is an evolutionary computing method, which finds the best solution for the environment by searching the solution space with a probabilistic exchange of information between each individuals or chromosomes. GA uses chromosomes composed of string-coded genotype. It simulates crossover and mutation like nature process to develop a powerful search capability [9]. Briefly principals of GA are as follows [10]:

a) Encoding: The chromosomes in the population are presented as strings of binary digits. This encoding has several advantages as simplicity of applying genetic operators. After this, chromosomes which have equal genes to the number of candidate nodes of network will be produced.

b) Evaluation: A chromosome should be evaluated to examine its fitness for being a solution. In fact chromosomes, which are proper or have better fitness are selected as parents or migration. The goal function in GA is neural net model of risk formula (6). Because of minimization nature of the problem, rank selection can be used to select the best individuals. After developing answers for the individuals produced by neural net, chromosomes sorted from worst to best and numbers in the range of 1 to the number of nodes attributed to each node as a fitness number. Then the roulette wheel can be used to select the chromosomes with proper probability [11]. The probability of selection *i*th chromosome is:

$$P_S(i) = \frac{fitness(i)}{\sum_{k=1}^{S} fitness(k)} \qquad (7)$$

where *fitness(i)* is fitness number attributed to *i*th chromosome and *S* is the total number of individuals in generation. Two chromosomes will be selected in each generation to produce offspring. One is the best individual and other elected randomly.

c) Crossover: Parents in each generation should have crossover to produce children. A single point crossover can be used. One point is selected randomly in parents string of genes, then first part of one parent is joined to the last part of the other one holding genes order and generates two offspring.

d) Mutation: Mutation is used to give this chance to algorithm to produce out of order individuals, which may be better or not. In the case of finding optimum position of arresters, there are two groups of individuals. Some chromosomes may have more or less ones in their string than suggested constant number of arresters. This group has obligatory mutation to fix number of ones. Here according to number of ones, some zero or one will be changed. For chromosomes, which have accurate number of ones in their string of genes, mutation is used to avoid stopping algorithm in very good chromosomes and some of these individuals have mutation with changing one or two genes of their strings.

5 CASE STUDY

The optimization method described before has been applied to obtain the optimum positions of five arresters, which should locate on Iranian southeast 400 kV network, Fig. 3. The network composes of four 400 kV overhead lines and one power plant. Reactors, transformers and other substation components have been ignored and the other end of radial lines are assumed be open to consider the worst case of overvoltages. Also the substation arresters have been removed to test the algorithm for placing the arresters in the end of open lines and estimate the most severe switching overvoltages. The worst case of switching operation, energizing the line having trapped charge on it, has been considered. For each position of arresters, 400 switching operations are performed statistically using the statistic switch of EMTP/ATP draw. Each overhead line is divided into three equal parts, so there are 12 candidate nodes in the network. All network simulation and modeling guidelines are based on [12]. In all cases the positions of 5 arrester sets were changed. The rated voltage of arresters is 336 kV and their protective characteristics are shown in Table 1.

Fig.4 represents the empirical cumulative distribution function (CDF), normal assumed CDF and weibull assumed CDF for overvoltage in node 4, when arresters are located on nodes 2, 3, 5, 8, 11. There is not much difference between distributions, so weibull distribution was adopted to calculate the failure risk.

Table 1. ARRESTER CHARACTERISITCS

I (kA)	1	5	10	10	20	40
V (kV)	666	751	790	790	869	972

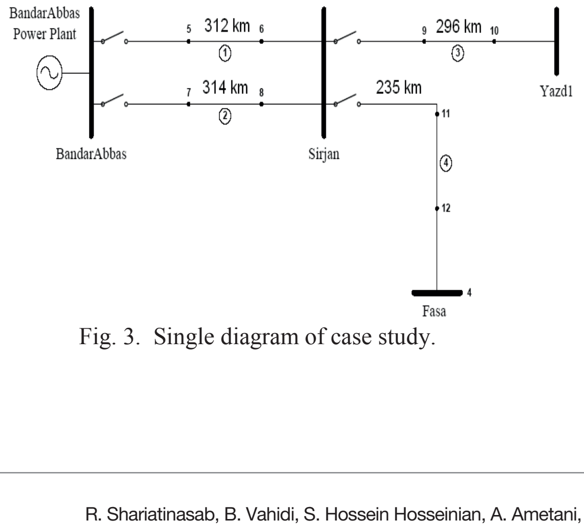

Fig. 3. Single diagram of case study.

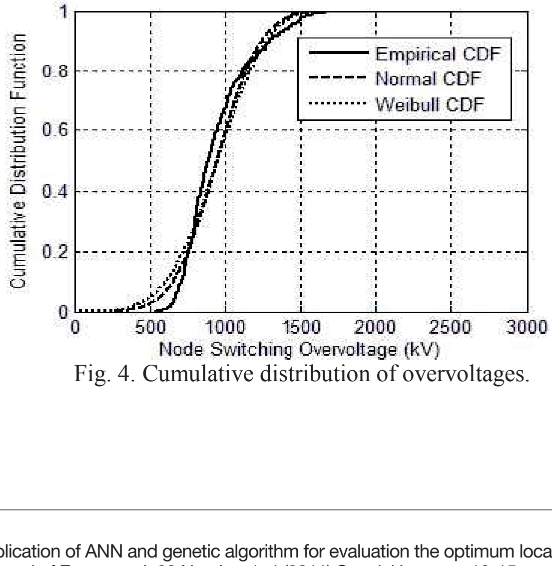

Fig. 4. Cumulative distribution of overvoltages.

The global risk of the network, eqn. (6), was calculated numerically for different position of arresters. The proposed method has been coded in Matlab v. 7.1 and all statistical calculations, ANN modeling and optimization procedure are calculated with this software. The program code runs the EMTP/ATP file, calls the results and evaluates the risk values directly. Totally 80 different position sets of arresters were simulated. Each position set consists of 5 candidate nodes for installation of arresters according to Appendix I.

For simplification voltage profile along the lines is assumed to be stepwise; then at all towers before one node the switching overvoltages are the same as the overvoltage at that node. Lines have been divided into three equal parts, so three-step voltage profile on each line is considered. However, with a flat assumed of voltage profile, switching flashover rate is much higher than the stepwise profile. Fig 5 presents global risk of the network for these two cases. Also Fig. 6 shows global risk of the network when BSL is 1050 kV or 950 kV. In this figure, the standard deviation i.e. *σ/CFO* is 5%.

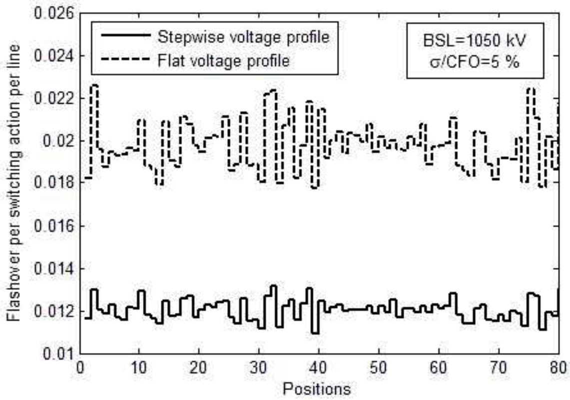

Fig. 5. Global risk of the netwrok for different position of arresters (According to appendix).

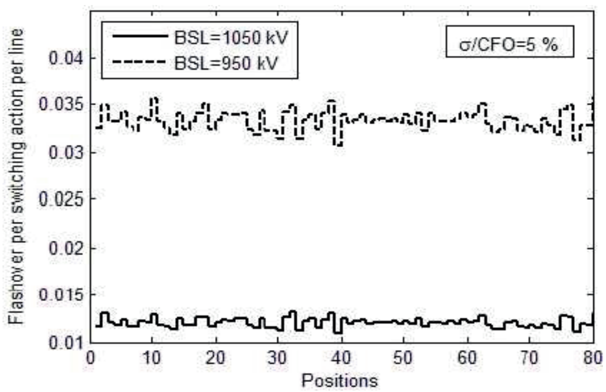

Fig. 6. Global risk of the netwrok for different position of arresters (According to appendix).

σ/CFO is per unit standard deviation which is considered 5% for tower insulation and 7% for station class insulation [13]. Fig. 7 shows the failure risk for these two values of standard deviation. From statistical data, 70 positions were selected to train the ANN. The mean square error of remaining 10 position sets that is predicted by ANN is 0.1%. Therefore, proposed ANN was qualified to be used in optimization process. A genetic algorithm with 45 initial population and 12 offsprings per generation has the role of optimizer. Mutation is done for 5 individuals per generation excluding the individuals that have incorrect number of 1 in their strings. Convergence process is shown in Fig. 8.

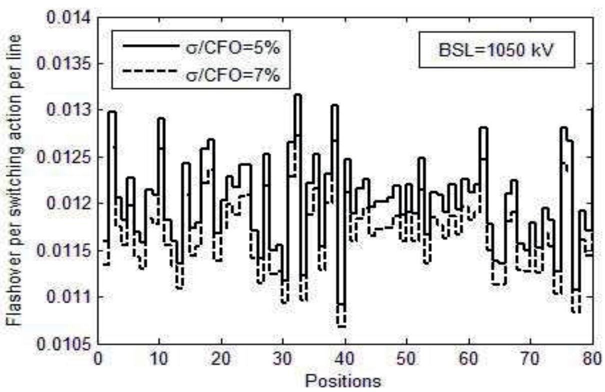

Fig. 7. Global risk values considering the value of σ/CFO.

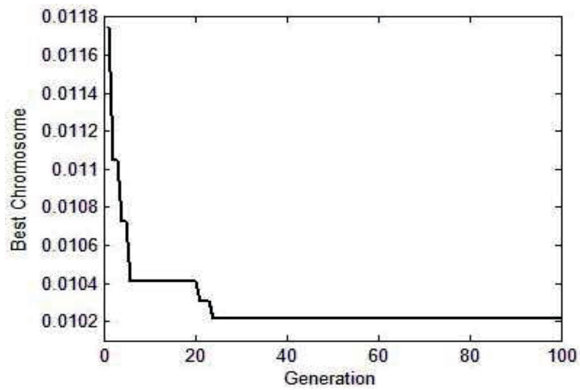

Fig. 8. Convergence process of genetic algorithm.

By appling the proposed method, optimum positions determined by ANN are nodes 3, 4, 5, 7 and 9 with predicted flashover rate per switching operation per line of 0.0102. Simulation by ATP with the same location of arresters (3, 4, 5, 7 and 9) gives the value of 0.0098. Therefore optimum position predicted by ANN will be acceptable for evaluation of minimum *SSFOR* in the network. Although all possible positions cannot be tested to verify the answer, but it is revealed that ANN model moves through optimum positions and determine a good answer in solution space, practically. What should be noted is that the algorithm placed the arresters on the line 3 and 4 ends as expected, to confine the open end line overvoltages at desirable level and reduce global risk of failure of the network.

6 CONCLUSION

In this paper a simulation optimization based method was used to find the best position of five sets of arrester to set failure risk of the networks as less as possible. The proposed method consists of an ANN as a metal model and genetic algorithm as optimizer. The ANN results are investigated by simulation and after verifying the ANN model, genetic algorithm is used to find the optimum location of arresters that minimize global risk of the network. Selecting proper ANN Model and training process are very important to explore acceptable results. The proposed method was applied on Iranian southeast 400 kV network, where some nodes have to be selected for installation of arresters in order to satisfy a desired value of risk. The implemented algorithms optimize the surge arrester location, working with known risks of failure.

7 APPENDIX

In each position set, interesting nodes are those where arresters are installed. Network simulations were performed for each position set and relative failure risk was calculated. For example 10 position sets are presented in Table 2.

TABLE 2. DIFFERENT LOCATIONS FOR A SET OF 5 ARRESTERS

Pos. Set	Interesting Nodes	Pos. Set	Interesting Nodes
1	2, 5, 7, 10, 12	6	4, 8, 9, 10, 11
2	2, 3, 5, 8, 11	7	2, 6, 8, 10, 11
3	1, 4, 6, 9, 12	8	1, 4, 8, 11, 12
4	1, 3, 4, 6, 7	9	2, 3, 4, 6, 9
5	2, 3, 5, 8, 9	10	1, 5, 6, 10, 11

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Reduction of the double-circuit flashovers on a 400 kV overhead line

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		France	Canada	Canada

SUMMARY

Double circuit flashovers may cause very severe system disturbances when taking place on some critical double-circuit lines of an electrical network. Line arresters offer an efficient solution to protect these specific lines against double circuit outages due to lightning.

This paper will study, on a double-circuit 400-kV line, the protection provided by line arresters against double circuit outages due to lightning. The efficiency of several configurations of line arresters will be compared. For that purpose, the double-circuit lightning flashover rates of the line with and without line arresters will be calculated using a newly developed software which includes a three-dimensional electro-geometric model and is able to take into account the random nature of lightning. This software automatically launches EMTP-RV (restructured version of EMTP) for analyzing fast front overvoltages impressed on line insulation. The energy stressing the line arresters will also be calculated in order to evaluate the risk of failure of the line arresters due to excess energy absorption.

Furthermore, the effects of several other parameters such as the tower footing resistances, the lightning withstand voltages of insulator strings as well as the protective levels of line arresters will also be investigated.

KEYWORDS

Lightning, flashover, energy duty, continuity of service, transient calculation, line surge arrester.

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1 Introduction

This paper is devoted to the protection against lightning of a double-circuit 400 kV line, which is essential for the utility because its absence of service might lead to severe stability problems. Single phase reclosing is used and each circuit is managed separately, therefore the priority of the protection of the line is to avoid simultaneous multi-phase flashovers on both circuits.
The line is protected with 2 sky wires but a significant number of the line towers are located on rocky areas where it is not feasible to obtain sufficiently low grounding resistances to avoid multi-phase flashovers (see Figure 1). So it has been decided to use line arresters and several questions needed to be answered especially regarding the technology (gapped or gapless), the rated voltage and the class of the arresters to be used. It is also necessary to determine the towers and the phase where arresters need to be installed.
This paper presents some elements of the study conducted by RTE and EDF R&D in order to answer these questions. It starts with a brief presentation of the methodology applied to evaluate the lightning flashover rate of the line. Then, after a description of the configuration of the line, it presents a study of the influence of the characteristics of arresters and of the configuration of line arresters on the flashover rate. The paper ends with considerations regarding energy duty of the arresters.

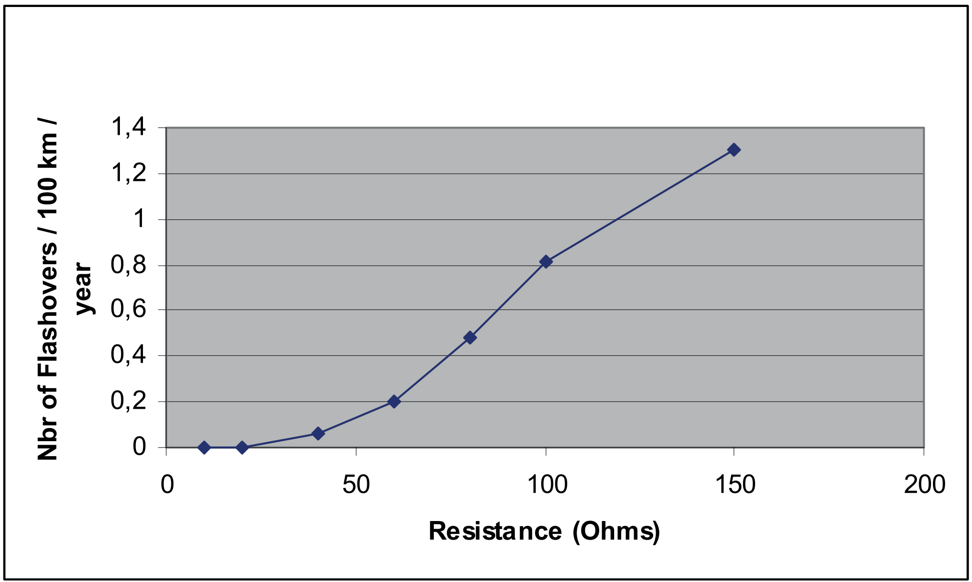


Figure 1 : Multiphase flashover rate of one circuit of the line considered in this study when it is not protected by line arresters.

2 Methodology used to evaluate the flashover rate

The methodology we have applied to evaluate the lightning flashover rate has been presented into details in [1]. It includes the following steps :

1) Application of the electro-geometric model to determine the number of lightning strokes impacting each element of the line and the probability density function of these strokes ;
2) EMTP-RV simulations of the electromagnetic transients due to lightning strokes impacting the line ;

3) Evaluation of the flashover rate of the line segment under consideration. The stochastic nature of lightning is taken into account and the results of the previous stages are included.

The software requires splitting the segment of line into elements (section of sky wires, section of phase conductors, etc.) which will be considered separately in the flashover calculation. Only one point of impact is considered when performing the EMTP-RV simulations. It is supposed that overvoltages due to a lightning stroke impacting an element do not change significantly with the position of the point of impact inside the element.
Different types of flashovers are distinguished : total flashover rate or multi-phase flashover rate of the line and of each circuit of the line, etc.

3 Description of the configuration

A 400 kV double circuit line is considered. The line is protected by 2 sky wires. All the towers of the line are of the same type but their height can be different. It has been decided to conduct the study considering only one tower configuration because differences between towers are limited. The following table presents the position of conductors at towers and in the middle of the span.

Type of conductor	Height at tower (m)	Height at midspan (m)	Horizontal distance to the axis of the tower (m)
Phase 1 -circuit 1	20.6	12.6	-10
Phase 2 – circuit 1	26.1	18.1	-17
Phase 3 – circuit 1	33.1	25.1	-4
Phase 1 – circuit 2	20.6	12.6	10
Phase 2 – circuit 2	26.1	18.1	17
Phase 3 – circuit 2	33.1	25.1	4
Sky wire 1	42.2	36.2	-9.6
Sky wire 2	42.2	36.2	9.6

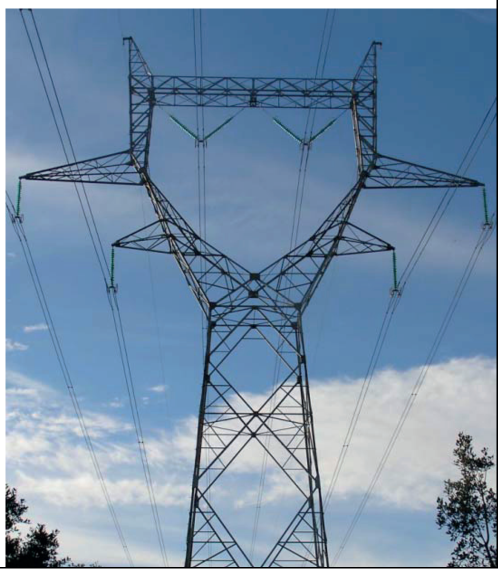


Figure 2 : Position of conductors at towers and in the middle of spans.

The length of the spans is 400 m and the lightning withstand voltage of the insulator strings is 1425 kV. The ground flash density is equal to 1.2 / km^2 / year.
In this paper the flashover rate has been calculated for different configurations of arresters, considering that the line is homogenous (all the towers and all the span are identical) in order to evaluate the effect of specific parameters on the flashover rate.

4 Influence of the characteristics of arresters on flashover rate

Since the early eighties RTE has been using gapped arresters. The main advantage of gapped arresters is that they allow the operation of the line even in case of failure of the active part of the arresters, but for the line considered in this paper the use of gapless arresters is considered because of clearance constraints at towers. In this paragraph we compare gapless and gapped arresters in terms of flashover rate reduction. We study also the influence of the residual voltage of arresters on flashover rate.

4.1 Gapped or gapless arresters

A configuration with arresters on both external phases of one circuit of the towers is considered (see Figure 3 below).

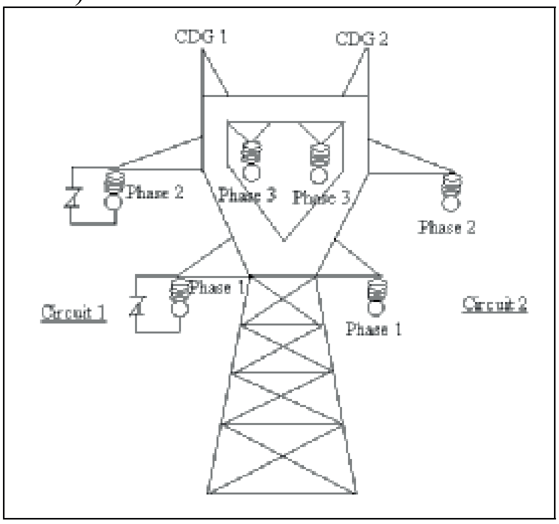


Figure 3 : Tower with line arresters installed on both external phases of circuit.

The gapless arresters have a residual voltage of 900 kV for 40 kA. The gapped arresters are constituted of an active part of residual voltage 630 kV for 10 kA and of a gap whose lightning impulse withstand voltage is 1 100kV.

The multiphase flashover rate of circuit 2 not protected with line arresters is calculated versus the grounding resistance of towers for both types of arresters and a comparison between both results is presented in Figure 4. We can see that the type of arresters does not have a strong influence on the flashover rate.

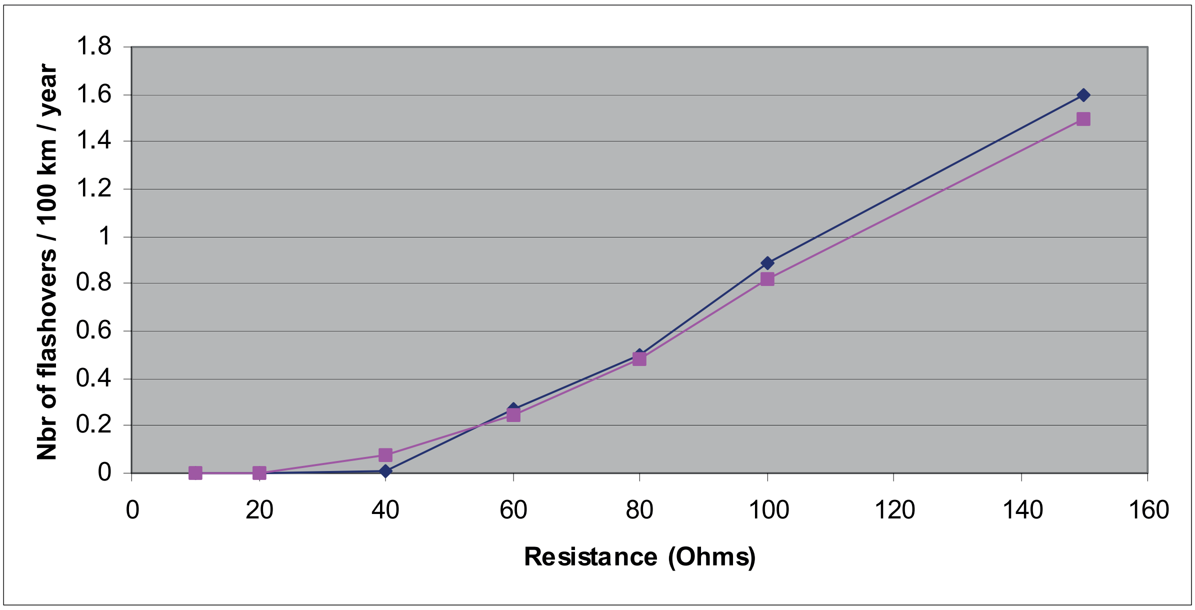


Figure 4 : Multiphase flashover rate of circuit 2 not equipped with line arrester when both external phases of circuit 1 are protected by line arresters (gapped arresters -■- , gappless arresters -◆-).

4.2 Modification of the rated voltage

The increase of the rated voltage of arresters allows the diminishing of the stress applied to arresters due to lightning overvoltages, but arresters with a higher rated voltage present the disadvantage of requiring more space in towers.

In the same configuration of arrester installation as in the previous paragraph the multiphase flashover rate of the circuit 2 (without arrester) is calculated versus grounding electrode of towers, for arresters of rated voltage 330 kV and rated voltage 360 kV (see annex 1).

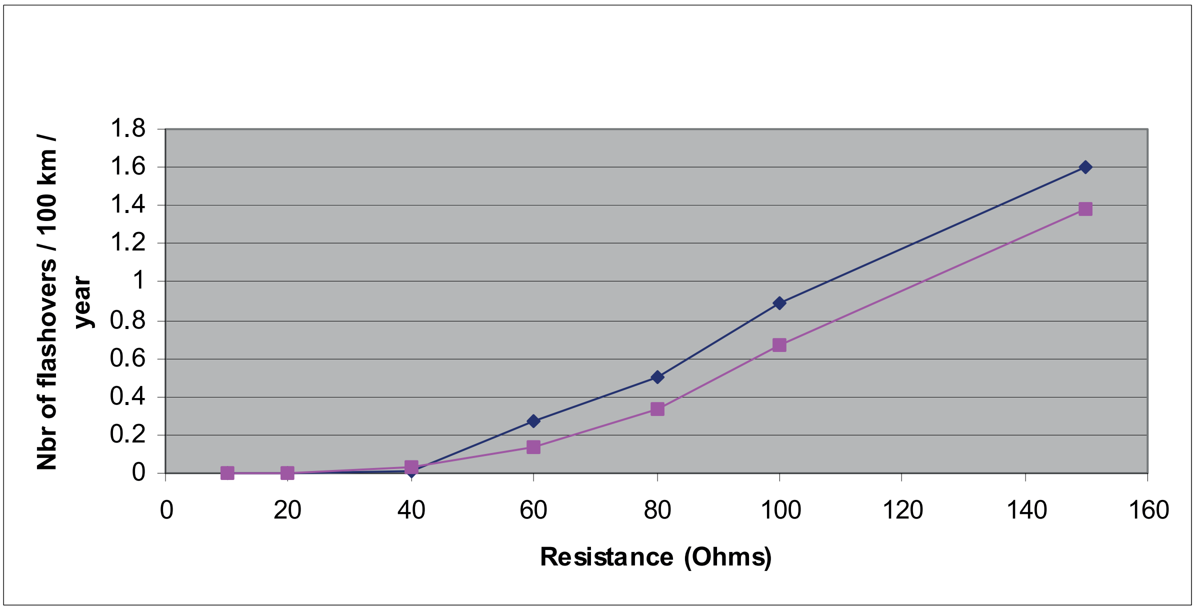


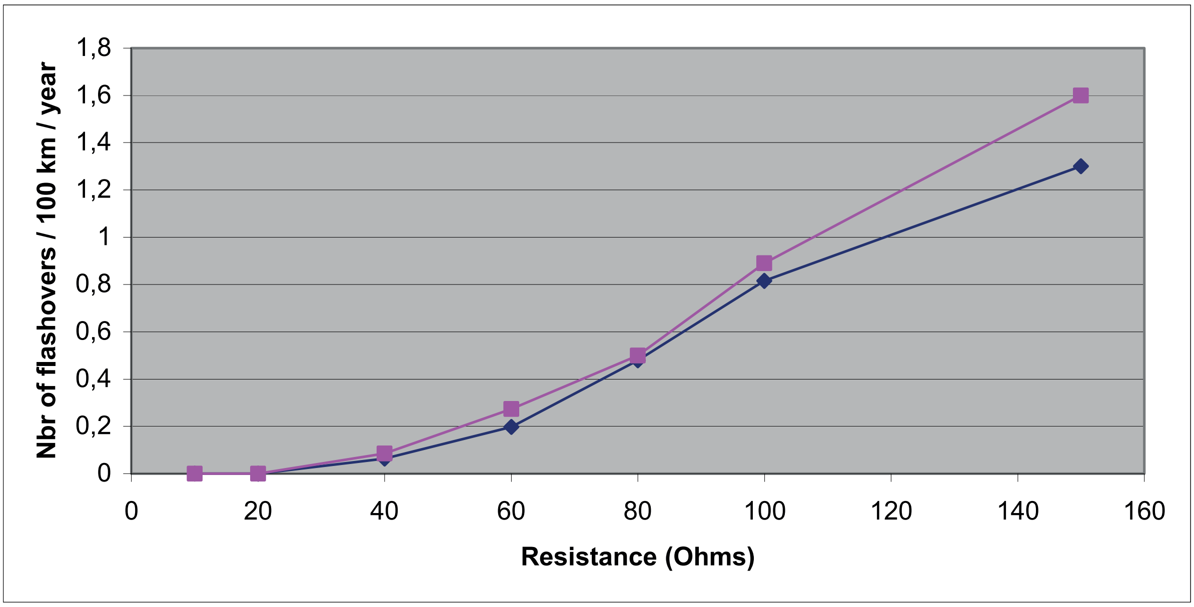
Figure 5 : Multiphase flashover rate of circuit 2, when both external phases of circuit 1 are protected by line arresters of rated voltage 330 kV (-◆-) or rated voltage 360 kV (-■-) .

The Figure 5 above shows that the rated voltage of the arresters used on circuit 1 has a limited effect on the multiphase flashover rate of circuit 2.

5 Study of different configuration of arresters

5.1 Arresters installed on the external phases of circuit 1

With two line arresters of rated voltage 360 kV installed on the external phases of circuit 1 and the multiphase flashover rate of circuit 2 is compared to its value when the line is not protected by line arresters. By avoiding any multiphase flashover on circuit 1 this configuration allows to keep on circuit always in service.



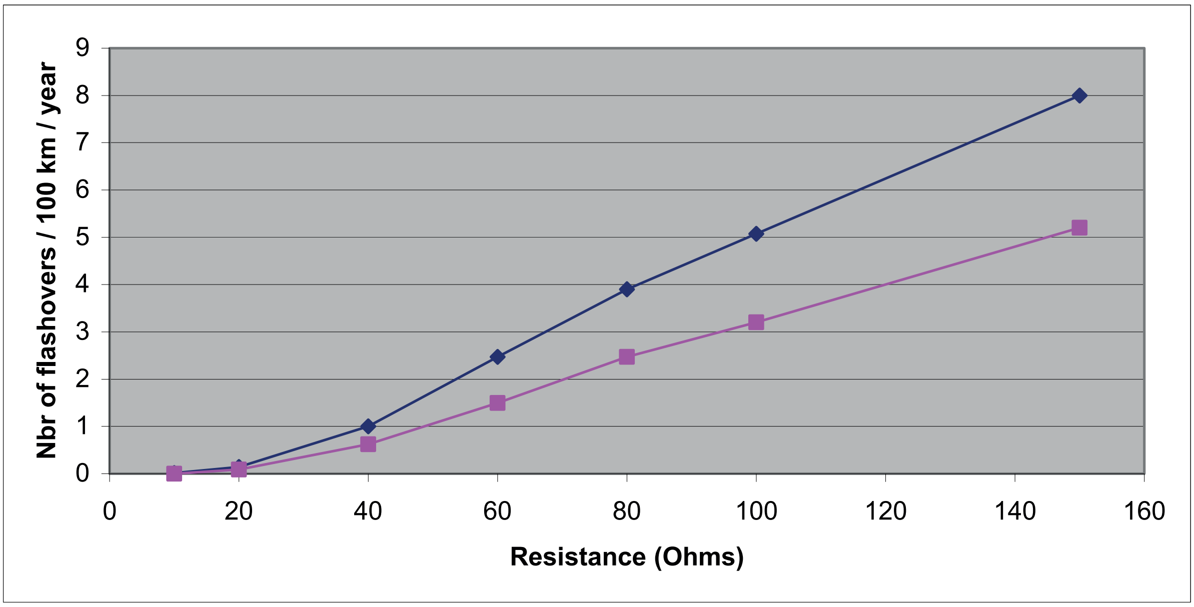


Figure 6 : (Higher Graph) Multiphase flashover of circuit 2, when the line is without arresters (-◆-) when line arresters are installed on the external phases of circuit 1 (-■-). (Lower Graph) Total flashover rate of circuit 2, when the line is without arresters (-◆-) when line arresters are installed on the external phases of circuit 1 (-■-).

The figure above shows that the presence of the surge arresters on circuit 1 leads to a strong decrease of the total flashover rate of circuit 2 but it leads to a slight increase of the multiphase flashover rate of circuit 2, especially for high grounding resistances.

5.2 Installation of a supplementary arrester on one phase of circuit 2

In this paragraph, we consider a configuration in which 2 arresters are installed on the external phases of circuit 1, but 1 supplementary arrester is installed on the external phase of circuit 2 (see Figure 7) in order to improve the lightning performance of this circuit.

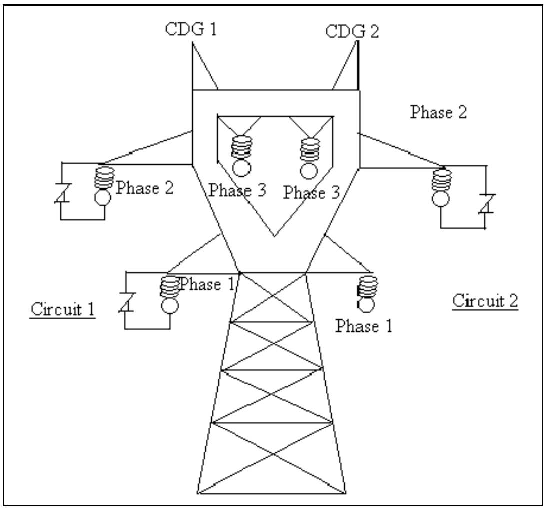


Figure 7 : Tower with arresters installed on both external phases of circuit 1 and phase 2 of circuit 2.

The figure below shows a strong decrease of the number of multiphase flashover of circuit 2 due to the presence of line arresters.

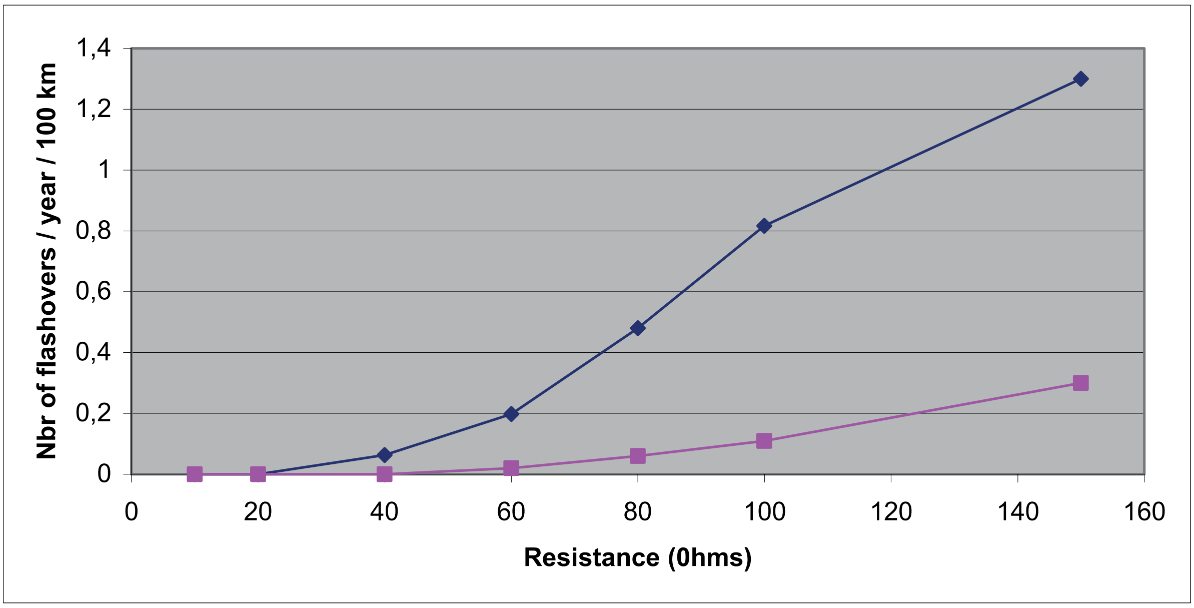


Figure 8 : Multiphase flashover rate of circuit 2, when the line is equipped with 2 arresters on circuit 1 and 1 arrester on circuit 2 (-■-) and when the line is not equipped with arresters (-◆-)).

6 Energy duty of the arresters

In order to determine the class to be used for gapless arresters, the energy stress has been evaluated by EMTP-RV simulations. Slow front overvoltages and fast front overvoltages have been considered.

6.1 Slow front overvoltages

The simultaneous reclosing of both circuits has been studied. Simulations have confirmed that, even if the line is partially protectedby line arresters, the stress applied to line arresters is very limited and that the essential part of the energy is absorbed by the arresters installed at the end of the line to protect the breakers of the substation.
It has been concluded that slow front overvoltages are not dimensioning, when specifying the energy class of the arresters [8].

6.2 Fast front overvoltages

The most severe fast front overvoltages are due to lightning. We consider here the case of a lightning stroke impacting a tower (impacts on sky wires are less severe regarding energy stress of line arresters) and of a lightning impact on phase conductors.

Lightning strokes on towers
In order to be conservative, the following configuration is considered. Each tower has a grounding resistance of 150 Ω and there are 5 line arresters per tower.
A lightning stroke of CIGRE-concave shape is supposed to impact one tower. The time to half value of the lightning current is taken equal to 110 µs. We consider that the 50 Hz voltage is, for one phase conductor, in opposite polarity with the lightning current. Subsequent strokes are not considered.
The table below gives the energy absorbed by the most stressed arrester versus the crest value of the lightning current. We can see that the energy stressing arresters is limited to 255 kJ.

Crest value of the lightning current (kA)	Energy dissipated in the most stressed arrester of the tower (kJ).
20	8.5
50	45
100	120
150	192
170	226
200.	255

Figure 9 : Energy absorbed by the most stressed arrester, for a lightning stroke impacting the tower.

Lightning strokes on phase conductors
The application of the electrogeometric model has shown that the maximum current crest value of lightning strokes which could impact phase conductors is lower than 14 kA. In order to be on the safe side, a lightning stroke of 20 kA is considered to impact a phase conductor at a moment when the 50 Hz voltage reaches its crest value of the same polarity as the lightning current. The grounding electrodes of towers are supposed to be equal to 10 Ω. Subsequent strokes are not considered.
EMTP-RV simulations have shown that an energy level of 310 kJ is dissipated in the most stressed arrester.

Conclusion
From the results above it can be concluded that it would be appropriate to use class 2 arresters. The use of class 2 allows to take into account uncertainties related for instance to general knowledge of lightning data (time to half value of the lightning current, presence of subsequent strokes…).

7 General Conclusion

This paper has presented a study of the protection against lightning of a double circuit 400 kV overhead line protected by 2 sky wires. Line arresters are used to reduce multiphase flashovers of both circuits.

The flashover rate has been calculated for different configurations of arresters using a software based on EMTP-RV. Some general information can be obtained from this study. It was shown that the type of arresters (gapped or gapless) or its rated voltage does not have a significant effect on the multiphase flashover rate.

The installation of two line arresters on one circuit avoids the presence of multiphase flashover on that circuit and therefore eliminates the risk of simultaneously tripping both circuits of the line because of lightning. This issue is essential in the type of application considered here and the fact that, as it is shown in the paper, the presence of line arresters on one circuit does not really protect the other circuit against multiphase flashovers is less important in practical terms.

The risk of failure of arresters due to energy stress has been studied. The energy stresses due to slow front overvoltages are limited. Fast front overvoltages are more severe. However due to the presence of sky wires it is sufficient to use arresters of class 1 or 2 [8].

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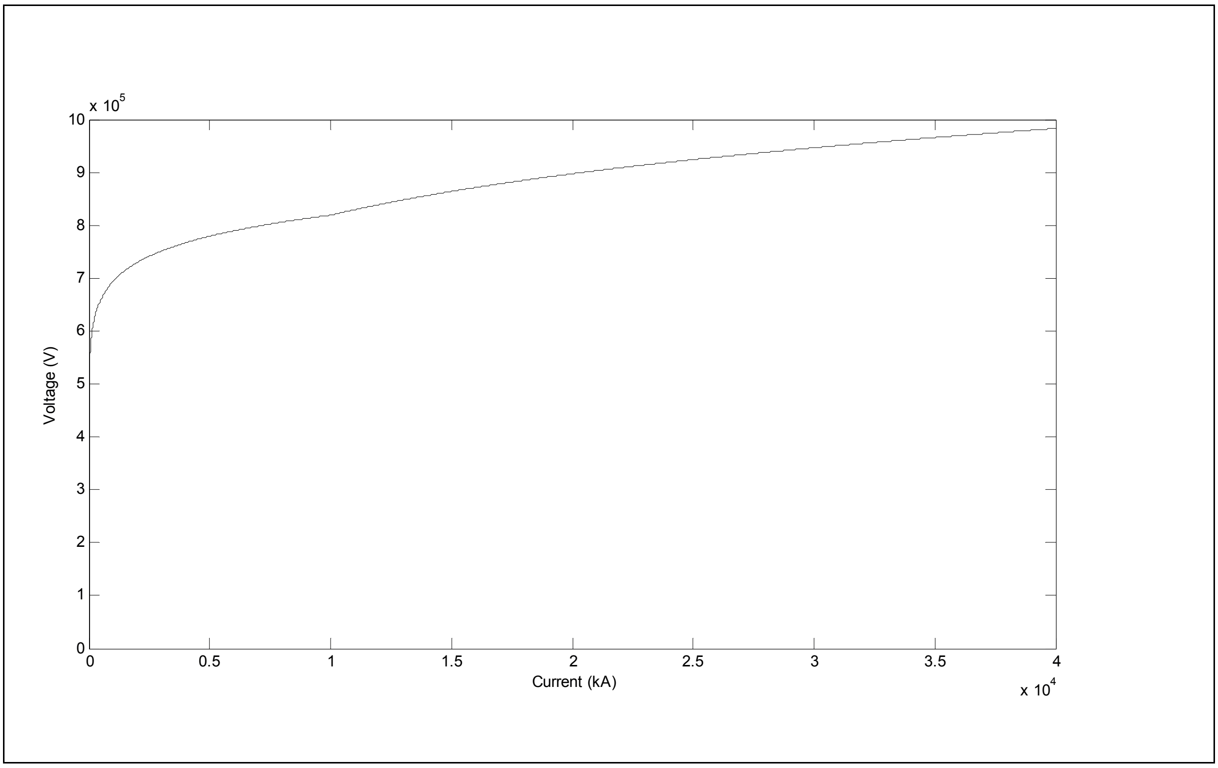
Annex 1 : Characteristic of the arrester of rated voltage 360 kV



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DECREASING BACKFLASHOVER NUMBERS ON MEDIUM VOLTAGE OVERHEAD LINES LOCATED IN REGIONS WITH HIGH SOIL RESISTIVITY

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SUMMARY:

The possibility of decreasing backflashover numbers on medium voltage overhead lines located in regions with high soil resistivity has been analyzed in this paper. Until now, activities in this field of protecting overhead lines have been limited by existing surge protection equipment and possibilities of grounding systems. The possibility of using chemical rods for getting better ground resistance and introducing metal oxide surge arresters like line arresters alongside the medium voltage overhead lines is analyzed here.
The idea of this paper is based on facts that metal oxide surge arresters have become very high quality products with low prices, and so many important experiences in using them like line arresters exist in the world; and we, in Croatia, have a 10-year-old experience in using chemical rods like part of grounding system.
The paper treats the problems of backflashover on medium voltage overhead lines, chemical rods working principles and ways of designing grounding systems like this. Finally the techno – economic analysis of using chemical rods and metal oxide surge arresters possibilities has been made, with determining justifiability criteria of using them.
In the conclusion, comparison with knowledge until now has been made, as well as a suggestion for future use.

KEYWORDS: backflashover, metal oxide surge arresters, overhead line arresters, chemical rods for grounding, medium voltage overhead line, grounding system.

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1. INTRODUCTION

Soil resistivity in many areas of Croatia is very high, exceeding 1000 Ωm. Quite often it is the case that it even reaches thousands Ωm. It is estimated that about 30 – 35 % of the Croatian territory belongs to the terrain of such (unfavorable) characteristics. For this very reason proper planning and implementation of grounding of electricity supply systems is of utmost importance. Furthermore, many parts of the region belong to a zone with 30 - 45 thunder days per year, which is considered high exposure to the impact of atmospheric overvoltages. The presence of such difficulties, along with the problem of impact of atmospheric overvoltages that cannot be completely solved, especially not in combination with high soil resistivity, enables this paper to make a contribution for increasing operation safety of electricity supply facilities located in such areas. This paper studies the possibilities of reducing the number of backflashovers on medium voltage overhead lines, by using line surge arresters and chemical rods [1] for grounding overhead lines.

For all analyzed variants techno-economic analysis will be conducted, which should then provide an answer to the fundamental issue – which are the justified conditions for the use of line surge arresters or grounding with chemical rods for the purpose of reducing the number of backflashovers.

2. BACKFLASHOVERS ON OVERHEAD LINE INSULATORS

Backflashovers pose a real danger of overvoltages to overhead lines with shielding wire, which appear after lightning strikes the tower or shielding wire [2]. It is thought that backflashover can be avoided if the groundng resistance of the pole remains under ceratian value:

$$R_{uz} \leq \frac{U_i}{I_m} \tag{1}$$

In the equation (1):

R_{uz} - grounding resistance of pole - shielding wire disconnected (Ω)
U_i - lightning impulse withstand voltage of line insulation (kV)
I_m - lightning current amplitude (kA)

Equation (1) represents a very simplified approach to the occurrence of backflashover on overhead line insulators. In reality, the following also affects the occurrence of backflashover:

- surge impedance of shieldig wire
- surge impedance of pole
- length of span
- height of poles
- mutual coupling between shielding and phase conductors.

The value of impulse ground resistance is relevant too, which mostly differs from the value of resistance during conduction of 50 Hz frequency current.

Determining the lightning current represents a specific problem. Today, data about lightning current are available from the Lightning Location System. However, such data, which would enable us to define possible lightning current with greater certainty, are not yet available in this area. For this reason different experience is used.

For determining the statistic distribution of lightning current, curves from various sources are used, which is shown in Figure 1. It is obvious from the figure that there are great differences among various standards. For further calculations we will use the curve-3 of the IEEE. The selected curve -3 may be relatively well approximated by the equation (2):

$$p(I_m) = e^{-I_m / 42} \tag{2}$$

where : I_m - amplitude of lightning current (kA).

For a more precise calculation, apart from the amplitude distribution, it is important to know the distribution of lightning current steepness. Two of those curves are shown in Figure 2. We adopt curve (2), which can be approximated by the equation:

$$p(I^{'}) = e^{-I^{'}/10{,}9} \tag{3}$$

where: I’- lightning current steepnes (kA/ µs)

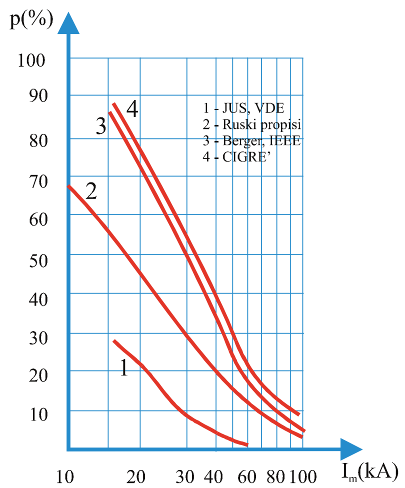

Figure 1. Distribution of current amplitudes

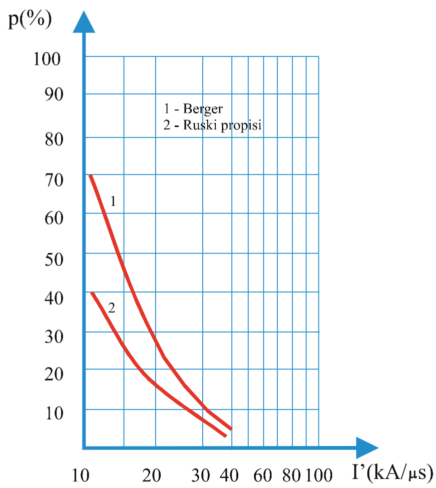

Figure 2. Distribution of current steepness

2.1 Backflashovers on overhead line 35 kV “Raša – Koromačno”

The cement factory Koromačno the biggest, and at the same time very sensitive customer in the distribution area with maximum load of 9 MW, was radially supplied by the overhead line 35 kV Raša – Koromačno. With its entire length of 13.2 km this line is located in the zone with 40 thunder days per year (Figure 3 - Isokeraunic map of the Region of Istria), and soil resistivity at several sections ranges from 1000 Ωm to as much as 5000 Ωm, which speaks enough about the danger of atmospheric overvoltages. The line also passes through a relatively high altitude terrain in relation to the surrounding area, which additionally exposes it to the influence of atmospheric discharging. Because of atmospheric discharging onto line there are often breakdowns and insulation faults, which are followed by outages or interruptions of supply.

Calculation of backflashovers on the line was done using computer software ATPREN [3], [4]. The calculation was made for the real lightnig impulse withstand voltage, which is 209 kV, then for the supposed increased level 260 and 330 kV. The graphic presentation of calculated results is shown in Figure 4.

From the obtained results it is obvious that with very low grounding resistance (R_{uz}<10Ω) quality results are achieved, whereas after it the curve rises steeply. The increase of lightning impulse withstand voltage of insulation contributes to the decrease of backflashover probability, but only 6 - 7%, between two levels. About 20% of the poles of the line have grounding resistance less than 7Ω, 60% of the poles have grounding resistance between 10 and 140 Ω, and in the remaining 10% of the poles it is over 200Ω.

It is obvious that with the two possible activities analyzed here, for reducing backflashover probability, although with a great cost, not much is achieved. It is especially difficult to count on the possibility of reducing grounding resistance with classical methods throughout the entire length of the line because of very diversified and partly inaccessible terrain through which the line passes.

The possibility of reducing grounding resistance by application of chemical rods for grounding has been considered, which showed good results on similar terrain, but as far as can be determined, never for grounding overhead line poles.

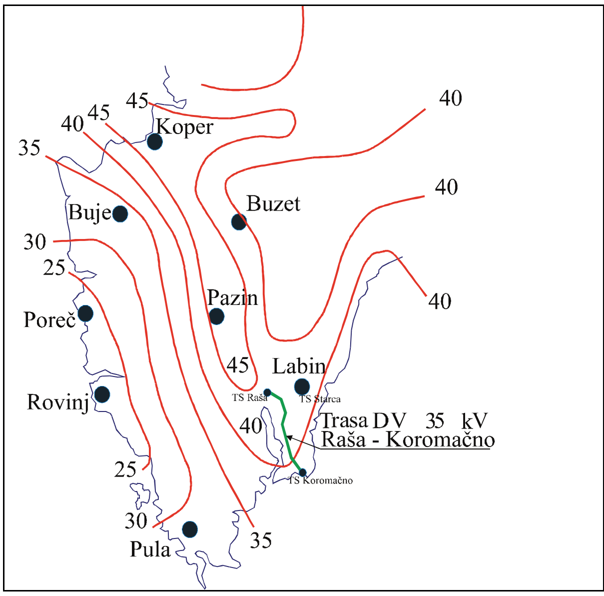

Figure 3. Isokeraunic map of the Region of Istria

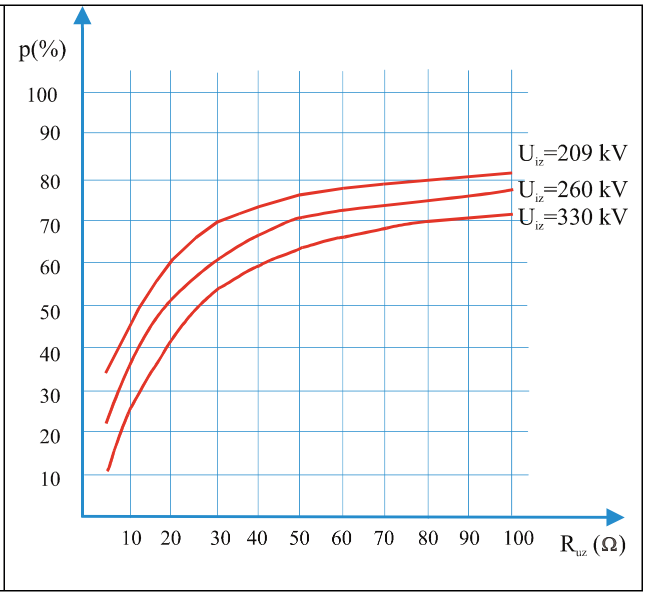

Figure 4. Probability of backflashover

2.2 Experiences in the application of chemical rods for reduction of grounding resistance

When the new connection system was built in "Elektroistra", five repeater stations were built. At two of them, Sveti Martin and Goli, it was not possible to achieve the required grounding resistance (< 5 Ω) by classical methods. It was decided to achieve the desired grounding resistance by application of a completely new grounding method, with chemical rods. Such grounding is common in some parts of the world specifically for these types of facilities, as well as for grounding classical electricity supply facilities. The implementation of such grounding was approached, but because of the lack of experience, some mistakes were made due to which the final result was not satisfactory, since the desired value of grounding resistance was not achieved. The final value of grounding resistance was small enough with regard to conditions present at the mentioned locations. It is certain that it would not have been achieved by classical methods of grounding, but it was considerably higher than the resistance required by the designer of the repeater's electronic part.
Chemical rods were also applied for the improvement of ground resistance on 35 kV overhead line Raša – Starca.

3. JUSTIFIABILITY FOR USE OF LINE SURGE ARRESTERS AND CHEMICAL RODS

In order to discuss criteria for using means of reducing the damaging effects of overvoltages, first the desired level of safety from atmospheric overvoltage influence should be defined. To define the desired safety level in terms of quality, the following needs to be done:

1. On the basis of the isokeraunic level define the number of lightning strokes near a line.
2. Calculate the extent (%) of their influence on the line.
3. Define the percentage of strokes in parts of span or poles.
4. Calculate the number of strokes, which may produce backflashover.
5. For existing line, study operational events in the past.
6. Select the safety level, which will achieve the desired aim in the most economical way.

Already from the previous sections of this paper it is obvious that the discussed lines may be divided according to:

1. voltage level:
   a) 10, 10(20) and 20 kV
   b) 35 kV
2. time of construction:
   a) existing
   b) new

With lines of rated voltage 10, 10(20) and 20 kV, whether existing or new, only the installing of line surge arresters will be used as a measure for decreasing backflashovers. Possible variants are:
1. Installing arresters along the entire line (in all three, two or just one phase).
2. Installing arresters only at critical sections (in all three, two or just one phase).

On 35 kV overhead lines without shielding wire, the measures to be considered are the same as those of overhead lines of lower voltage level, whereas on 35 kV overhead lines with shielding wire, the following is possible:
1. Improvement of grounding resistance along the line by installing chemical rods.
2. Improvement of grounding resistance along the line by installing chemical rods, with installing surge arresters at characteristic locations in lower phase.
3. Installing surge arresters only at critical sections of the line in all three phases.

After the selection of technically the best solutions, in terms of line characteristics, areas which it passes through and area it supplies, it is necessary to determine the economic acceptability of proposed solution. It is difficult to generalize the question of price acceptability, and it should be analyzed for every case separately.

If the solution is too expensive, a cheaper one should be found that is still an effective variant (if such exists), to finally give up this way of protection, or carry out works according to the proposed solution. After completing the work and once again putting the line under voltage, it is necessary to have exact statistics about operation events on the mentioned line, to be able to determine the real effectiveness of performed protection.

3.1 Discussion

A metal oxide arrester by its technical characteristics, reliability, dimensions and price, is a device which in large numbers could be present in medium voltage networks, too. It is also important to notice that its installing and replacement are very simple, so from the maintenance point of view there is no change for the worse.
Chemical rods are also a technologically quality solution, with all aforementioned limitations, for achieving low grounding resistance in special cases when it is cost-effective, or when with classical methods it is impossible to reach the given necessary low resistance.

Only information about the possibility of using chemical rods is presented here, and the area concerning specific use of line surge arresters on medium voltage – distribution lines is discussed, whereas until now, mostly their application on 110 kV lines and higher has been discussed.

Based on global experience, the possibility of application of line surge arresters on overhead lines of 10, 20 and 35 kV rated voltage has been analyzed. The conclusions are:
1. Line surge arresters may limit voltage to the level under critical amount of flashover voltage for particular insulator.
2. Depending on the number of installing on overhead lines, line surge arresters may eliminate faults caused by flashovers up to 100%.
3. Line surge arresters may be used along the entire line or only at critical sections.
4. Line surge arresters may be used with high grounding resistances as well.

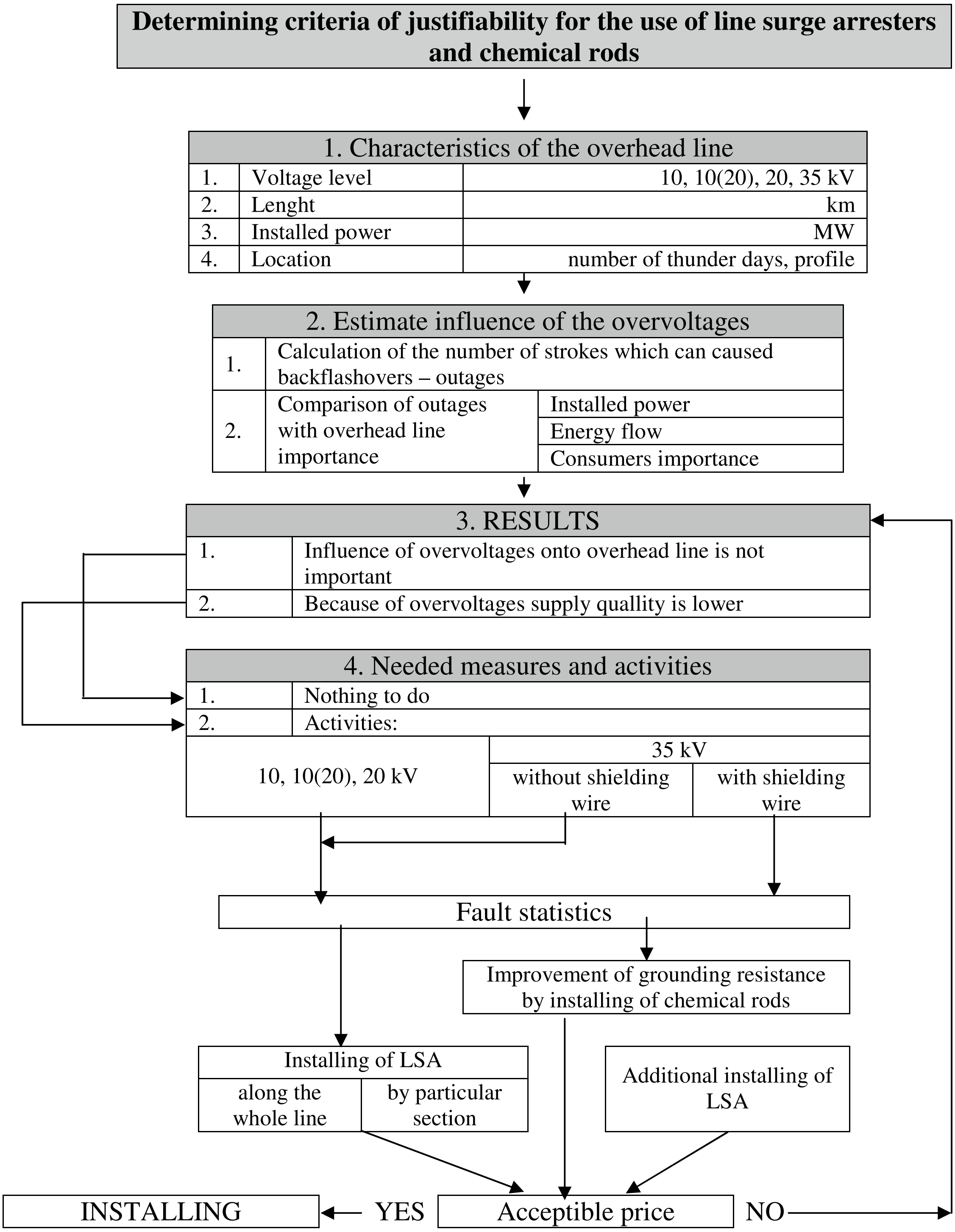

Figure 5. Flow chart of suggested method [5]

4. CONCLUSION

Taking into consideration all technical advantages and disadvantages, price, as well as maintenance requirement, the final conclusions can be made, as recommendations for future use.

- For medium voltage overhead lines up to 20 kV (10, 10(20) and 20) of rated voltage, depending on threat of overvoltages, line surge arresters can be used, in a way defined by techno-economical analysis carried out for each particular case. This means an investment of about 2.8 - 8.5 % of line price, or less if line surge arresters are used only at certain sections.
- For medium voltage overhead lines up to 20 kV of rated voltage the use of chemical rods for improving grounding resistivity is not cost-effective.
- For medium voltage overhead lines of 35 kV rated voltage with shielding wire, analysis should be carried out. If correction on a small number of grounding is sufficient for overvoltage protection needs, the use of chemical rods is justified for improving grounding resistance. Otherwise, line surge arresters may be placed at certain - most endangered sections, in variants a) in lower phase or b) all three phases.

If a medium voltage overhead line has a relatively large number of supply interruption (depending on supplying area) caused by overvoltages, it is justifiable to install line surge arresters, of course when it is possible to reach satisfactory grounding resistance. In case the resistance value is not satisfactory, analysis for decreasing it is required. One possibility is to install chemical rods, but probably in exceptional cases. This way of protecting overhead lines guarantees much better safety and availability of lines.

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EVALUATION OF ENERGY STRESS ON LINE ARRESTERS

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SUMMARY

Line Surge Arresters (LSAs) are efficient means for the improvement of the lightning performance of transmission lines. Determination of optimal LSA number, location and rating is important for the improvement of the reliability and availability of a transmission system. In selection of the LSA special attention should be paid to their energy stress which depends on complex interactions between the arrester locations, grounding, shielding and the local lightning environment. LSAs experience higher energy stress compared to station arresters, because the incoming surge to a station is limited by insulator flashover on the transmission line and impulse corona.

In this paper calculations of energy stresses were carried out for a double-circuit 220 kV line with a single shielding wire. Parametric studies were conducted in which arrester discharge energy was a function of: time to half value of stroke current, number of towers with arresters, footing resistance, span length and angle of power frequency voltage. Arrester energy stress is analyzed in case of stroke to tower and shielding failure. From conducted analysis it can be concluded that energy stress on LSAs is lower for shorter span lengths. Tower footing resistance has only minor effect on the discharge energy. Arrester discharge energy strongly depends on time to half of the stroke current, number of towers with installed arresters and angle of power frequency voltage.

KEYWORDS

Line surge arrester, modelling, energy stress calculations, double-circuit line, parametric analysis, ATP-EMTP simulations

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1. INTRODUCTION

Short circuits on transmission lines need to be avoided, not only to ensure continuous electricity supply for consumers but also to prevent stresses and damage they can cause to power system elements. Interruptions provoked by lightning are usually the most frequent cause of transmission line outages. One way for improving the lightning performance of transmission lines is LSA installation on critical places on transmission line corridor (high tower footing resistance and high lightning stroke density). LSAs are already employed by numerous electrical utilities around the world. In this paper calculations of energy stresses were carried out for a double-circuit 220 kV line with a single shielding wire. Parametric studies were conducted in which arrester discharge energy was a function of: time to half value of stroke current, number of towers with arresters, footing resistance, span length and angle of power frequency voltage.

2. MODELLING PROCEDURE FOR CALCULATING LSA ENERGY STRESS

The lightning stroke hitting a tower or a phase conductor can be replaced by a surge current generator and a resistor (Norton generator). The peak current magnitude and the tail time are important when observing the line arrester energy stresses, while the influence of the rise time is hardly noticeable in such a case. In contrast the current wave front is an important parameter with regard to insulator flashover. The slope ramp model was used in simulations for arrester discharge energy analysis. Tower surge impedances [1] were calculated using equation (1). Each tower was divided in four parts. First part is from tower top to upper arm, second one from upper arm to middle arm, third part from middle arm to lower arm and the last part from lower arm to ground. On this way it was possible to calculate transient voltages of tower arms.

$$Z = 60 \cdot \left\{ \ln\left(\frac{H}{R}\right) - 1 \right\} \qquad (R << H) \qquad (1)$$

where:
H – tower height [m],
R – tower equivalent radius (determined by equivalently replacing the tower with a cylinder) [m].

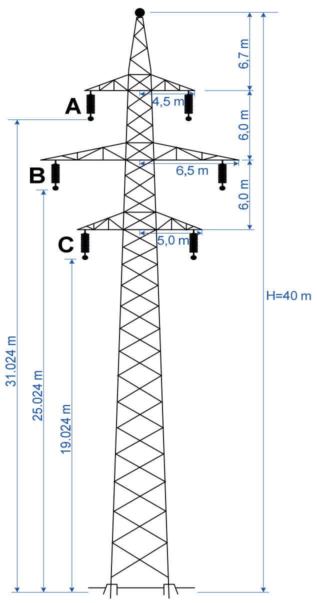

Figure 1. – 220 kV tower

Table 1. Line conductor data

	Resistance	Radius
Shield wires	0.28 Ω/km	1.33 cm
Phase conductors	0.08 Ω/km	0.69 cm

Figure 1 shows a double-circuit 220 kV tower used in simulations with line conductor data in Table 1. The transmission line, earth wire and conductors were represented by 6 untransposed frequency-dependent spans at each side of the point of impact. Each line span has been simulated with the “Jmarti” model of ATP-EMTP. A line termination was added at each side. Figure 2 depicts the model used for simulation of LSA energy stress on a double-circuit 220 kV line. All simulations were conducted with parameters from Figure 2. When the influence of single parameter on arrester energy was analysed, one parameter was varied while the other parameters remained the same.

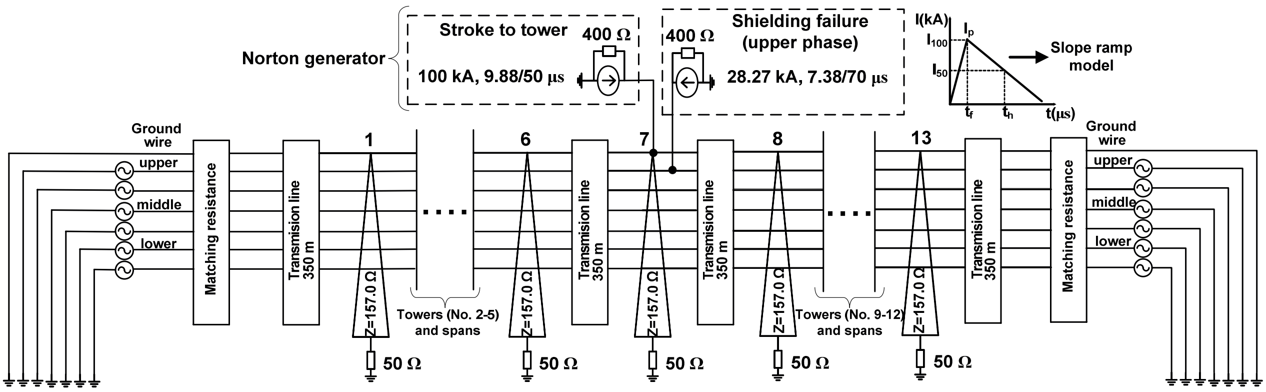

Figure 2. – Model of 220 kV double-circuit line

Tower footing resistances were modelled taking into account ionization [2]. The ionization model according to equation (2) takes into account the soil ionization that is caused by the lightning currents:

$$R_i = \frac{R_o}{\sqrt{1+\left(\frac{I}{I_g}\right)}} \qquad (2)$$

where:
R_o - footing resistance at low current and low frequency, i.e. 50 or 60 Hz [Ω],
I - stroke current through the resistance [kA],
I_g - limiting current to initiate sufficient soil ionization [kA].

The tower footing resistance remains R_i=R_o if $I < I_g$ and varies according to the given equation if $I > I_g$. The limiting current [4] is given by:

$$I_g = \frac{\rho \cdot E_0}{2 \cdot \pi \cdot R_o^2} \qquad (3)$$

where:
ρ - soil resistivity [Ωm],
E_0 - soil ionization gradient, recommended value: 400 [kV/m].

In the ATP-EMTP calculation the tower grounding was represented as non-linear resistors using Models and TACS-controlled time-dependent resistor. The model of gapless type line surge arrester includes non-linear and dynamic behaviour of the arrester. The non-linear behaviour was represented by the U-I characteristic depicted in Figure 3. while the frequency-dependent arrester model takes into account its dynamic behaviour. A frequency-dependent arrester model is depicted in Figure 4. Model parameters were identified using a formula that does not require any iterative correction and that makes use only of the data reported on manufacturers’ datasheets [3].

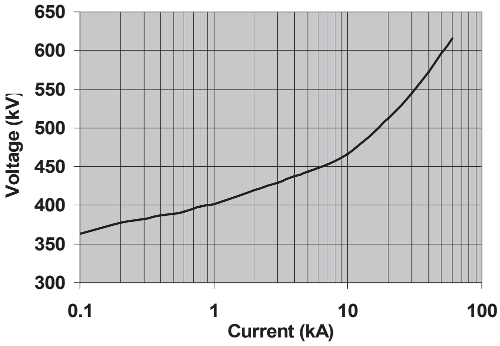

Figure 3. U-I characteristic of surge arrester for 220 kV line (U_r=198 kV)

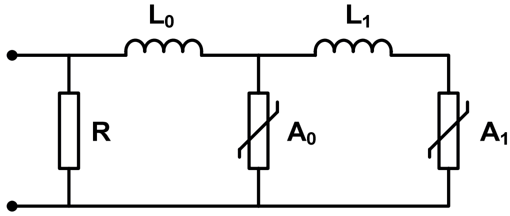

Figure 4. Frequency-dependent arrester model

Surge arrester electrical data is shown in Table 2.

Table 2. Electrical data for line surge arrester

Rated voltage [kV_{rms}]	Line discharge class	Lightning discharge capability [kJ]	Maximum residual voltage with current wave 8/20 μs [kV]			
			5 kA	10 kA	20 kA	40 kA
198	3	1544.4	443	466	512	573

Circuit without LSAs was modelled with flashover volt-time characteristic using Models and TACS-controlled switch in an ATP-EMTP calculation.

3. CONDUCTED SIMULATIONS

Arrester energy stress was analyzed in case of stroke to tower and shielding failure. In all conducted simulations three arresters were installed on one circuit of a double-circuit line.

3.1. Arrester energy analysis in case of stroke to tower

Although lightning currents can have very high magnitudes in case of stroke to tower, only a part of the total current flows through arrester in a short time period. Therefore the energy stress of arrester remains low.

In all conducted simulations following data was used:
- lightning current 100 kA, 9.88/50 μs strikes the tower No. 7 (Figure 2),
- soil resistivity ρ=1000 Ωm,
- footing resistance R=50 Ω,
- span length 350 m,
- angle of power frequency voltage in phase A is 0°.

Figure 5 shows the energy discharged by arresters at the three phases of the struck tower as a function of the number of towers with arresters. The energies taken by the arresters at struck tower increase when arresters are installed in adjacent towers. This phenomenon occurs because the currents through arresters at the adjacent towers are of opposite polarity to the currents through arresters at the struck tower, they flow back to the point of impact, and result in an increase of energy [4].
Figure 6 shows the effect of the tower footing resistance on energy discharged by arresters in all phases at the struck tower when arresters were installed in one circuit of all towers. The tower grounding resistance was varied from 20 Ω to 110 Ω. Arrester energy in phase C changed form 20 kJ (R=20 Ω) to 55 kJ (R=110 Ω).

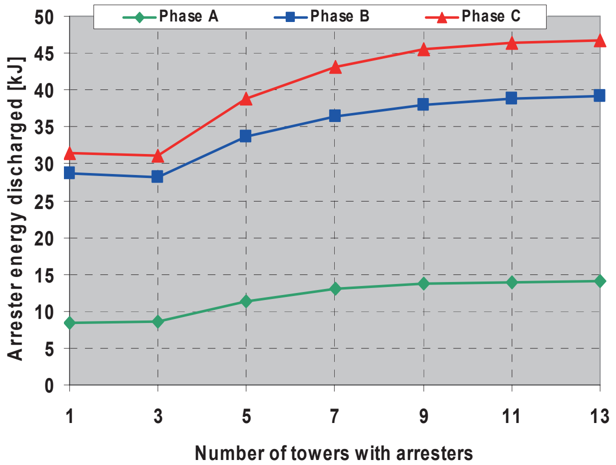

Figure 5. Influence of number of towers with arresters on discharge energy

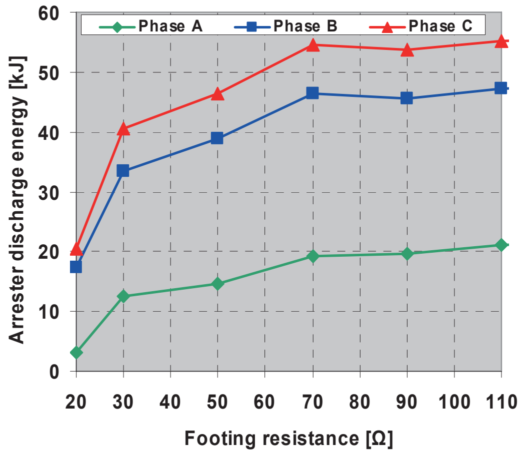

Figure 6. Influence of footing resistance on discharge energy

Figure 7 shows the effect of span length on the energy discharged by the arresters at the struck tower when arresters were installed in one circuit of all towers. The longer spans produce higher inductances of the transmission line, which tends to increase the current time constants and hence, the energy discharge levels.

Arrester energy value depends on the angle of power frequency voltage [5]. Figure 8 shows the effect of power frequency voltage angle on arrester energy in all phases at struck tower when arresters were installed in one circuit of all towers. Power frequency voltage source is represented with a cosine function. For power frequency voltage angle of 180˚, arrester in phase A takes a highest discharge energy of 37 kJ (highest voltage difference on arrester). Because of difference in coupling factors arrester in phase C had the highest discharge energy of all phases (54 kJ for power frequency voltage angle of 60˚ in phase A).

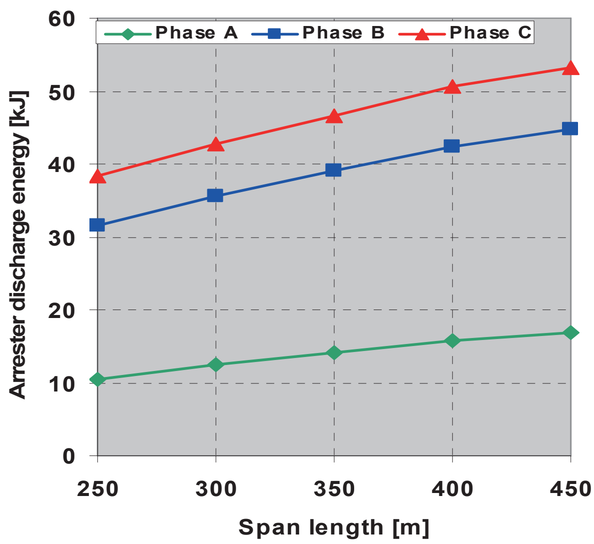

Figure 7. Influence of span length on discharge energy

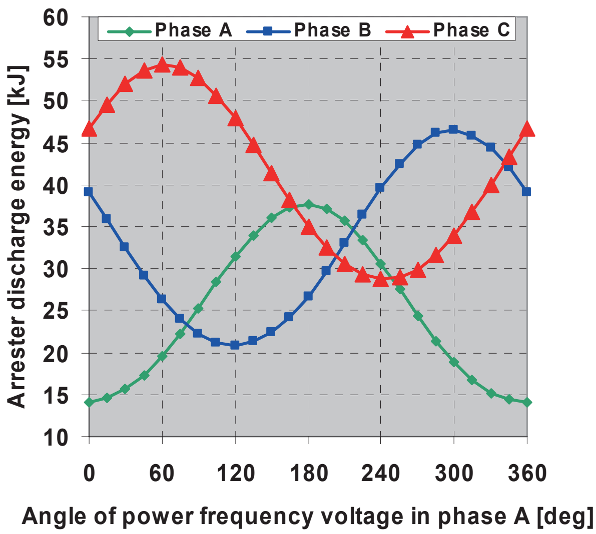

Figure 8. Arrester energy as function of the power frequency voltage angle

3.2. Arrester energy analysis in case of shielding failure

A shielding failure event or a stroke to the conductor is essentially a single-phase event. Although the probability of a shielding failure is very low, the energy stress is much higher when the return stroke hits a phase conductor than when the impact is produced at a shield wire. Lightning currents are of smaller amplitudes, but they are directly striking the phase conductor and stressing the LSAs and in this case overload (failure or damage) can occur. A previous study of the lightning performance of the double-circuit 220 kV line showed that shield wires prevent return stroke with a peak current magnitude greater than 28.27 kA. Therefore a lightning stroke (28.27 kA, 7.38/70 µs) to phase A conductor at tower No. 7 was analyzed (Figure 2). In all conducted simulations the same data was used as in case of stroke to tower.

In case of shielding failure in phase A (Figure 9) the energy reached maximum when arresters are installed only in a single tower. This energy rapidly decreased as additional arresters were installed in adjacent towers. For time to half of 70 μs the energy stress of arrester was 739 kJ. For time to half of 200 μs the energy stress of arrester was 2219 kJ, which exceeded arrester's rated discharge capability of 1544.4 kJ. Conducted analysis showed that (for simulated stroke current amplitude of 28.27 kA and time to front of 7.38 μs) arrester will be endanger for time to half values higher than 140 μs.

The primary reason for the decrease in energy as additional arresters were added on adjacent towers is that the time to half value of the arrester current decreased (Figure 10). When arresters were installed on single tower, time to half value of current through the arrester in phase A was approximately equal to that of the stroke current. With additional arresters installed on adjacent towers time to half value of arrester current rapidly decreased.

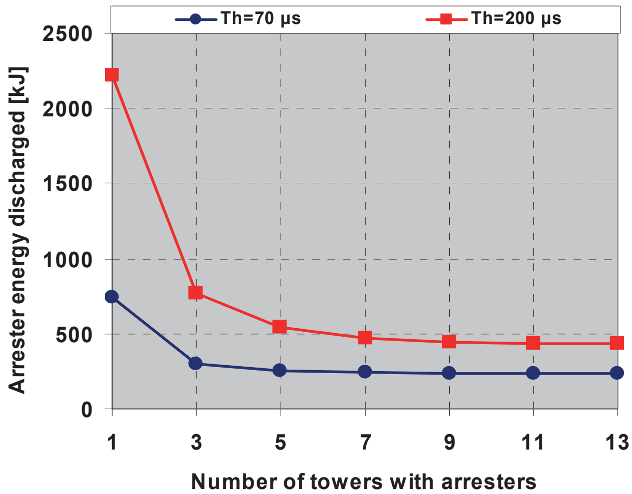

Figure 9. Influence of number of towers with arresters on discharge energy

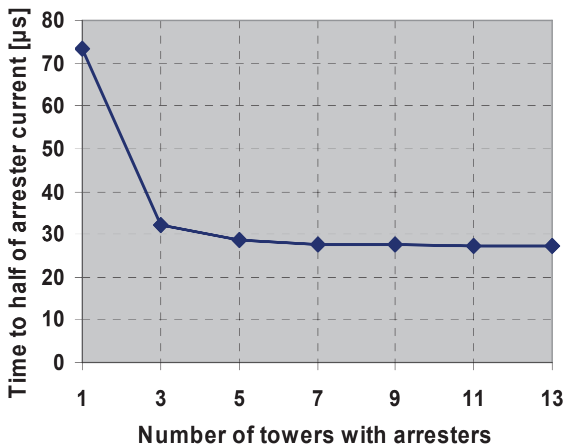

Figure 10. Influence of number of towers with arresters on time to half of arrester current

Arrester discharge energy strongly depends on time to half of the stroke current. Figure 11 shows the effect of the time to half value of the stroke current for 3 and 13 towers with arresters. For the case of three towers with arresters, the energy appears to be linearly dependent, but for 13 towers with arresters, the energy increased more moderately. The rise time of the return stroke has a small influence.

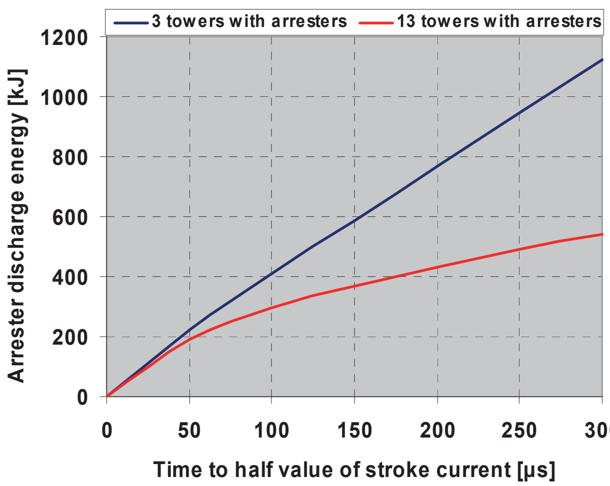

Figure 11. Influence of time to half of stroke current on arrester discharge energy

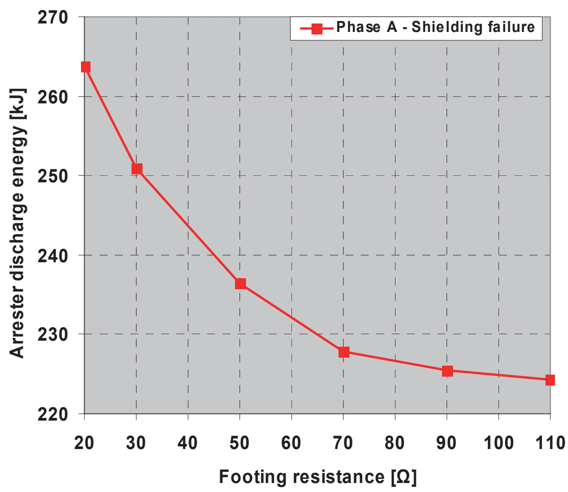

Figure 12. Influence of footing resistance on discharge energy

Figure 12 shows the effect of the tower footing resistance on energy discharged by arrester. The tower grounding resistance was varied from 20 Ω to 110 Ω. The effect of the footing resistance on the discharge energy was minor - arrester discharge energy changed from 264 kJ (R=20 Ω) to 224 kJ (R=110 Ω). Thus the shielding failure event produced more arrester energy than the stroke to a tower.
Figure 13 shows the effect of span length on energy discharged by arresters at the struck tower. Energy in phase A changed from 203.12 kJ (span length=250 m) to 262.09 kJ (span length=450 m). The longer spans produce higher inductances of transmission line, which tends to increase the energy discharge levels.
Figure 14. shows the effect of power frequency voltage angle on the arrester energy in phase A. For power frequency voltage angle of 0˚ in phase A, arrester energy reached 739.64 kJ when arresters were installed on a single tower and 236.36 kJ when arresters were installed on 13 towers.

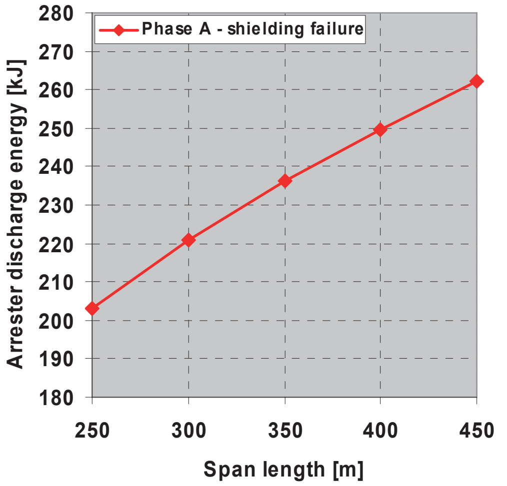

Figure 13. Influence of span length on discharge energy

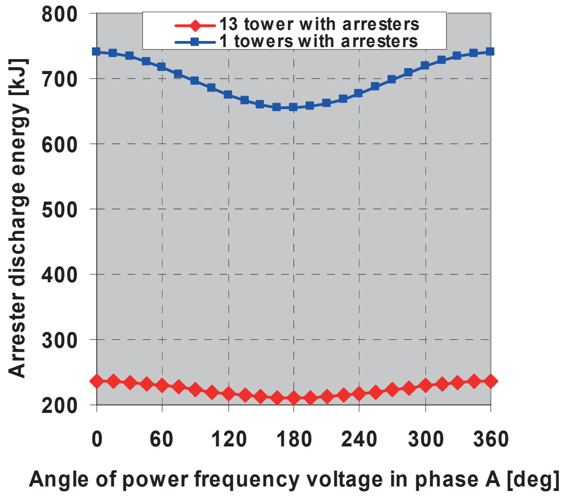

Figure 14. Arrester energy as function of the power frequency voltage angle

For power frequency voltage angle of 0˚, arrester in phase A had a highest discharge energy (highest voltage difference on arrester). Arrester energy value depends on the angle of power frequency voltage. The influence of power frequency voltage is more evident when the stroke hits a tower, but the energy discharged in those cases is rather low and very rarely will exceed the maximum absorption capability of arresters installed in a shielded transmission line.

4. CONCLUSIONS

Calculations of energy stresses were carried out for a double-circuit 220 kV line with the single shielding wire. Modelling procedure for arrester energy calculation was described. Developed ATP model provides a good tool for calculating the arrester energy duties. Case study was performed to show how arrester energy behaves under different conditions. From conducted analysis it can be concluded:

- LSAs energies and currents are acceptable for almost all cases except direct strokes to phase conductors with time to half longer than 140 µs (for simulated stroke 28.27 kA, t_f=7.38 µs),
- Energy stress on LSAs is lower for shorter span lengths.
- The tower footing resistance has only minor effect on the discharge energy (in case of stroke to tower, increase of tower footing resistance resulted with increase in discharge energy; in case of shielding failure, increase of tower footing resistance resulted with decrease in discharge energy).
- Arrester discharge energy strongly depends on time to half of the stroke current, number of towers with installed arresters and angle of power frequency voltage.
- The influence of power frequency voltage is more evident when the stroke hits a tower, but the energy discharged in those cases is rather low and very rarely will exceed the maximum absorption capability of arresters installed in a shielded transmission line.
- The rise time of the return stroke has a small influence on discharge energy.

The demonstrated principle can be applied in different situations for selection of LSA when concerning energy stress.

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Line Surge Arresters Applications On The Compact Transmission Lines

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SUMMARY

This paper presents application of line surge arresters on the compact transmission lines. Single and double circuit compact transmission lines are considered. Line lightning performance is computed using sigma slp simulation software.

Different line surge arrester installation configurations are considered. Line lightning performance is computed for different tower footing resistance. Line performance before and after line surge arrester installation are compared.

Line lightning performance of the unshielded line with line surge arresters is compared with the performance of the shielded line without line surge arresters.

For double circuit shielded compact lines, double circuit outage rate is computed. Influence of the tower footing resistance on the double circuit outage rate is presented.

KEYWORDS

Compact line, line lightning performance, line surge arrester, double circuit outage rate.

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1. INTRODUCTION

The use of line surge arresters for the quality of service improvement has increased over the last decade. Line surge arresters (LSA) are mainly used for the transmission line lightning performance improvement and for the reduction of double circuit outages on double circuit lines. Many line surge arresters are in service today and substantial service experience has been accumulated.

Thanks to the development of the composite line post insulators, compact line designs becomes a very realistic alternative to the standard line designs. Efficient use of the right-of-ways with minimal environmental impact has become one of the primary objectives when planning new line designs. When designing compact lines a very careful analysis of its electrical and mechanical parameters is necessary because of the reduction of design margins.

In addition to the application of line post composite insulators to the compact lines, application of these insulators will become extremely important in the existing lines voltage upgrading. Transmission and distribution line voltage upgrading requires also detailed insulation co-ordination studies.

In this paper we analyze application of line surge arresters in compact line design.

2. SOFTWARE FOR LINE LIGHTNING PERFORMANCE COMPUTATION

Line lightning performance is computed using **sigma slp** [1] software package. This is PC Windows based software, which has been specially developed to enable quick and easy determination of transmission line lightning performance. This package, which uses a Monte Carlo statistical method, enables simulations with three dimensional Electro-geometric modelling, a multiphase travelling wave method, arresters with or without external gaps, leader propagation flashover model, soil ionisation tower footing model, corona effects, etc.

sigma slp main characteristics are:

- Shielded and unshielded single or multi circuit lines can be simulated. Standard configuration and compact lines can be analysed. In the case of multi circuit lines, each three-phase system can have different voltage level.
- For multi circuit lines, multi circuit outages are directly obtained. Unbalanced (differential) insulation can be simulated.
- Phase to tower and phase-to-phase flashovers using a leader propagation or equal area flashover model can be simulated. Each tower in the simulation section of the line can have different flashover data. Line insulation flashover voltage is randomly selected in the Monte Carlo simulations.
- Surge arrester data taken directly from the arrester database.
- Statistical representation of surge arresters currents and energies.
- Soil ionisation tower footing resistance model automatically implemented. Counterpoise or constant resistance tower footing model can be also implemented.
- Transients on the conductors separately computed from that on the towers. Corresponding interconnections done in each time step using Thevenin equivalents. This enables extremely fast electromagnetic transients simulations.
- Transients on the tower top, guy wires with a separate grounding, under built ground wires and neutral conductors can be represented.
- Each span of the line divided into short segments in order to accept strokes between towers and to take into account corona influence.
- In the Monte Carlo simulations, initial power frequency voltages is randomly represented.
- Very powerful graphic processor enables visualization of travelling waves along phase conductors and ground wires.
- During statistical simulations, line insulation flashovers and stroke positions are visually indicated.
- Nearby objects in the electro geometric simulations are taken into account.

3. SHIELDED STANDARD DESIGN LINE AND UNSHIELDED COMPACT LINE

The lightning performance of 123 kV single circuit unshielded compact line is compared with that of the "standard" design shielded line. Line insulation critical flashover voltage for all lines is 590 kV, line span of 175 m and ground flash density of 2,8 strokes/km^2/y is used in all simulations. Tower surge impedance for the standard line configurations is 180 Ω, while compact line design towers have this value equal to 205 Ω. Conductor data for the standard single circuit is given in Figure 1.

The compact line has composite line post insulators. The line surge arresters installed on the compact line have MCOV equal to 84 kV.

Standard line conductor data:

No	x (m)	y(m)	r (mm)
1	2,6	21	11
2	-3,1	18,5	11
3	3,6	16	11
4	0	26	4,5

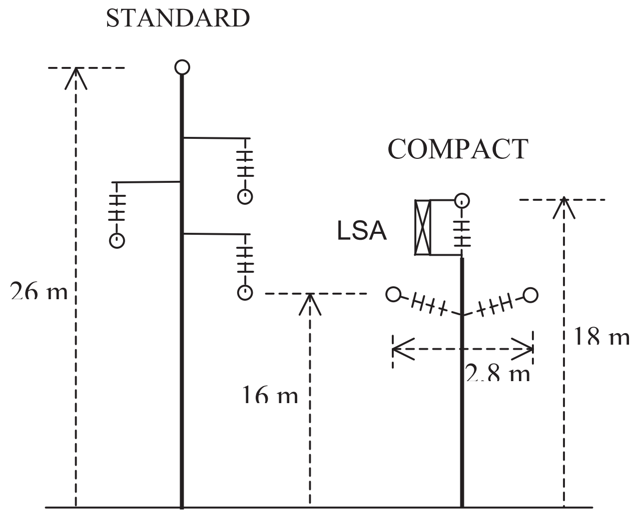


Figure 1 - "Standard" shielded and Compact unshielded single circuit line designs

The low current tower footing resistance varies from 10 Ω to 80 Ω, while a non-linear tower footing soil ionization model is implemented. The ratio between soil resistivity and tower low current footing resistance is equal to 30.

Single circuit compact line has phase conductors arranged in a delta configuration, while line surge arresters are installed on the upper (centre) conductor at each tower (Figure 1). In this case, the upper phase conductor plays the role of the ground wire. The height of the bottom conductor for both line designs is the same.

The line shadow width (W_E), number of strokes collected by the line (N_L) and median current of strokes to line (I_M) are given in Table 1. The lightning performance is determined for several values of tower footing resistance, while a thousand electromagnetic simulations are performed for each case. The results of simulations are given in Figure 2.

Table 1
Results of the electro geometric simulations

	STANDARD	COMPACT
W_E (m)	147,4	96,3
N_L (str/100 km/y)	41,3	26,9
I_M (kA)	31,9	30,3

According to the presented results, we see that the compact line with surge arresters installed on the top conductor has a much better lightning performance than the shielded line of standard design. The reasons for this are as follows:

- The compact line is lower, which means that this line collects less lightning strokes than the standard line design.
- The compact line has a conductor arrangement, which enables excellent coupling between the upper conductor and other phase conductors. Coupling between conductors is further improved by the corona effect.
- Flashovers on one (centre) conductor are completely eliminated due to the line surge arrester installation.
- Line surge arrester installed on the top conductor controls overvoltage distribution on the tower, which reduces overvoltages between tower top and the bottom phase conductors.

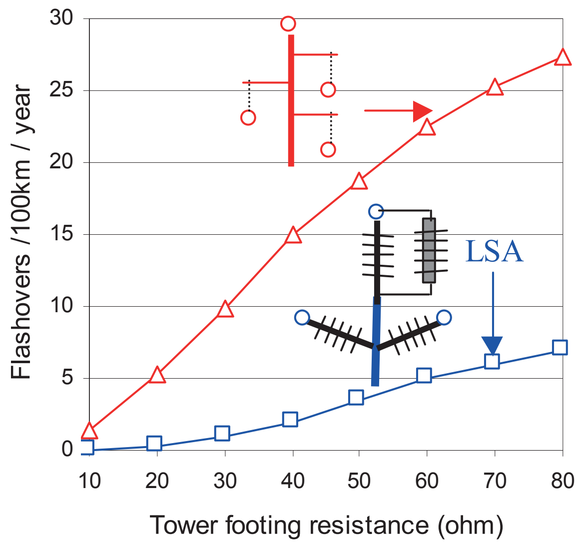


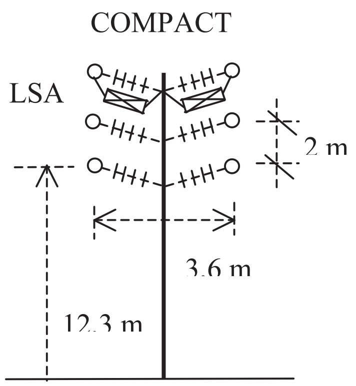
Figure 2 - Comparison of lightning performance for single circuit unshielded compact line and standard shielded line design

4. DOUBLE CIRCUIT COMPACT LINE

Lightning performance of the double circuit 138 kV unshielded compact lines without and with line surge arresters is studied and compared. Line geometry is given in Figure 3.a. Line insulation critical flashover voltage of 770 kV, ground flash density 8,09 strokes/km^2/y, line span 106 m and tower surge impedance of 182 Ω is used in all simulations. The ratio between soil resistivity and tower low current footing resistance is equal to 30. Total number of 1000 statistical cases is used for each value of tower footing resistance and arrester installation configuration. Line total flashover rate and double circuit outage rate for different arrester installations are monitored.
IEC Class II polymer housed line surge arresters, having rated voltage of 120 kV are installed in parallel to line post insulators (Figure 3.b).

Results of the simulations for the different tower footing resistances and different line surge arrester installation configurations are presented in Figures 4 and 5.

Figure 4 presents line total flashover rate. For line without line surge arresters almost all stokes collected by the line produce line insulation flashover (86,47 Flsh./100km/y). By the installation of line surge arresters on the top conductors only, line lightning performance is substantially improved.



a) Line geometry

b) LSA installation (FPL)

Figure 3 - Double circuit 138 kV compact line / LSA Installation

Figure 5 presents line double circuit outage rate, which highly depends on the tower footing resistance. Double circuit outage rate may be improved by the installation of line surge arresters.

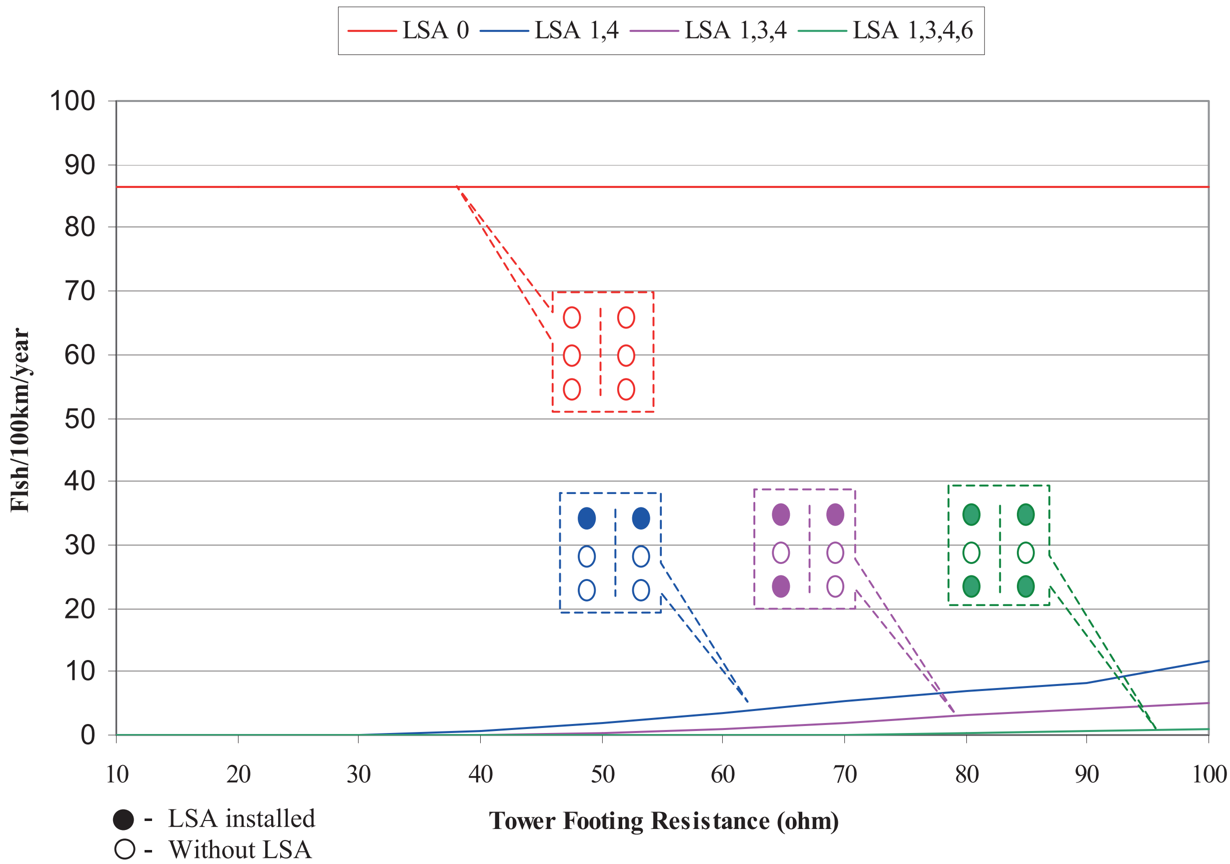


Figure 4 - Line Total Flashover Rate
[Flashovers/100 km/year]

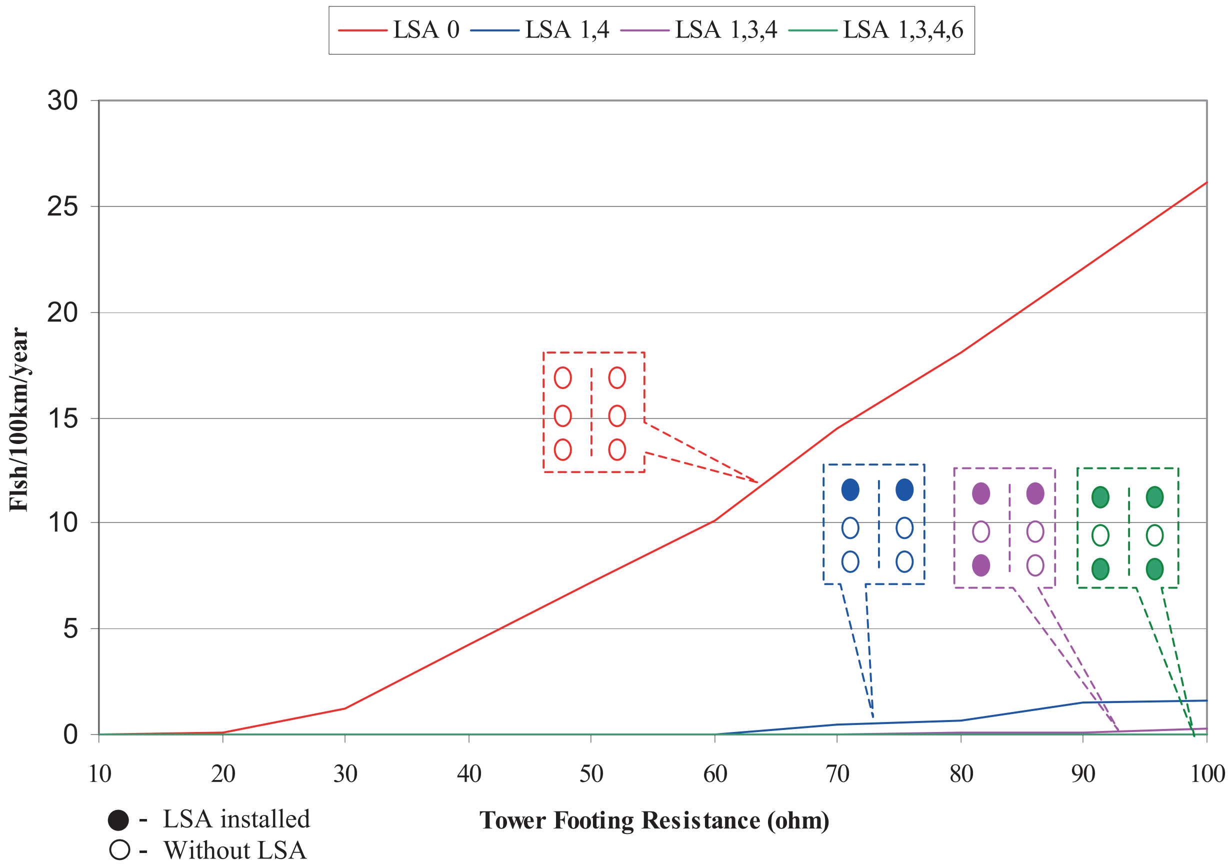


Figure 5 - Line Double Circuit Flashover Rate
[Flashovers/100 km/year]

5. CONCLUSIONS

1. Thanks to the development of the composite line post insulators, compact line designs become a very realistic alternative to the standard line designs. Line voltage upgrading of the existing lines will also benefit from the composite line post insulators.
2. The application of the polymer housed line surge arresters has increased over the last decade. These devices are mainly used for the improvement of the line lightning performance and for the reduction of the double circuit outages.
3. The use of line surge arresters in the compact line design insulation coordination becomes a very important task. The quality of the service of the compact lines can be substantially improved by the use of these devices.
4. Software packages **sigma slp** enables very easy and fast determination of an optimum arrester installation configuration.

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The Possibility of Insulation Level Reduction on 110 kV Overhead Line with Built-in Post Insulators Using Line Surge Arresters

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SUMMARY

Installation of line surge arresters (LSA) on overhead lines is normally accomplished with aim of line performance improvement. Co-ordination insulation procedure carried out during the line design in most cases doesn't take into account a suppression of overvoltages by using any overvoltage limiting devices. The decision supported by poor line performance to install LSA is usually made later. The reduction of overvoltage level depends mainly on the number of LSA installed, but in any case it is considerable. It means that insulation regarding dielectric strength might this way be over dimensioned. This fact could be considered for reduction of phase-to-ground and phase-to-phase distances, which lead to greater level of line compaction. This is of the most importance for lines with post insulators, since shorter insulators could be used and consequently narrower right of way achieved. Our target was to investigate the possibility of reducing lightning overvoltages by using LSA's attached parallel to the insulators. For the analyses purpose we implemented a mathematical model of a single-system 110 kV compact overhead line. The Sigma Slp software was used for computer simulations. The line was investigated from the perspective of lightning over-voltages as they are the factors the most severely stressing the insulation. We focused to lightning strikes at a tower top for the case of single-phase (C) LSA installation configuration. The main influencing parameters were varied such as lightning current, surge shape and tower earthing resistance according to their most probable values to obtain overvoltage properties. We concluded, that adoption of LSA's does not only reduce the overvoltage amplitude in that phase but also changes its shape, which has to be taken into account for test impulses generation. The physical model of wooden pole with composite line post insulators was built for testing in high-voltage laboratory. Power frequency and impulse tests were performed on insulators (phase-to-ground) and between phase conductors (phase-to-phase) in dry and wet conditions when necessary. Besides standard also non-standard impulse shape tests were accomplished to obtain withstand voltages for different arching distances. Based on our comparison with the simulation results we concluded that - speaking in terms of lightning overvoltages - it is possible to use insulators for the insulation level U_m = 72,5 kV (140/325 kV), if LSA's in phases A, B and C would be installed. To verify the conclusion in all other respects, further analyses are needed.

KEYWORDS

Compact line, 110 kV, post insulators, overvoltages, insulation level reduction, line arresters, high-voltage laboratory, tests, Sigma SLP, computer simulations.

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1. Introduction

Improvement of the overhead power transmission line (OL) performance is usually accomplished by installation of OL surge arresters (LSA). In majority of cases, the insulation coordination procedure, undertaken in the line design phase, pays no attention to suppression of overvoltages by using any of the currently available overvoltage limiting devices. The decision to cope with the poor OL performance by installing LSA is usually taken much later. Decreasing the overvoltage level depends mainly on the number of LSA's installed. While the decrease is, irrespective of this number, always considerable, there might be cases – speaking in terms of dielectric stress – when insulation can be unnecessarily over-dimensioned. This fact should be considered in order to reduce phase-to-ground and phase-to-phase distances thus allowing for a greater level of line compaction.

The above is particularly important for OL's equipped with post insulators for which shorter insulators can be used assuring numerous advantages (a narrower OL right-of-way, reduced environmental impact, possibility of uprating the MV line to operate on the 110 kV voltage level, etc.). The focus of our study was on a 110 kV single-circuit OL equipped with in-built composite post insulators and ground wire. OL was investigated from the perspective of lightning overvoltages as they are the factors the most severely stressing the OL insulation. On the other hand, temporary voltages are moderate due to the directly grounded neutral (earth-fault factor k_{ef} being less than 1.4 in 94 % of the power stations, earth-fault clearing time $t_{ef} = 1$ s). The same can be said also for switching overvoltages (only single-phase re-closure is used) which can be further suppressed by means, for example, controlled switching. Our target was to investigate the possibility of reducing lightning overvoltages by using LSA's attached parallel to the insulator in the lowest phase C (smallest coupling factor k_c [1]). In order to improve the OL performance, LSA can by all means be installed in two or all the three phases. We investigated only LSA with no serial gap because the residual voltages it produces are lower, meaning that overvoltages can be limited more effectively.

2. Lightning overvoltage simulations

To define the OL insulation level, we analysed any of the possible variations in the lightning overvoltage level. The nature of overvoltages under various OL operating conditions was determined by performing several computer simulations (lightning flash striking at OL), for which we used the Sigma Slp software. Let us mention at the beginning, that "phase-to-ground voltage" in following text is actually related to the tower top, which during transients is not at the ground potential.

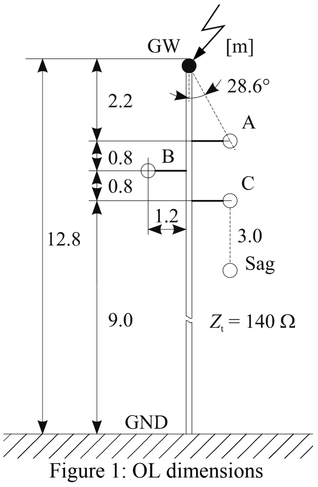

Figure 1: OL dimensions

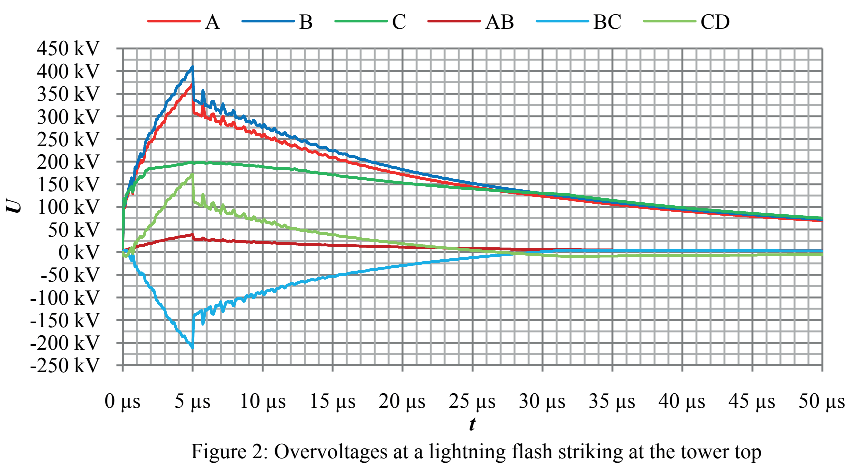

Figure 2: Overvoltages at a lightning flash striking at the tower top
($I_l = 40$ kA, 5/75 µs, $R_g = 10\ \Omega$, line voltage is 0 kV)

For the purpose of our investigation we implemented a mathematical model of a single-system compact OL. The tower was represented with OL with surge impedance $Z_t = 140\ \Omega$ and ionisation footing resistance (IEC 60071-2). The constant value of 10 was taken for low-current resistance R_g to soil resistance ρ [Ωm] ratio. Three OL post insulators were used for conductor attachment. The OL dimensions are shown in Figure 1. As the vertical distances between insulators were short, the tower top wave travelling paths were neglected. We modelled five representative successive towers (the OL span was 92 m). They were terminated so as to ovoid reflections on each side. The line was energized with a three-phase 110 kV voltage, because the total overvoltages, consisting of the OL voltage and lightning overvoltages, have to be considered [1]. As the rated LSA voltage had to be as low as possible (the system parameters being $U_m = 123$ kV, $k_{ef} = 1.4$, $t_{ef} = 1$ s) in order to enable better overvoltage limitation, $U_r = 90$ kA was selected.

Our main interest was to know what happens when a lightning strikes at a tower top for the case of single-phase (C) LSA installation configuration on all towers (Figure 2). The current impulse shape used in our simulations was triangular (linear - front, tail). The main parameters were varied according to their most probable values [1]: lightning current $I_l = 10 \dots 40$ kA (first stroke), surge front $t_f = 10 \dots 40$ µs and tail duration $t_t = 30 \dots 200$ µs, earthing resistance $R_g = 5 \dots 100$ Ω. The most unfavourable parameter values were combined (for example high R_g high I_l taking place at the same time) and examined in more detail. In each case, the operating voltage instant value was added to the overvoltage amplitudes. Figure 3 shows the total overvoltage amplitudes with respect to operating voltage phase angle. Maximum values (U_B, U_{BC}, U_C) for different parameters (R_g , I_l) can be found in Figure 4.

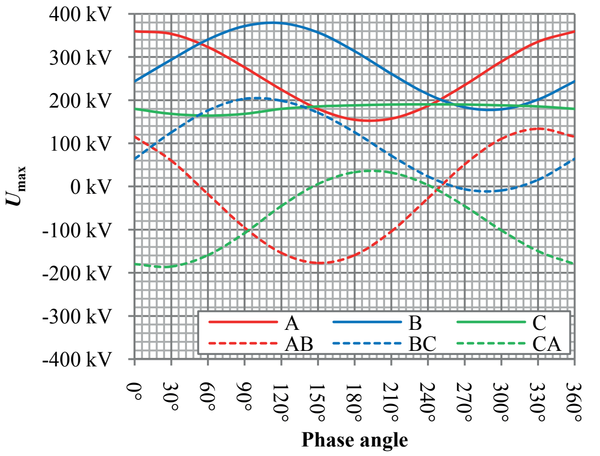

Figure 3: Maximum overvoltages (operating voltage 110 kV included)

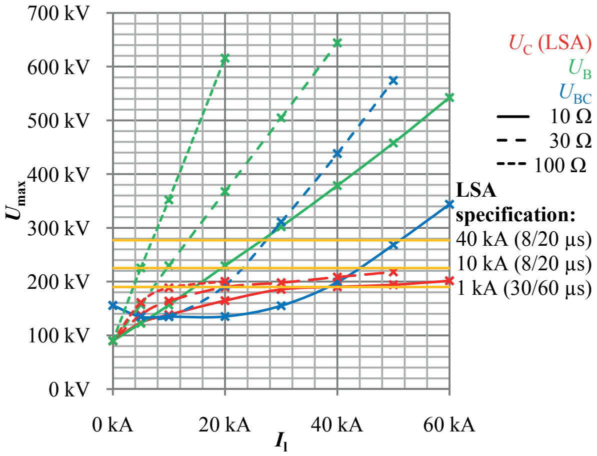

Figure 4: Maximum $U_{max}(I_l , R_g$, 5/75 µs) with respect to 110 kV

Judging from the results obtained with our simulations of overvoltages involving phases A and B (without LSA), the following conclusions can be drawn:

- The overvoltage amplitudes for typical wave front duration t_f are affected mostly by lightning current peak value I_l and tower footing resistance R_g (Figures 4 and 6).
- Higher lightning current steepness (t_f) increases the overvoltage amplitude (Figures 5 and 6). On the contrary, surge tail duration t_t (time to 50 % amplitude) is of no importance with this respect.
- Overvoltage duration t_t is moderately affected by I_l shape (the descending part) which is the consequence of travelling wave reflections, mainly from the tower grounding [1].
- Phase-to-phase overvoltages are small because of short distances between conductors and thus similar coupling factors k_c. In fact, LSA operation in phase C increases them (Figure 2). Anyway, they are never higher than the phase-to-ground overvoltages.

The overvoltages in phase C (LSA installed) are defined by I_l and *U-t* arrester characteristics and thus becoming flat with long impulse duration t_t (Figure 2). Except in case of a shielding failure, they take the value of some 200 kV (roughly).

We also considered some other typical cases. The reference values valid for the following statements are: LSA installed in phase C, BIL 550 kV (phase-to-ground and phase-to-phase insulation), I_l shape 5/75 µs, $R_g = 10$ Ω, no operating voltage on OL. It should be noted that the shielding failure (lightning stroke to phase A or B) initiates a single-phase flashover even when the current is very low, such as

I_l = 3 kA. An exception is a direct stroke to phase conductor C. Anyway, because of high I_l through the arrester, the overvoltages can increase considerably. In phases A and B, induced voltages are not so high, but the polarity is opposite for high I_l values. This means that phase-to-phase overvoltages become critical reaching 550 kV at approximately I_l =100 kA.

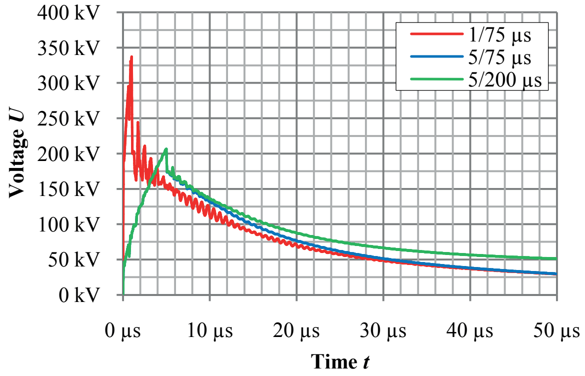

Figure 5: Phase B overvoltages for variable t_f – samples (I_l = 40 kA, R_g = 10 Ω, line voltage is 0 kV)

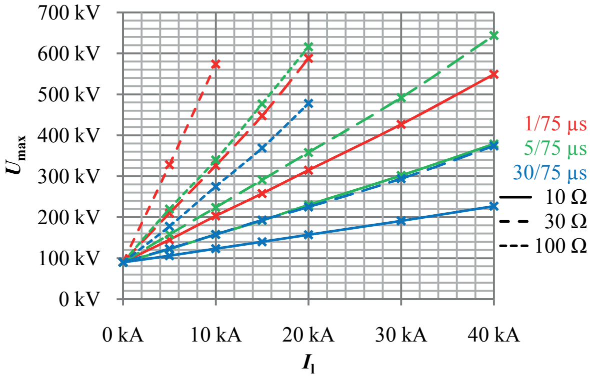

Figure 6: $U_C(t_f, I_l, 240°)$ characteristics

The best line performance for the standard case is to be expected with LSA installed in phases A, B and C resulting in low overvoltages in any of them. Again, the insulators are dielectrically stressed by the arrester residual voltage. In this way, the phase-to-phase overvoltages are practically zero. The shielding failure causes no flashover even at I_l =100 kA and R_g = 50 Ω despite higher overvoltages for which the highest phase-to-phase values were obtained as a result of the reasons given above.

Speaking in terms of the OL insulation dielectric stress, we can in general conclude that shapes of the phase-to-ground and phase-to-phase overvoltage are well matched with the standard lightning impulse of 1.2/50 µs. Adoption of LSA's does not only reduce the overvoltage amplitude in that phase but also changes its shape. The top is flattened and surge duration t_t is longer especially under unfavourable operating conditions, for example at high I_l and long t_t. Since the dielectric strength in air gaps depends on overvoltage characteristics [2] [3], the test voltage shape for this last case has to be adapted accordingly. For any other overvoltage level, the standard lightning impulse is appropriate.

3. High-voltage tests

The crucial characteristics for an insulator is its withstand voltage U_w. We began our measurements with standard dialectic tests performed on the entire insulator. As a reference we took the withstand voltages U_w for the insulation level U_m = 72.5 kV. For this purpose we made a physical model of the compact line tower equipped with line post composite insulators. They were attached in a vertical delta configuration. The conductor was represented with a 3 m long aluminium pipe and hanged up on the insulator with suspension and coupling fittings. The electric field was evenly distributed with spheres at both ends of the pipe. Thus developed model (Figure 7) provided the basis for our testing.

Figure 7: Model of compact line tower with line post composite insulators

We preformed a standard dielectric positive and negative lightning impulse voltage test in dry and alternating voltage test in dry and wet according to specifications of the IEC 60060-1 standard. Our investigation began with lightning-impulse voltage tests (entire insulator). The methods up-and-down (UDM) and multi-level (MLM), each preformed 50 times were used to obtain needed results. 50 %

S. Vižintin, I. Kobal, M. Bečan, The possibility of insulation level reduction on 110 kV overhead line with built-in post insulators using line surge arresters, Journal of Energy, vol. 60 Number 1–4 (2011) Special Issue, p. 47-54

disruptive discharge voltage U_{50} and the overall discharge characteristics were determined with a statistical analysis of the obtained test results on the basis of the maximum likelihood method [4].

The insulators U_{50} at a positive (649 kV) lightning impulse test is lower than at a negative (689 kV) one. We therefore preformed tests at a shorter phase-to-ground arcing distances l_{ad} only for positive lightning impulses. The insulator creepage distance sheds were bridged with a copper ring connected to the ground and in this way l_{ad} was shorter. An equivalent to the shorter insulator was thus achieved and the impact to U_{50} assessed. The obtained results are shown in Figure 8.

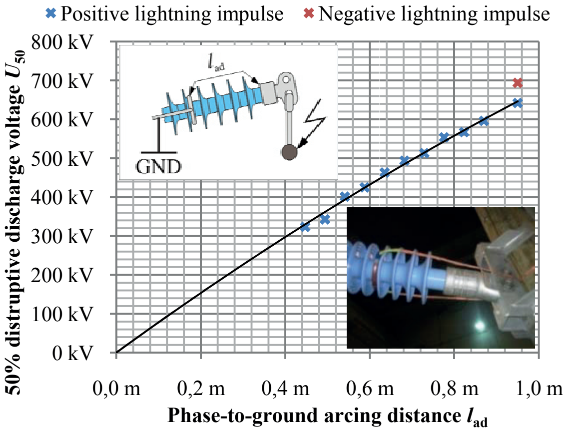

Figure 8: U_{50} as a function of phase-to-ground l_{ad}

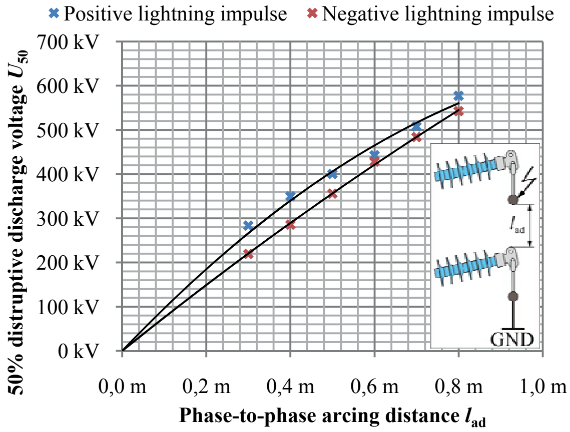

Figure 9: U_{50} as a function of phase-to-phase l_{ad}

We then determined U_{50} as a function of phase-to-phase l_{ad}. The conductor was at both phases replaced by an aluminium pipe. Shortest l_{ad} was found to be between phases that are one above the other. The lower phase was connected to the ground and the upper to the impulse generator. The obtained results are given in Figure 9. It can be seen that the worst case scenario is the one with the negative lightning impulse. The required lightning impulse withstand voltage for $U_m = 72.5$ kV is $U_w = 325$ kV and is equal to 10 % disruptive discharge voltage U_{10}.

Our next step was determination of alternating withstand voltage U_w as a function of phase-to-ground and phase-to-phase l_{ad} in dry or wet conditions. The obtained results are presented in Figure 10 and 11. The required alternating withstand voltage (50 Hz, 1 min.) for $U_m = 72.5$ kV is $U_w = 140$ kV.

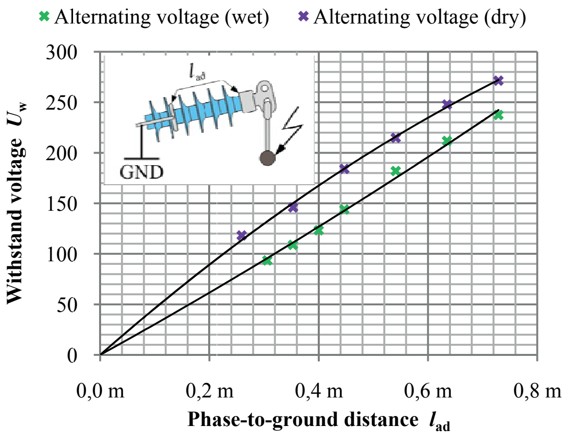

Figure 10: U_w as a function of phase-to-phase l_{ad}

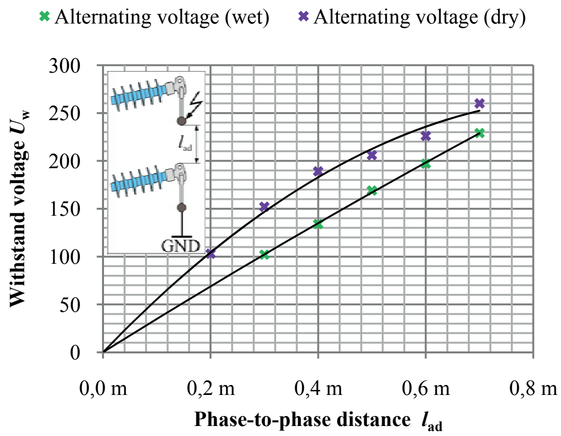

Figure 11: U_w as a function of phase-to-phase l_{ad}

U_{50} being dependent on the impulse descending part [2], the impulse-generator discharge resistors were changed so as to achieve longer times to the half-value, i.e. approximately 900 µs, with the front time remaining the same. From this point onwards it is described as a 1.2/900 µs impulse. The results obtained with 1.2/900 µs positive impulse tests are shown in Figure 12. U_{50} decreases if the length of the wave increases.

As it was established by computer simulation results the overvoltage shape in phases with LSA installed is specific, i.e. flat top and longer durations (Figure 2). We took an effort to achieve a similar overvoltage shape by varying the flat top width and peak voltage. A certain impulse width and peak voltage are achieved by placing the surge arrester parallel with the insulator. To adapt the parameters, we changed the arresters rated voltage. This requires fine adjustment which can be achieved by a different number of zinc oxide ZnO blocks connected in series. Using the testing UDM method was found inappropriate. Namely, the ZnO surge arresters and blocks heated up upon each lightning impulse for which reason their characteristics altered. We therefore used another approach in which the charging voltage was changed in small steps. We wrote down the last peak voltage and width t_{90} (at 90 % peak value) of withstand prior to discharge. Figure 13 shows the dependence of the peak value on t_{90}.

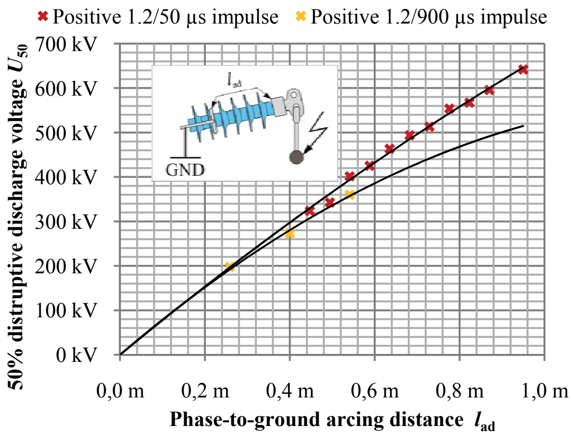

Figure 12: U_{50} as a function of phase-to-ground l_{ad}

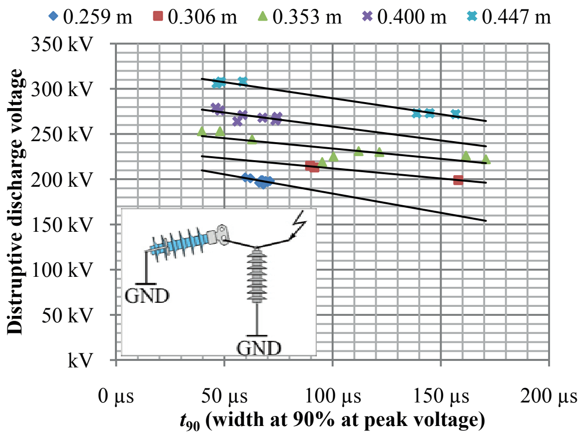

Figure 13: Voltage and shape dependency on discharge

The purpose of our next test was to determine the impact of the potential rings on U_W and U_{50}. We bridged nine sheds and l_{ad} was 0.494 m regarding the copper ring and upper metal part of the insulator. The test was preformed with a 1.2/900 µs positive impulse in dry and alternating voltage in dry and wet. The results are shown in Figures 14 and 15. We were also searching the point where the arc changes its sink or origin position. This transition point for different test types is at different distances *d*. Value *d* = 0.00 m is reached when the potential ring is aligned with the copper ring.

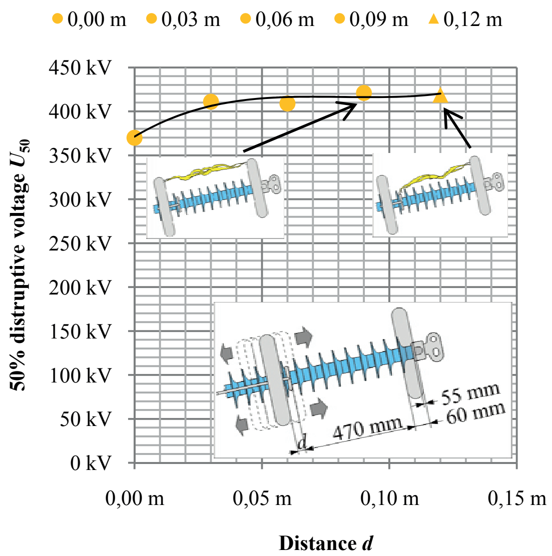

Figure 14: Searching for optimum with positive 1.2/900 µs impulse test

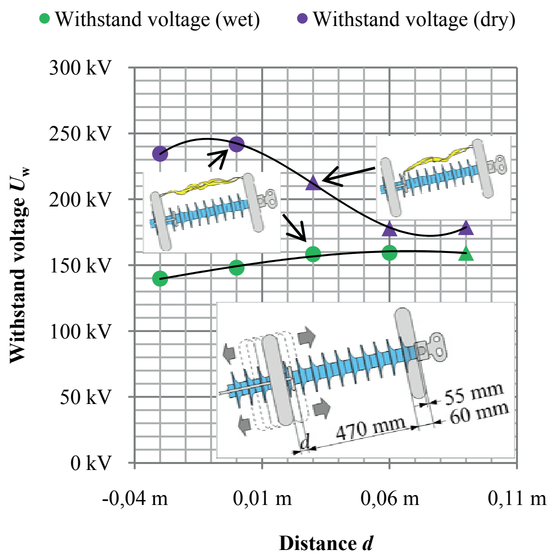

Figure 15: Searching for optimum with alternating voltage test

When shortened insulators are used, surface dielectric stresses caused by the operational voltage are increased. To detect any possible partial discharges under different operational states, we used a corona camera. No surface corona activity at normal voltages in dry was observed.

4. Conclusions

Our investigation of the 110 kV compact OL was based on the assumption that the greatest stress the OL insulation has to withstand is the one caused by lightning overvoltages. To have them defined, we first made several sample overvoltage simulations at lightning strokes for various OL parameters (LSA number, flashover current I_l, wave shape, various grounding resistances R_g). By taking into account the determined overvoltages (amplitude, shape) we then made on a physical model of the OL tower a series of dielectric tests in our high-voltage laboratory. The final target of our investigation was to establish the extent to which the phase-to-ground (support insulators) and phase-to-phase distances can be reduced by applying LSA's.

Based on our investigation results, the following conclusions can be drawn for the case envisaging installation of LSA on each OL tower in the lowest OL phase, i.e. phase C, and under assumption that BIL (phase-to-ground and phase-to-phase) is 550 kV:

- The most unfavorable lightning overvoltages take place at lightning flashes directly striking into the OL tower if shielding failures are avoided.
- The increase in the phase-to-ground overvoltage levels is mostly affected by higher amplitude values or front duration t_f of flashover current I_l and tower grounding resistance R_g . Also to be taken into account is the momentary value of the operating voltage.
- In majority of cases the lightning flash that strikes into either conductor A or B (with no surge arrester) gives rise to unwanted flashover.
- The phase-to-phase overvoltages are lower than the phase-to-ground ones except at the time of a shielding failure occurrence, in which the lightning strikes into phase C (phase with LSA).
- The overvoltage in the phase with LSA is determined with the *U-I* arrester characteristic.
- The highest possible OL operational reliability rate (close to 100 %) is obtained by installing LSA's in all the three phases, i.e. phase A, B and C.

To provide for a comparison, Figure 16 lists the required flashover lengths l_{ad} at the insulator and between two phases with regard to the observed insulation level U_m = 72.5 kV (140/325 kV), the first one being lower related to U_m = 123 kV (IEC 60071-1).

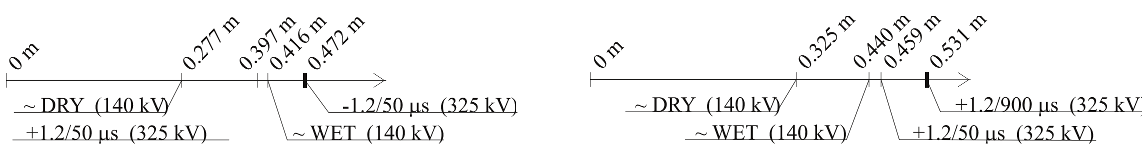

Figure 16. Flashover *clearing* distance l_{ad} at the insulator and between two phases with regard to the insulation level U_m = 72,5 kV (140/325 kV).

Based on our comparison with the simulation results we can see that - speaking in terms of lightning overvoltages - the insulators for insulation level U_m = 72,5 kV (140/325 kV) might be used, if LSA's in phases A, B and C would be installed. The insulators could then be substantially shortened. Off course l_{ad} = 0,54 m is not the lowest level since for insulator dimensioning we have to take into consideration at least the insulation co-ordination correction factors. On the other hand using potential rings, this distance could again be considerably shortened. The same applies for the phase-to-phase distances. To determine criteria allowing for reliable operation of such designed OL, a considerable number of simulations of overvoltage phenomena should be accomplished, to obtain statistical results. Such analyses for OL with reduced number of LSA (i.e. phase C only) would probably show poor line performance. The investigation should address also temporary and switching overvoltages.

It should herewith be well noted that by doing so one of the basic insulation co-ordination rules has been violated, namely, $U_m = 72{,}5$ kV does not correspond to the system operating voltage ($U_m = 123$ kV). This gives rise to an increase in the dielectric stress on the insulator surface which - particularly at the time when pollution is critical - may result in accelerated material ageing (silicone rubber) and eventual flashovers at the time of temporary overvoltages and even during normal operation. Though the investigation made with a corona camera in our high-voltage laboratory revealed no occurrence of partial discharges, the issue of insulation ageing under the condition of strong electric field should be dealt with under a special research.

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Experience of Tyco & Antamina in the Lightning Performance and Reliability Improvement of 220 kV Transmission Lines in Peru

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SUMMARY

The Antamina Mine is located in the Antamina valley in the Andes Mountains in the Ancash region of north-central Peru, approximately 270 kilometers north of Lima, Peru. Antamina Mine operations began in late 2001, with an estimated mine life of more than 20 years. The deposit is one of the largest copper-zinc ore bodies in the world.

Antamina Mine is electrically connected to five 220 kV transmission lines located in regions with isokeraunic levels from 15 to 90 thunderstorm days per year. In the period from 2002 to 2006, 80 non-schedule outages due to lightning which have affected the process productive have been observed in these lines. Antamina has too a 23 kV overhead shielded distribution ring network in which outages due to lightning have been also observed. In the middle of 2003 Antamina started to work in partnership with Tyco Electronics in order to evaluate the lightning performance of the distribution and transmission lines. With basis in these studies from January 2006 till June 2007, approximately 450 units of line arresters were installed along the distribution network and 265 gapless transmission line arresters (TLA) were installed along the sections of the two 220 kV transmission lines with poorer lightning performance. From October 2006 on only one outage due to lightning was recorded in these two lines, proving the effectiveness of this protection system.

This paper presents details about the transmission line lightning performance studies and evaluation carried out by Tyco Electronics and Antamina in this partnership project. Methods to select the arresters characteristics and to define the quantity and the optimized arresters location along the lines are presented. Field experience obtained in these two first years and the line performance / reliability of the system after the TLA application in comparison with the performance before the arresters' installation are presented and discussed.

KEYWORDS

Transmission Line Arresters, Lightning performance, Lightning outages, Lightning Protection.

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INTRODUCTION

The Antamina Mine is located in the Antamina valley in the Andes Mountains in the Ancash region of north-central Peru. It is situated in the Western Cordillera range at an altitude of 4,300 m above the sea level, approximately 270 kilometers north of Lima, Peru.

The Antamina Mine, mill, and related support facilities are located at an elevation between 3500 m and 4500 m in the Andes, in the headwaters of two small streams which are tributaries of Rio Pucha, which is part of the upper Amazon Basin. The mean annual temperature of the area is about 3°C, with a minimum of -30°C. Mean annual precipitation is approximately 884 mm (recorded at 3,980 m) is mainly between October and May. Topography ranges from humid forest in the valleys and alpine fluvial tundra to very wet sub-alpine formations at higher levels.

Antamina Mine operations began in late 2001, with an estimated mine life of more than 20 years. The deposit is one of the largest copper-zinc ore bodies in the world. The mine is expected to produce an average of 675 million pounds of copper and 625 million pounds of zinc annually in its first 10 years. The mill has a rated capacity of 70,000 tones per day. A 302 km long slurry concentrate pipeline transports concentrates to the port facility at Huarmey on the Pacific Ocean, where they are dewatered, stockpiled, and shipped by sea. The operations produce separate copper, zinc, lead and molybdenum concentrates. Antamina employs over 1,400 people directly and 3,500 indirectly.

Antamina Mine is electrically connected to five 220 kV transmission lines with a total length of approximately 566 km, which are located from 500 m up to 4,800 m above the sea level in regions with isokeraunic levels varying in the range from 15 to 90 thunderstorm days per year. In the period from 2002 to 2006 these lines presented 80 non-schedule outages due to lightning which have affected the process productive. Antamina has too an overhead shielded distribution ring network with length of approximately 14.4 km and outages due to lightning have been also observed on this line.

In the middle of 2003 Antamina started to work in partnership with Tyco Electronics in order to evaluate the lightning performance of the distribution and transmission lines. Studies have been done to evaluate the current lightning performance of the lines and to define the critical sections with a poor lightning performance. During the years of 2006 and 2007, approximately 450 units of line arresters with rated voltage of 27 kV were installed along the distribution network. The good results obtained after the arresters installations have encouraged Antamina to install arresters along the 220 kV transmission lines and in September / October of 2006, 135 units of gapless transmission line arresters with rated voltage of 192 kV were installed on the most critical sections of two lines that had previously recorded a poorer lightning performance. During the first thunderstorm period (October / May) after arresters' installation only one outage was recorded on one of these lines, in the section of the line not covered yet by line arresters. In the first semester of 2007, more 130 units of TLA with same electrical characteristics were installed along the critical sections of L-2254 and until February 2008 no outages were recorded on both lines, proving the effectiveness of this protection system.

TRANSMISISON LINES CONNECTED WITH ANTAMINA SYSTEM

Antamina Mine is connected to five 220 kV transmission lines with a total length of approximately 566 km and 1280 steel towers. The lines are located from 300 m up to 4,800 m above the sea level in regions with isokeraunic levels varying in the range from 15 to 90 thunderstorm days per year. The main source of electrical energy for Antamina Mine comes from the Aguaytia's thermal headquarters through a 220 kV transmission line that connects it with the principal North-South energy system in Paramonga. This line connects a series of existent substations including the substation Tingo Maria to 73 km of the headquarters of Aguaytia (L-2251), the substation Vizcarra (L-2252) and the substation Paramonga Nueva (L-2253). The substation Paramonga Nueva is an important regional substation since it receives energy coming from the hydroelectric headquarters of Cahua and it provides a 66 kV transmission line to supply energy to the substations of Huacho and Huarney, in the port facilities of the Antamina's project.

The electric power supply for the operation of the Mine is provided by a 220 kV transmission line operating between the substation Vizcarra and the substation Yanacancha from Antamina (L-2255). The route of this transmission line rises in a mountainous land from 3,500 meters above the sea level in Huallanca to a maximum altitude of 4,600 m. This line has a length of 52.5 km with 131 steel towers. Antamina Mine is still connected with 220 kV transmission line "Paragsha – Vizcarra" (L-2254), whose operation was begun in September 2002. This line has a length of 121.1 km with 287 steel towers and the route of the line presents mountainous regions with altitude from 3,250 to 4,600 m above the sea level. Since September 2007 a new line L2262 (Vizcarra – Huallanca nueva) has been taking part of the 220 kV system connected to Antamina. A schematic diagram of the lines connected to Antamina is shown in Figure 1. Table 1 shows information about the characteristics of the lines.

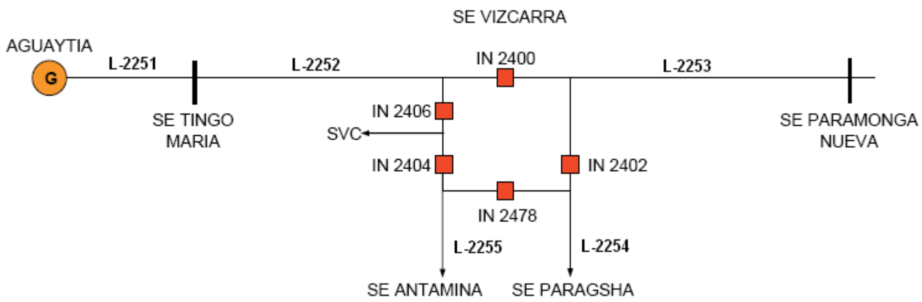

Figure 1 – Schematic diagram of the 220 kV transmission lines connected to Antamina

Table 1 – Parameters of the transmission lines

Transmission line	Length (km)	Number of towers	Altitude (m.a.s.l.)	Keraunic Level
L-2251	73.3	158	300 - 1,800	70 – 90
L-2252	173.3	366	700 - 4,100	40 – 60
L-2253	145.6	338	300 - 4,800	15 – 40
L-2254	121.1	287	3,250 – 4,600	60
L-2255	52.5	131	3,500 – 4,600	60

Antamina has too an internal 23 kV overhead shielded distribution ring network with length of approximately 14.4 km, that is for feeding of several load centers used for the mine's production process. This line begins in main 220 / 23 kV substation and is located to an average altitude of 4,500 m above the sea level. Typical configuration of the line presents horizontal disposition in wood poles. However there are sections of the line with steel towers and triangular disposition, besides a smaller section with vertical disposition in wood poles. The whole line is shielded by an overhead ground wire type EHS with section of 38 mm^2 and the line insulation is basically composed by insulators strings type suspension with 4 insulators and by insulators type pin ANSI 56-4.

TRANSMISSION LINES LIGHTNING PERFORMANCE AND GENERAL STUDIES TO EVALUATE THEIR IMPROVEMENT

From 2002 to 2006 Antamina has experimented 80 non-schedule outages due to lightning on five 220 kV transmission lines, which have affected the process productive with significant losses, in spite of more than 95% of these outages have transitory characteristics. Information about the number of outages due to lightning are shown in Table 2. From these outages, 33 outages (approximately 41%) have occurred along the transmission lines L-2254 and L-2255. Outages due to lightning have been also observed on the 23 kV distribution network. From January 2005 to January 2006, 11 outages were recorded carting total losses of 720 MW to the interruption in the production, with an average loss of 55.4 MW / month. Aiming the improvement of the lightning performance of the lines and its system reliability, Antamina started to develop in the middle of 2003 technical studies in partnership with Tyco Electronics. Studies have initially been done to evaluate the lightning performance of the distribution lines; to define the critical sections of the 220 kV transmission lines with a poor lightning performance; and to improve the earthing systems of the 23 kV and 220 kV lines.

Table 2 – Outages on 220 kV transmission lines due to lightning from 2002 – 2006

Year	L-2251	L-2252	L-2253	L-2254	L-2255
2002	4	6	0	4	1
2003	2	2	3	3	3
2004	3	6	3	8	2
2005	0	6	1	9	0
2006	4	2	5	3	0
Total	13	22	12	27	6
Outages / 100 km . year (Average from 02-06)	3,55	3,17	1,65	4,46	2,31

With basis in these studies, improvements were done in the earthing system of the line L-2255 and during the years of 2006 and 2007, approximately 450 units of class 2 gapless line arresters with rated voltage of 27 kV were installed along the 23 kV overhead shield distribution network. Figure 2 shows details of the line arresters installed on steel and wood structures for 23 kV.

Figure 2 – Class 2 arresters installed on 23 kV overhead shielded distribution network

The Antamina's production interrupted from January 2005 to January 2006 due to lightning outages on 23 kV lines before arresters' installation was 720 MW, with an average of 55.4 MW / month. After arrester's installation the losses from Feb. 06 till March 07 were reduced to 32 MW with an average of 2.5 MW / month. The good results obtained during the first thunderstorm period after the arresters installations in the distribution network have encouraged Antamina to install arresters along the 220 kV lines and, in the second stage of the study, more detailed lightning performance studies have been done to evaluate the lightning performance of the lines L-2254 and L-2255, which have shown approximately 41% of the total outages that have affected the process productive of the Mine.

The transmission line L-2254 has a total length of 121.1 km, 287 steel towers and typical configuration of the line presents four types of steel towers for single circuit with a triangular disposition of the conductors. Phase conductors are type FINCH ACSR 1113 MCM and the insulation is basically composed by insulators type composite and glass insulators with 18 insulators. Transmission line L-2255 has a total length of 52.5 km, 131 steel towers and typical configuration of the line presents three types of steel towers for single circuit. Phase conductors are type CURLEW ACSR Section of 591.2 mm^2 and the insulation is composed by glass insulators type Socket-Ball with 20 insulators for suspension and 21 for deadend strings. Both lines are shielded by two overhead ground wires type Extra High Strength (EHS) with diameter 9.52 mm and have the grounding systems composed by vertical electrodes and counterpoises. Lines L-2254 and L-2255 present approximately 88% and 92% of the towers with tower foot resistance values lower than 15 Ω. In spite of this from 2002 to 2006, 27 and 6 outages due to lightning affecting the Antamina system have been observed in the lines L-2254 and L-2255 respectively, carting average losses due to the interruption in the production of 45.6 MW / interruption for line L-2254 and 69.8 MW / interruption in the line L-2255.

Two different studies have been performed to evaluate the overhead lines lightning performance, using the procedures proposed by CIGRÉ [1] and IEEE Std.1243 [2]: (1) – lightning line performance estimate studies, in which transitory overvoltages across the insulators strings were obtained through computational simulations for different lightning current magnitudes and rise times. The main purpose of this study was to estimate the number of outages per hundred kilometres a year of the both lines due to backflashover, for the current configuration and for the different methods considered and proposed for the lightning performance improvement; (2) - studies to define the maximum energies absorbed by the line arresters, taking into account the lightning characteristics, the grounding system behaviour for fast transients and the probability of multiple strokes occurrence. Surge arresters models for fast transients were considered to get more reliable results in the energy studies.

Initially was evaluated the effect of the different towers types on the transmission line lightning performance. Towers which have presented the most critical behaviour were considered in the next stage of the study. Then transmission lines outages were evaluated for the critical towers, considering current configuration and the lightning performance improvements methods evaluated. These studies were done considering altitudes above the sea level from 3,200 m to 4,600 m. Starting from the results obtained in the studies and in the target outages desired for the lines, 135 units of class 2 gapless transmission line arresters (TLA) with rated voltage of 192 kV were installed in the second semester of 2006 on the most critical sections of the lines L-2254 and L-2255, considering the following criteria: (a) - for line L-2255, 45 TLA were installed on all phases of the 15 critical towers. These towers were chosen with basis on the lightning performance studies and in the historical of the critical points of the line, obtained through the failures analysis. Figure 3 shows TLA installed along the L-2255; (b) - for line L-2254, 90 TLA were installed on 49 towers along the sections of the line with poorer lightning performance. The locations of TLA were chosen with basis on the lightning performance studies, on the historical of the critical points of the line, and on the technical report from ISA Colombia [3]. Three TLA were installed on 19 towers; two TLA on 3 towers in the bottom and in the middle phases; and one TLA on 27 towers, being 16 in the bottom phase, 5 in the middle phase and 6 in the top phase (in this case for shielding failure protection). The installation procedure was witnessed by Interconexión Eléctrica ISA Perú S.A., owner of the line. During the first thunderstorm period (October / May) after arresters' installation no outages have been recorded on line L-2255 and only one outage was recorded on line L-2254 in the section not covered yet by line arresters.

Figure 3 – Class 2 TLA with rated voltage of 192 kV installed along 220 kV line

The rated voltage of 192 kV was selected to TLA taking into account the maximum temporary overvoltages for the lines and their durations considering the systems effectively earthed. Maximum energy obtained in the studies was below 650 kJ to a discharge current of 100 kA and tower foot resistance of 150 Ω. It corresponds to class 2 arresters. Due to the installation in the altitude from 3,250 m to 4,800 m above the sea level, combined with the contamination and environmental characteristics of the region, the TLA were selected with a minimum creepage distance of 9,765 mm. It means 25 mm / kV, taking into account the correction factor by the altitude. Lightning impulse withstand voltage for the TLA housing is 1050 kV, while the lightning impulse protective level of TLA is 510 kV. It corresponds to a factor 1.29 between the lightning impulse withstand voltage of the housing (taking into account the correction factor due to the altitude) and the TLA protective level.

In May / June of 2007, more 130 units of TLA with same electrical characteristics were installed along the line L-2254. After this, the line L-2254 presents 220 TLA installed on 137 towers along its sections, being 80 towers with 1 TLA installed in the bottom phase, 31 towers with TLA installed in the bottom and in the middle phases, and 26 towers with TLA installed on all three phases.

From January till September 2007 Antamina has experienced four outages on transmission lines which have affected the Mine, being 2 outages in the line L-2251 and 2 in the line L-2252. Until February 2008 no outages were recorded on lines L-2254 / L-2255, proving the effectiveness of this protection system. Based on the initial results obtained in these two lines, Antamina and Tyco have started to work in the lightning performance evaluation of the lines L-2251, L-2252 and L-2253, in which there is an intention of installing TLA in this year in order to improve their lightning performance.

CONCLUSIONS

- Antamina Mine is connected to five 220 kV lines that presented from 2002 to 2006 a number of 80 non-schedule outages due to lightning which have affected the productive process. From these, 33 outages (approximately 41%) have occurred along the lines L-2254 and L-2255.
- Aiming the improvement of the lightning performance and its system reliability, Antamina has developed in partnership with Tyco Electronics technical studies in order to evaluate the lightning performance of the lines. With basis in these studies, approximately 450 arresters with rated voltage of 27 kV were installed along the 23 kV distribution network and the good results obtained have encouraged Antamina to install arresters along the 220 kV lines.
- Lightning performance study has been done to evaluate the lines L-2254 and L-2255. Starting from the results obtained in the studies, 135 units of class 2 gapless line arresters with rated voltage of 192 kV were installed on the most critical sections of these lines, with significant improvement in their lightning performance. In the first semester of 2007, more 130 units of TLA were installed along the line L-2254, totaling 265 units of TLA installed on these two lines. No outages were recorded on lines L-2254 and L-2255, proving the effectiveness of this protection system.
- Based on the initial results obtained in the lines L-2254 / L-2255, Antamina and Tyco have started to work in the lightning performance evaluation of the lines L-2251, L-2252 and L-2253, in which there is an intention to improve their lightning performance.

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Improvement of the transmission and sub-transmission overhead lines lightning performance using line arresters – Experience in Brazil

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SUMMARY

Lightning has been reported as the major cause of non-scheduled outages that occur in Brazilian's power system, being responsible for approximately 50 – 70% of the outages verified in overhead lines with rated voltages up to 230 kV and creating many issues for power supply utilities and consumers.

In agreement with the information of the National Institute for Space Researche (INPE) Brazil is the country with the largest incidence of lightning activities in the world, with about 50 - 70 million lightning outages a year somewhere in the country. With this considerable amount of lightning caused distubances, the resulting damages caused to the electric power systems are high such that the costs of losses and repairs exceed an annual value of 350 million dollars. This fact has been taken up by several power supply utilities and industrial consumers and caused them to invest in partnership with universities and research centers in the development of theoretical studies and the promotion of improvements along the critical sections of their overhead lines with poor lightning performance, thereby increasing their reliability. In many cases line arresters have been considered as the most effective method to improve the lightning performance.

In Brazil, the first application of line arresters was in the middle of the nineties and from this time on more than 3,000 units of gapless line arresters were installed on overhead lines from 34.5 kV up to 230 kV. The analysis and evaluation of overhead lines lightning performance before and after the line arresters installation have shown a good effectiveness, with average indexes for the improvement higher than 70%. Good field experience and the proven results obtained in the improvement of the overhead lines lightning performance after the line arresters installation have been encouraging more and more Brazilian power supply utilities and industrial consumers to develop studies to evaluate the line arresters application along their overhead lines presenting poorer lightning performance.

This paper presents information about the experience of the Brazilian power supply utilities as well as industrial consumers in the application of line arresters to improve the overhead lines lightning performance. Procedures used to optimize the characteristics of the line arresters, quantity and location along the critical sections of the lines; field experience as well as the lightning performance of the lines before and after the line arresters application are presented and discussed.

KEYWORDS

Line arresters, Overhead line performance, Lightning performance improvement

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INTRODUCTION

The quality and reliability of a power system is related to its ability to supply continuous and uninterrupted energy without significant momentary disturbances. Several factors may affect the indexes of energy quality, such as the system performance against lightning discharges, its configuration and operation characteristics. Lightning has been reported as the major cause of non-scheduled outages that occur in Brazilian's power system, being responsible for approximately 50 – 70% of the outages observed in overhead sub-transmission and transmission lines with rated voltages up to 230 kV. Some undesirable outages have been also observed in overhead transmission lines of 345 kV and 500 kV.

Although most of the non-scheduled outages have transitory characteristics, in many cases this is still deemed, creating many issues for power supply utilities and their consumers. Power supply utilities themselves have verified the load losses due to voltage sags on their systems from transitory outages caused by lightning activity and in some regions they have found serious permanent damages caused to the system itself due to these transitory disturbances occurring on important lines. Losses of power supply are critical for all modern industries now so reliant on sophisticated electronic equipment and especially production processes very sensitive to momentary disturbances on the system.

The Brazilian power system presents as particularity a great extension of transmission and sub-transmission overhead lines, with more than 180 thousand kilometres of extension, being more than 65% of this extension for overhead lines with rated voltage up to 230 kV. The consuming market concentrates mainly on the South and Southeast areas, which are the regions more industrialized.

In agreement with information from the National Institute for Space Research (INPE) Brazil is the country with the largest incidence of lightning activities in the world, with about 50 - 70 million lightning outages a year somewhere in the country. With this considerable amount of lightning caused distubances, the resulting damages caused to the electric power systems are high. Recent studies done by the Atmospheric Electricity Group (ELAT) from INPE show that losses and damages in the Brazilian power supply utilities caused by lightning exceed an annual value of 350 million dollars.

This fact has been taken up by several power supply utilities and industrial consumers and caused them to invest in partnership with universities and research centers in the research programs and field studies, aiming the development of theoretical studies and the promotion of improvements along the critical sections of their overhead lines with poor lightning performance, thereby increasing their reliability. Most of these studies are basically addressed in the optimization of the lightning protection for overhead lines; in the evaluation, better understanding and monitoring of the lightning activities in Brazil and their effects on overhead lines; and in the evaluation, better theoretical understanding and improvements of the grounding systems behaviour for fast transients.

BASIC CONSIDERATIONS ABOUT LIGHTNING INCIDENCE AND ITS EFFECTS ON OVERHEAD SUB-TRANSMISSION AND TRANSMISSION LINES

Lightning phenomena on transmission lines have important consequences in many safety and technical aspects. The problem has special importance in Brazil due to the high lightning activity and unfavorable electric parameters of soil in a large part of the Brazilian territory.

The frequency in which lightning discharges strike on overhead lines depends on some factors and has a strong influence of the environmental conditions: ground flash density level for the area crossed by the line; physical dimensions of the overhead line in special its height and length; presence of naturally shielding objects or other lines within the same corridor, etc. Besides, the transmission line lightning performance usually can vary at each year, depending on the lightning activities of the area.

Environmental conditions highly affect the power system reliability, and the lightning performance of the power installations seems to be unsatisfactory and disagree, sometimes, with conventional performance predictions and simulations [1]. Since the environment where the transmission line is inserted has a direct influence in the lightning activities and in the quality and reliability of the power supply, many technical publications have been presented aiming the monitoring of the lightning activities in Brazil and their effects on overhead lines [2-5].

The lightning detection aiming the monitoring in wide scale began in Brazil in 1988 in Minas Gerais state for initiative of CEMIG. Along the years, several institutions began the development of the similar activities, expanding the lightning monitoring area.

In 2005 three large lightning detection networks were in operation in Brazil [5]: (1) - the National Integrated Lightning Detection Network (RINDAT), that began its operation in 1998, covering the Southeast and some areas of South and Center-west regions of the country; (2) - the Integrated Information System based on a Lightning Detection Network (SIDDEM), that began its operation in the middle of 2005, covering part of the South and Center regions; and; (3) - the SIPAM Lightning Detection Network, that began its operation in the beginning of 2005 covering part of the North and Northeast regions. As a result of the effort of ELAT in partnership with several institutions in Brazil, it was possible to accomplish the integration of these three regional detection networks resulting in the Brazilian Lightning Detection Network – BrasilDAT. Nowadays BrasilDAT network is the largest network in the tropics and the third larger lightning detection network in the world, with detection efficiency (DE) of about 70 – 90% and location accuracy (LA) below 1 km. It provides good information for power supply utilities about the lightning incidence and their locations.

Most of the researches seeking the evaluation and the lightning improvement of the overhead transmission and sub-transmission lines have been done in Brazil using the Ground Flash Density map. Figure 1 shows the cloud-to-ground (CG) flash rate observed in Brazil from 1998 to 2005 by LIS data [5]. Since LIS sensor does not discriminate between CG and intracloud (IC) discharges, its information corresponds to total lightning data. Thus, the values presented in Figure 1 were computed based on IC/CG average ratios assessed by INPE in previous studies.

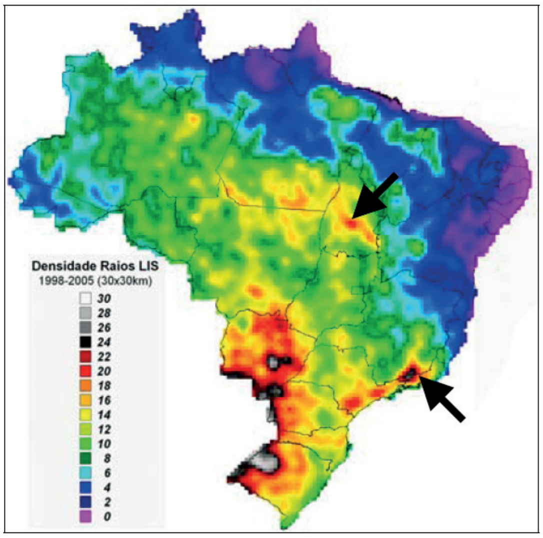

Figure 1 – Geographical distribution of the CG lightning in Brazil estimated from 8 years of LIS data

STUDIES FOR THE IMPROVEMENT OF THE OVERHEAD LINES LIGHTNING PERFORMANCE

The transient behaviour of an overhead line reached by lightning depends on several parameters and factors which need to be take into account during the theoretical studies to evaluate its lightning performance [6-8]: the discharge incidence point; the lightning current characteristic: its magnitude, wave shape and rise time; the transient response of the tower; the electromagnetic coupling among shield wires and phase conductors (for shielded lines); the distance from the tower reached to the adjacent towers; the grounding system response for fast transients; altitude of the tower reached by the lightning, etc. Overhead lines may present several different configurations for the towers, overhead conductors and tower-footing, which establish different transitory responses under lightning stress. Computatonal models and methodologies have been developed to evaluate the lightning transient response of overhead lines taking into account the interaction off all components presented in the line.

Many technical research programs have been developed in Brazil in order to obtain a better knowledge of the transient phenomena associated with the lightning striking on shielded and unshielded overhead lines. Most of these studies are basically addressed in the optimization of the lightning protection for overhead transmission and sub-transmission lines; In the evaluation, better understanding and monitoring of the lightning activities in Brazil and their effects on overhead lines; and in the evaluation, better theoretical understanding and improvements of the grounding systems behaviour for fast transients. Some publications written with basis in these studies until September of 2006 are shown in the references of the technical papers [9-10]. From September 2006 on, technical reports and publications have been published starting from the results obtained in these researches [11-13].

In agreement with the Brazilian Organ Electricity Regulator, the maximum number of transmission lines outages due to lightning depends on the voltage level: one outage per a hundred kilometres a year for voltages equal to or higher than 345 kV; and two outages per a hundred kilometres a year for overhead lines with rated voltage of 230 kV. For overhead lines with rated voltages of 138 kV and below doesn't exist defined yet a maximum number of outages due to lightning. In this case, the maximum number of outages admitted for a specific overhead line is defined by the power supply utility, and depends basically on the importance of the line for the reliability of the whole system and on the economical effects of its outages on the loads connected to the overhead line.

Starting from the results obtained in the theoretical studies and knowing the target number of outages desired for the line evaluated, it is possible to define the methods and procedures more appropriate to improve the lightning performance of the line considered. A technical evaluation should be usually followed by an economical analysis, allowing to the user to analyze and optimize the cost – benefit balance. Among the methods used to improve the overhead lines lightning performance, line arresters have been usually considered in most of the cases as the most effective. Sometimes, its effectiveness and cost – benefit balance increases with the improvement of the grounding systems for fast transients associated with line arresters application.

FIELD EXPERIENCE OF THE BRAZILIAN UTILITIES WITH LINE ARRESTERS APPLICATION

The first application of line arresters in the Brazilian system was in the middle of the nineties, to improve a 34.5 kV overhead radial distribution line from CEMIG. From this time on more than 3,000 units of gapless line arresters were installed on overhead distribution, sub-transmission and transmission lines with rated voltages from 34.5 kV up to 230 kV. From this total, more than 75% were applied in the improvement of the lightning performance for 69 kV and 138 kV lines.

Approximately 70% of all the gapless line arresters installed in Brazil are in the area under concession of CEMIG, located at Minas Gerais State. Besides CEMIG, FURNAS, Ampla, Light, CFLCL, UTEJF, Escelsa, RGE, CEEE, Porto Primavera Transmissora de Energia – PPTE and one industrial consumer - CVRD have been already installed or acquired line arresters to install along their 34.5 kV to 220 kV overhead lines. Details of the line arresters installed are shown in Figures 2 to 4.

The selection criteria used by these utilities to define arresters quantity and location were based on the evaluation of overhead lines or their sections with poorer lightning performance even after the improvement of the grounding systems, and by consumer complaints. Line arresters have been installed in parallel with the insulators strings and the number of line arresters per tower has been depending on the protection philosophy used by the users. In order to obtain good solutions in the technical and economical point of view, lightning performance estimate studies have usually been performed to select the appropriate line arresters characteristics and to optimize the quantity and location of the line arresters along the more critical sections of the overhead lines [14-18].

Figure 2 – Line arresters installed on 34.5 kV line – CEMIG [1]

Figure 3 – Line arresters installed on 69 kV lines: Left CEMIG / Right Ampla

Figure 4 – Line arresters installed on 138 kV lines: Left – CEMIG / Right - UTEJF

The analysis and evaluation of the Brazilian's overhead line lightning performance expressed as the average number of outages per a hundred kilometers a year before and after the line arresters installation have shown a good effectiveness, with average indexes for the improvement higher than 70% for overhead lines with rated voltages from 34.5 kV to 138 kV. Recent publication [19] has shown for CEMIG averages indexes for lightning performance improvement after line arresters installation of approximately 70%, 83% and 90% for overhead lines with rated voltages of 34.5 kV; 69 kV; and 138 kV, respectively. These indexes obtained are in reasonable agreement with the indexes shown in Mexican and Japanese systems.

These indexes can be higher for overhead lines more protected with line arresters. An example is the "Ouro Preto - Mariana", 138 kV overhead line from CEMIG, which presents a high ground flash density level and towers with high tower foot resistances values. Before the installation of the line arresters this line had an average outage index of 41.0 outages per hundred kilometers per year. A partnership project between CEMIG and its industrial consumers fed by this line was developed, and in 1998 line arresters were installed on three phases and on all towers. From 1998 on no outages due to lightning were recorded in this line.

Few registrations of electric and mechanic failures in the line arresters have been observed and detected. Electric failures were attributed to the higher energies absorbed by line arresters during the lightning, while mechanic failures were attributed to the disconnection of some line arresters due to failures in the flexible cable and in the links connection (eye screw) caused by the incidence of strong winds. This mechanic problem was solved by the utility through the reinforcement of the flexible cable and links connection using a steel cable in parallel with the flexible cable connection. This procedure has been applied for the user in the installation of news line arresters and in case of the occurrence of mechanic failures in the arresters already installed. No mechanic fails were observed by the user in the line arresters using this new mechanical configuration.

More detailed information about line arresters performance in the field and their effectiveness in the improvement of the overhead lines lightning performance in the Brazilian's systems have been reported in [1; 10; 16, 19-21].

Good field experience and the proven results obtained in the improvement of the overhead lines lightning performance after the installation of line arresters, have been encouraging more and more Brazilian power supply utilities and industrial consumers to develop studies and research programs to evaluate the line arresters application along their overhead lines with poor lightning performance.

In way to diffusing the technical information referring to the criteria used in the studies seeking the improvement of the overhead lines lighning performance; to increase the line arresters application field and its reliability; as well as to encourage more users and researchers in the participation of lightning studies, the Brazilian CIGRÉ Working Group A3.17 – Surge arresters has created the Task Force A3.17-05 - studies for application of line arresters, whose basic objectives are: (1) - to evaluate the influence of the quantity and the location of the line arresters; the magnitude and wave shape of the discharge current; the grounding impedance; and the multiple strokes on the energy absorbed by the line arresters; (2) - to evaluate the statistical behaviour of the energy absorbed by line arresters and its failure probability in function of the critical energy absorbed, taking into account the magnitude and wave shape of the discharge currents flowing through the line arresters; (3) - to evaluate the electric and mechanic performance of the line arresters in the field; (4) - to give more detailed information about the overhead lines lightning performance in the Brazilian system after the application of line arresters or other method to improve the lightning performance; (5) - to analyse and evaluate special applications for line arresters, such as: compact lines; control of the switching overvoltages; up grade in the system voltage of the line; etc;

This Task Force has been working in the development and elaboration of an application guide and has as main objective to define the basic guidelines regarding to the technical analysis and evaluation of the methods and procedures used for the improvement of the overhead lines lightning performance, with emphasis in the application of line arresters and its dimensioning and selection criteria.

CONCLUSIONS

- Lightning has been reported as the major cause of non-scheduled outages in Brazilian's power system, creating many issues and damages for power supply utilities and their consumers. Losses and damages in the Brazilian power supply utilities caused by lightning exceed an annual value of 350 million dollars.
- Power supply utilities and industrial consumers with partnership with universities and research centers have been establishing and developing research programs seeking the lightning - performance improvement of their overhead transmission and sub-transmission lines.
- Among the methods used to improve the overhead lines lightning performance, line arresters have been usually considered in most of the cases as the most effective. Sometimes, this effectiveness and cost – benefit balance increases with the improvement of the grounding systems for fast transients associated with line arresters application.
- Studies about overhead lines lightning performance shall be done through computational simulations, in way to optimize the quantity and the best location of the line arresters along the line. Usually an economical analysis allows to the user an optimized solution. At same time, studies to estimate the maximum energy absorbed by the line arresters during lightning shall be done in order to get a good field arrester performance and increase its reliability. These studies allow the utilities to estimate arresters fail rates, based on most critical lightning occurrence and grounding impedance conditions for fast transients.
- Brazilian's transmission system has more than 3,000 units of gapless line arresters installed along overhead lines from 34.5 kV up to 230 kV. The analysis and evaluation of lightning performance before and after the installation of line arresters have shown a good effectiveness, with average indexes for the improvement higher than 70%.
- Good field experience and the proven results obtained in the improvement of the overhead lines lightning performance after the installation of line arresters, have been encouraging more Brazilian power supply utilities and industrial consumers to develop studies and research programs to evaluate the line arresters application along their overhead lines with poor lightning performance.

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Lightning Performance Improvement Of 123 kV Line Ston – Komolac By Use Of Line Surge Arresters

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SUMMARY

This paper presents HEP - Transmission System Operator Ltd. Line surge arrester (LSA) application pilot project on the Ston – Komolac 123 kV line.

This 44 km long single circuit shielded transmission line operates in the region with a high lightning activity (keraunic level about 70 thunder days). In addition, it was very difficult to obtain good footing resistance. For these reasons, considered line used to have very bad lightning performance.

It was decided to install Line surge arresters for line lightning performance improvement. In order to optimize arrester installation configuration sigma slp software simulations were performed. LSA are installed according to the results of the software simulations.

LSA are installed in summer 2007 (110 gapless, IEC-class II Line arresters). Sixty one LSA are equipped with Excount - II monitoring sensors (monitoring arrester leakage current and peak of the impulse current).

Based on the 8-month experience, LSA installation has improved line lightning performance. New line performance is close to the targeted once (improvement by 50 to 60 %). Surge arrester monitors collect very interesting information. Collected info will be compared with the software simulations.

KEYWORDS

Line surge arrester. Lightning performance improvement. Tower footing resistance.

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1. INTRODUCTION

There are several methods used for the improvement of the lightning performance of the existing transmission lines, such as: tower footing resistance reduction, increase of line insulation level, installation of additional ground and guy wires, addition of under-built ground wires, etc. Some of them have limited effect, while others are too expensive and unsuitable to application.

The use of line surge arresters for the quality of service improvement has increased over the last decade. Line surge arresters are mainly used for transmission line lightning performance improvement and for the reduction of double circuit outages on double circuit lines. Many line surge arresters are in operation and substantial experience has been accumulated. Thanks to the development of the polymer housed line surge arresters with and without an external gap it is possible to establish and maintain complete control on the line lightning performance.

It was decided to install Line surge arresters for line lightning performance improvement. In order to optimize arrester installation configuration sigma slp software simulations were performed. LSA are installed according to the results of the software simulations, statistics and outages data of the considered overhead line.

LSA were installed in summer 2007 (110 gapless, IEC-class II Line arresters). Sixty LSA are equipped with Excount - II monitoring sensors (monitoring arrester leakage current and peak of the impulse current).

2. 123 kV LINE STON – KOMOLAC

The Ston - Komolac 123 kV, 44 km long single circuit shielded transmission line operates in the region with a high lightning activity (keraunic level about 70 thunder days in the year). In addition, concerning composition of ground it was very difficult to obtain favorable footing resistance. For these reasons, considered line has a bad lightning performance.

Line was constructed in 1961, and major reconstruction has been done in 1994 due to increasing transmission power priority. Porcelain insulator strings were replaced by glass insulators, phase conductor and shield wire (single) has been changed and appropriate work has been done in order to improve tower footing resistance.

Line insulation critical flashover voltage of this line is 550 kV and tower footing resistance of some towers is still high (higher than 60 Ω).

Unfortunately, after the reconstruction work line outage rate remained rather high. Table 1 presents line outage rate for the last 11 years. Average line outage rate is 12,54 outages / year, which is equivalent to 28,50 outages / 100 km / year.

Table 1 - Line outage rate (O.R.)
[Outages / per year]

Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
O.R.	13	5	17	18	13	9	18	11	10	11	13

3. LINE SURGE ARRESTERS

Used gapless polymer housed LSA has the following characteristics:

Rated voltage:	108 kV
MCOV:	86 kV
IEC Class:	II
Nominal discharge current:	10 kA
Housing:	Silicone rubber

LSA were installed in summer 2007 (110 gapless, IEC-class II Line arresters). LSA are installed by hanging from the phase conductors. Photo of the installed arresters is given in Figure 1.

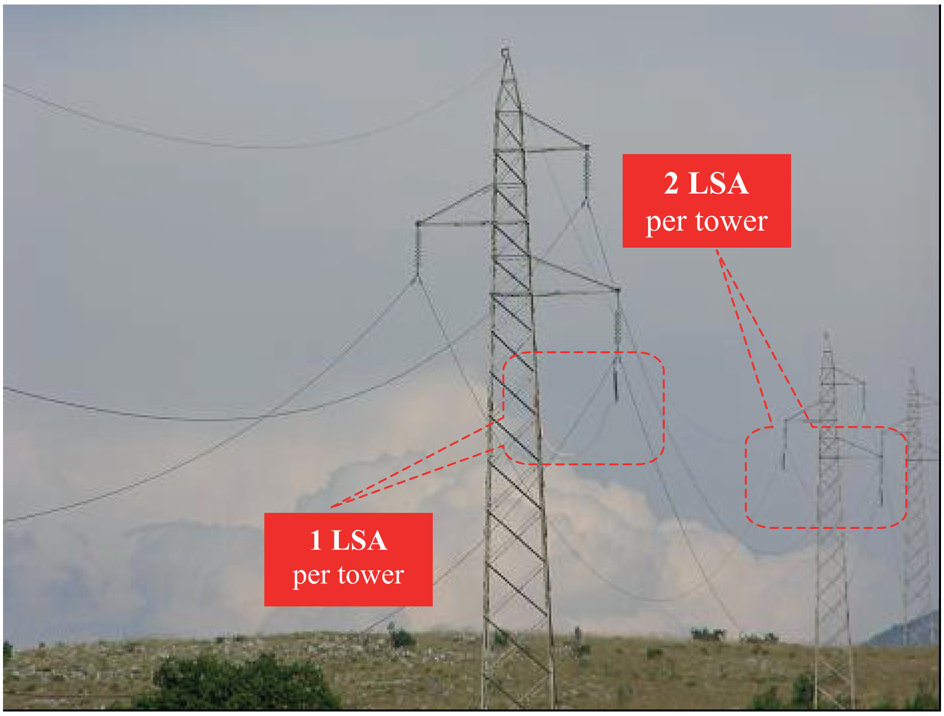

Figure 1 - LSA hanging from the phase conductors

4. LIGHTNING PERFORMANCE COMPUTATION

The Sigma slp software [2], [3] was used for the computation of the line lightning performance for different arrester installation configurations and different tower footing resistances. Detailed results of the software simulation, along with the line data are given in [6]. Here Line total flashover rate is given as a function of the tower footing resistance and different LSA installation configurations (Table 2). These results are graphically presented in Figure 2.

Table 2 - Line Total Flashover Rate
[Flashovers / 100 km / per year]

R(Ω)	ρ(Ωm)	LSA 0 (○ ¦ ○ ○)	LSA 3 (○ ¦ ○ ●)	LSA 2, 3 (● ¦ ○ ●)
10	400	3,4	1,11	0,39
20	800	17,22	9,97	3,9
30	1200	34,05	21,29	9,92
40	1600	52,89	33,83	16,38
50	2000	68,39	46,15	23,35
60	2400	77,7	56,96	30,71
70	2800	84,95	64,55	37,12

○ - Without arrester
● - Arrester installed

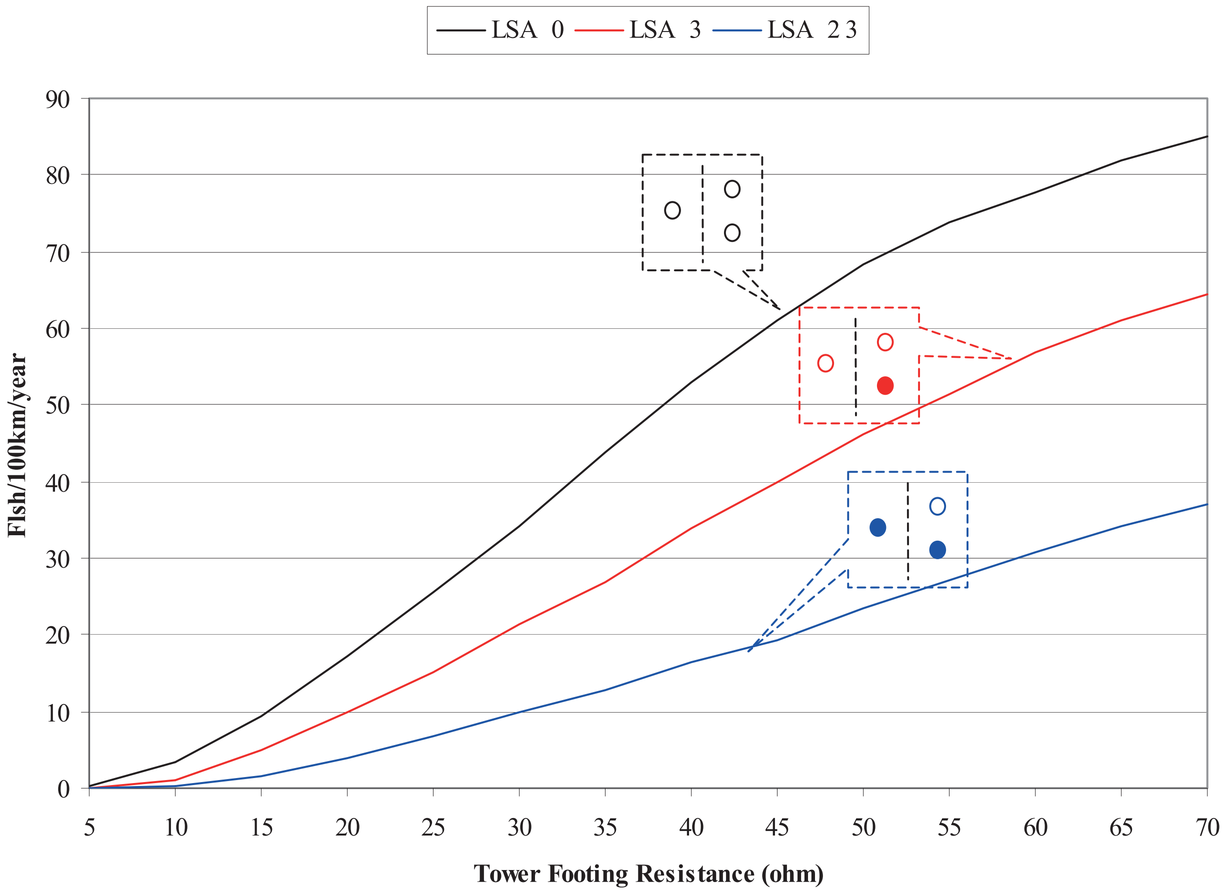

Figure 2 - Line lightning performance for different tower footing resistances and different LSA installation configurations

5. ARRESTER INSTALLATION STRATEGIES AND FIELD EXPERIENCE

Line Ston - Komolac consists of 144 towers. Tower footing distribution along the line was available (measured).

Using the so called ‘Multiple study‘ option of the sigma slp software it was possible to determine line composite performance, taking in account different tower footing resistance of each tower.

Based on the real tower footing resistance distribution and on the simulation results presented in Table 2, line composite performance of the line before LSA installation is calculated, being equal to 10,91 flashovers / year or 24,79 flashovers / 100 km / year. These values are in rather good agreement with the filed experience for the considered line (12,54 and 28,50).

It was reason to improve line lightning performance using 110 LSA only. The target was to improve line performance by 50 % to 60%. The following installation strategy was adopted:

a) No LSA (tower footing resistance ≤ 10 Ω)

b) Bottom conductor LSA (tower footing resistance > 10 Ω and ≤ 30 Ω)

c) Middle and Bottom conductor LSA (tower footing resistance > 30 Ω)

According to the available tower footing resistance values and adopted LSA installation strategy, sigma slp software line lightning composite performance tool is used to get line performance after LSA installation (Figure 3).

Results of the simulation (after 110 LSA installation) gives line lightning performance of 5,07 flashovers / year, which is an improvement for 54 % (close to the target improvement of 50% to 60%).

LSA installed in mentioned line are in operation for 8 months. It is too early to draw general conclusions from the field, but in this 8-month period, 4 lightning produced outages were registered. This is equivalent to 6 flashovers / year, meaning that the field experience indicates 52 % improvement in the line lightning performance (close to the target improvement).

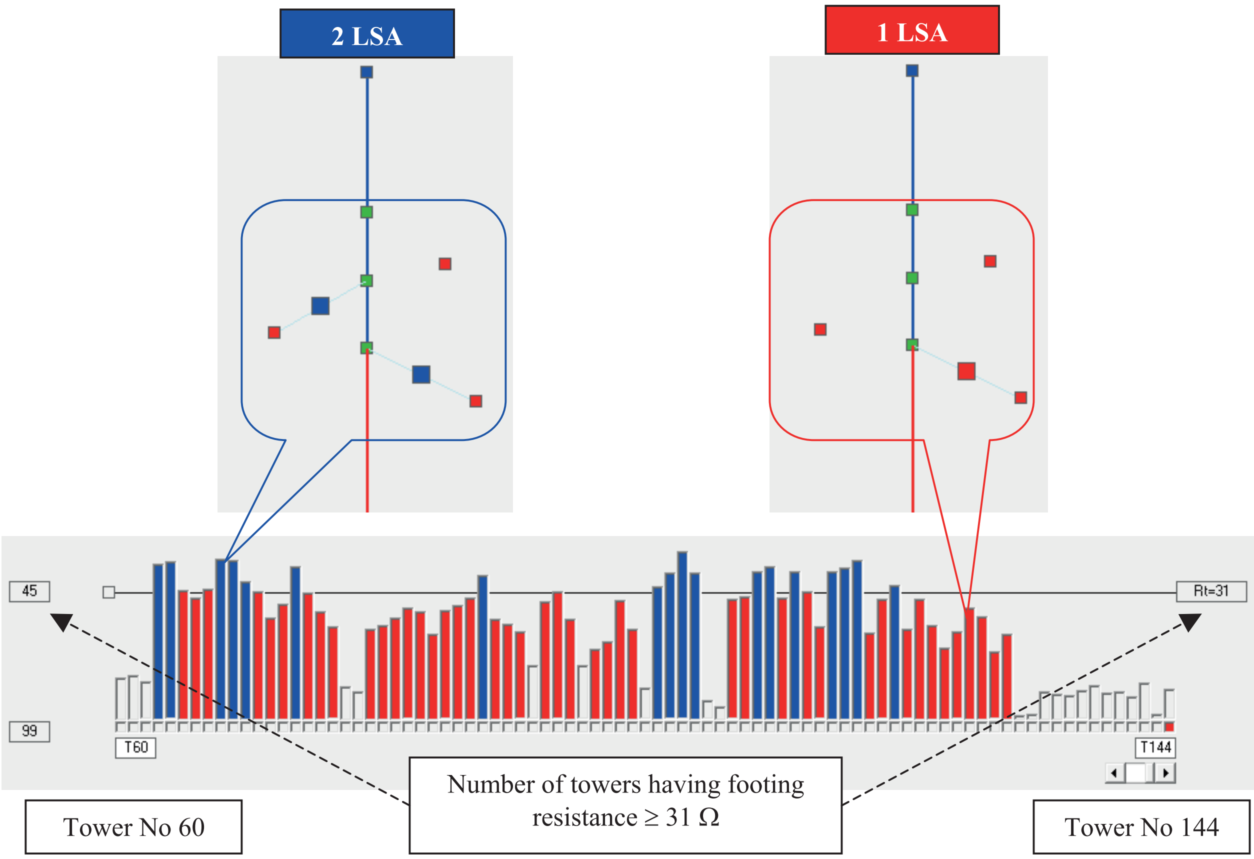

Figure 3 - Tower footing resistance distribution and the selected arrester installation configurations [From Tower No 60 to Tower No 144]

During 8 months of the operation surge arrester monitors have collected a lot of interesting data. These data is under a separate study and will be presented during the Colloquium. Collected data will be also compared with the software simulation results.

Table 3 presents LSA lightning strokes related currents collected by the surge arrester monitors.

Table 2 - LSA lightning strokes related currents

Current Range (kA)	Number of readings
> 10	2
5 - 10	1
1 - 5	9
0,1 - 1	5
< 0,1	89

No change in the arrester leakage currents is registered. Resistive component of the leakage currents is in the range of 40 μA, while arrester total leakage current is in the range of 400 μA.

In order to monitor LSA current shapes it was decided to install on the most exposed towers remote real time surge arrester monitoring system.

Based on data related to operation and outages for the considered line, including monitoring data, the effects and possibilities of LSA application will be estimated. This experience is of the great importance for the application of this technology to the other lines in transmission network.

6. CONCLUSIONS

1. In order to improve transmission line lightning performance of 123 kV line Ston – Komolac, 110 polymer housed LSA were installed in summer 2007. LSA rated voltage is 108 kV.
2. LSA installation strategy is based on the sigma slp software simulations. There is a rather good agreement with the field experience and software simulations (for both: before and after LSA installation).
3. According to the 8-month field experience line lightning performance is improved for 52 % (target improvement was between 50% to 60 %).
4. Intelligent current sensors are installed for LSA monitoring (61 monitors installed). During 8 months of the operation surge arrester monitors have collected a lot of interesting data. This data is now under a separate study and will be presented during the Colloquium.
5. In order to monitor LSA current shapes it was decided to install on the most exposed towers remote real time surge arrester monitoring system.
6. Depending on the results of this LSA application pilot project, it will be decided about future applications of this technology to the other lines.

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Line Surge Arresters Applications On The Multi Circuit Overhead Lines

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SUMMARY

This paper presents application of line surge arresters (LSA) on the different voltage level multi circuit overhead lines. Double circuit shielded compact line with and without distribution circuit on the same tower is analyzed.

Distribution circuit has lower insulation level, meaning that almost all flashovers will happen on that circuit. Flashovers on the distribution circuit help to improve lightning performance of the transmission circuits. Flashovers on the distribution circuit diverts fraction of the lightning current along its phase conductors, improving at the same time coupling between distribution and transmission circuits.

All software simulations are performed using sigma slp software package. A short description of the modeling for multi circuit flashover rate determination is given.

In order to prevent flashovers on the distribution circuit LSA are installed on this circuit only. The improvement in the transmission circuit lightning performance is similar to that obtained without LSA. LSA installed on the distribution circuit are much cheaper than transmission LSA.

KEYWORDS

Multi circuit line, line lightning performance, line surge arrester, multi circuit outage rate.

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1. INTRODUCTION

Some utilities install on the same towers different voltage level circuits. Insulation levels of the circuits are different. Lightning strokes hitting tower tops or shield wires will produce backflashovers on the lower level insulation circuits.

It is a common practice in some countries to have transmission and distribution circuits on the same towers. Distribution circuits will suffer from the lightning strokes hitting the line, but in the same time overall lightning performance of the transmission circuits will be improved. Flashovers on the distribution circuits will divert lightning current over its phase conductors, reducing lightning current flowing in the tower footing resistance. In addition, the flashed distribution circuits will bring tower and shield wire high potential below the transmission circuits improving the overall coupling situation between conductors.

2. STUDY DATA

We have studied two shielded compact line designs (Figure 1):

a) Line Design A: Double Circuit 138 kV line (Circuits C_1 and C_2).

b) Line Design B: Double Circuit 138 kV line (Circuits C_1 and C_2) and 44 kV Distribution line on the same tower (Circuit C_3).

Transmission circuits (C_1 and C_2) have insulation critical flashover (CFO, $U_{50\%}$) voltage equal to 770 kV, while distribution circuit (C_3) insulation critical flashover voltage is 350 kV.

Line conductor data is given in Annex 1. Line span is 100 m. Ground flash density is 2,8 strokes/km/year.

Taking into account that distribution circuit has much lower insulation critical voltage than transmission circuits, the majority of the strokes to the tower top and to the shield wire will produce flashover on this circuit. In order to improve lightning performance of this circuit, application of the Line surge arresters on this circuit only is considered.

IEC Class II polymer housed gapless LSA, having rated voltage of 39 kV is used for the line lightning performance improvement.

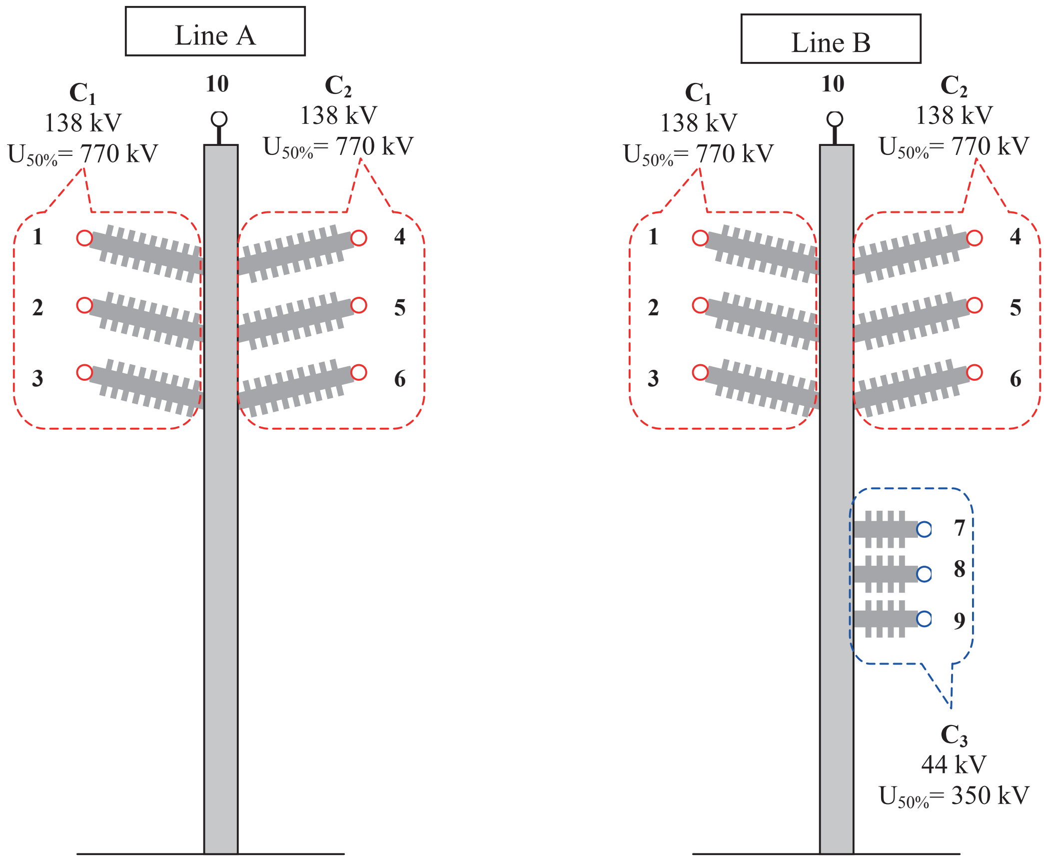


Figure 1 - Studied compact shielded multi circuit lines
(Transmission line without and with distribution circuit)

3. LINE LIGHTNING PERFORMANCE

Sigma slp software [1] is used for the line lightning performance determination. The following data and representations are used:

- Insulation flashover is modeled between phase conductors and towers, using the leader propagation model. The insulation critical flashover voltages are 770 kV (Circuits C_1 and C_2) and 350 kV (Circuit C_3), while the standard deviation was taken to be 3%.
- Tower footing resistance is represented by a soil ionization model. Tower footing resistance was varied from 10 Ω to 100 Ω. The ratio between soil resistivity and tower low current footing resistance was 30 in all cases.
- For each study, one thousand simulations are performed.
- The power frequency initial voltages are randomly selected.
- Transients on the tower top are modeled using inductive branches with parallel damping resistors. The bottom section of the tower is represented by surge impedance.
- A three dimensional Electro geometric model is used

Lightning performance of the line without distribution circuit (Line A) is given in Table 1. The following values are presented:

BFR - Back Flashover Rate [Flashovers/100 km/year]
SFFR - Shielding Failure Flashover Rate [Flashovers/100 km/year]
Total - Total Flashover Rate [Flashovers/100 km/year]
Double - Double Circuit Flashover Rate [Flashovers/100 km/year]

Table 1 - **Line A** - Lightning Performance
Without Distribution Circuit
[Flashovers/100 km/year]

R_T (Ω)	BFR	SFFR	Total	Double
10	0,03	0,15	0,19	0
20	1,07	0,15	1,23	0,03
30	2,61	0,15	2,77	0,26
40	5,00	0,15	5,15	0,96
50	7,16	0,15	7,31	2,19
60	9,85	0,15	10,00	2,88
70	12,04	0,15	12,20	3,61
80	13,74	0,15	13,89	4,50
90	15,05	0,15	15,20	5,50
100	16,70	0,15	16,86	7,00

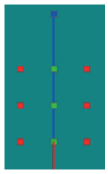
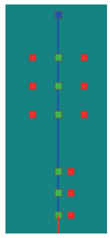


Table 2 presents lightning performance of the line with distribution circuit (Line B).

Line total and double circuit flashovers rates for both line design are compared in Figures 2 and 3. From the presented results we can see substantial improvement in the lightning performance of the transmission circuit because of the presence of the distribution circuit. Flashovers on the distribution circuit divert a fraction of the lightning current along its phase conductors, reducing current flowing through tower footing resistance (reducing back flashover rate on the transmission circuits). In addition, flashovers on the distribution circuit conductors transfer high tower top potential to these conductors (below transmission circuits) improving coupling conditions on between conductors.

Table 2 - **Line B** - Lightning Performance: Transmission Circuits Only
With Distribution Circuit
[Flashovers/100 km/year]

R_T (Ω)	BFR	SFFR	Total	Double
10	0	0,15	0,15	0
20	0	0,15	0,15	0
30	0,04	0,15	0,19	0
40	0,12	0,15	0,27	0
50	0,31	0,15	0,46	0
60	0,71	0,15	0,86	0,08
70	1,10	0,15	1,25	0,11
80	1,58	0,15	1,73	0,12
90	2,23	0,15	2,38	0,15
100	2,54	0,15	2,69	0,23



In order to improve lightning performance of the distribution circuit, LSA are installed on this circuit only. Several LSA installation configurations on this circuit are considered. To completely eliminate flashover on this circuit it is necessary to install LSA on all phase conductors. Results of the simulations for different tower footing resistances and LSA installation configurations are given in Table 3 (flashovers on the distribution circuit only).

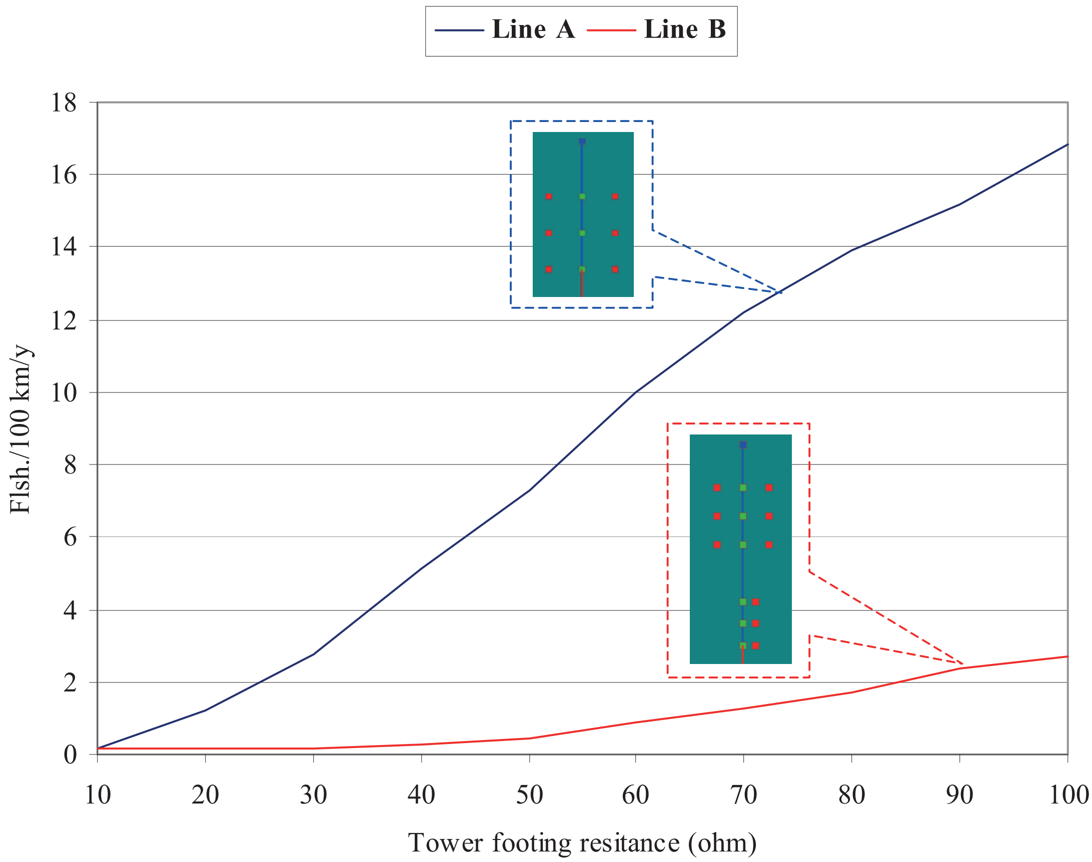


Figure 2 - Comparison of the Total Flashover Rate For
Line Design A and Line Design B (Without LSA)

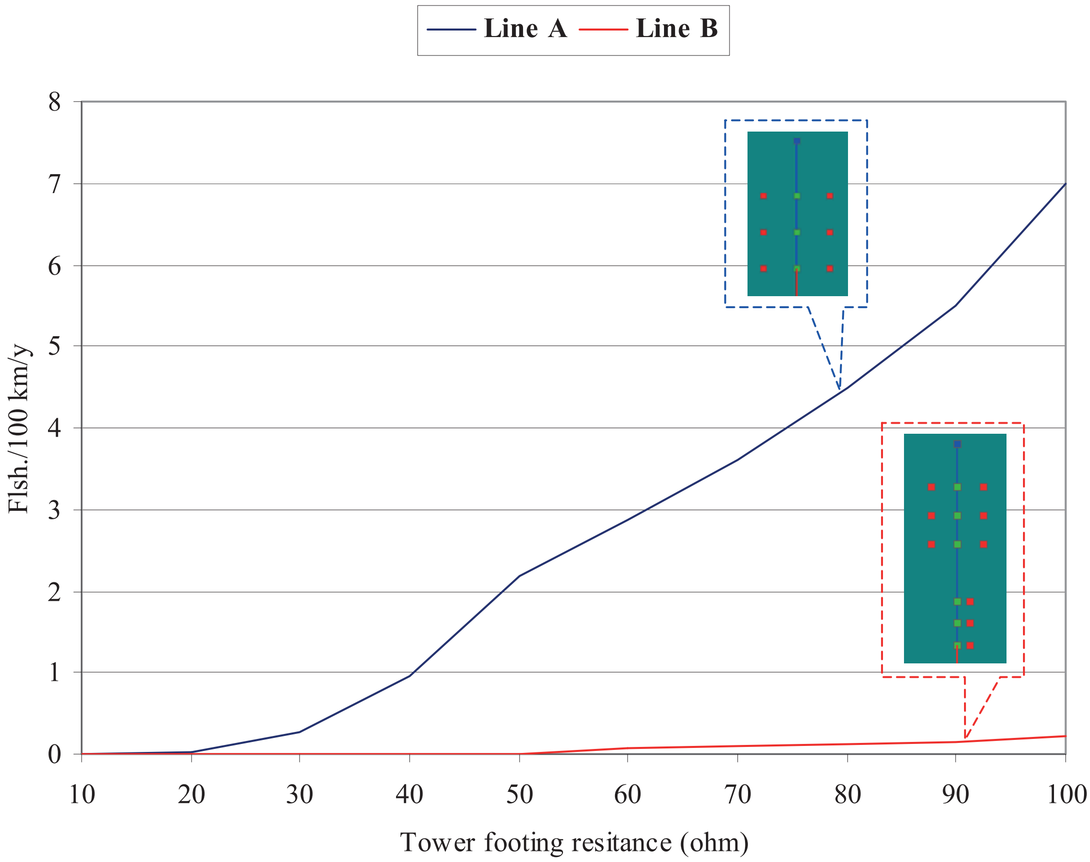
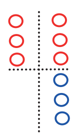
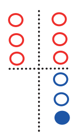
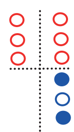
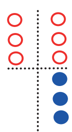


Figure 3 - Comparison of the Double Circuit Flashover Rate For Line Design A and Line Design B (Without LSA)

LSA on the distribution circuit divert also lightning current along its phase conductors, reducing lightning current that flows through tower footing resistance. In addition, LSA transfer tower top potential below transmission circuit, improving coupling between conductors. Improvement of the transmission circuit lightning performance is similar to that without LSA.

Table 3 - Circuit C_3 (44 kV) Total Flashover Rate
Different LSA Installations
[Flashovers/100 km/year]

R_T (Ω)				
10	4,54	1	0,03	0
20	15,16	5,61	0,8	0
30	20,66	10,15	2,23	0
40	24,31	13,81	4,34	0
50	27,43	16,96	6,15	0
60	30,35	19,16	8,11	0
70	32,2	21,04	9,54	0
80	32,93	23,24	11,12	0
90	33,93	24,66	12,96	0
100	34,39	26,12	14,62	0

○ - Without LSA
● - LSA Installed

S. Sadovic, T. Sadovic, Line surge arresters applications on the multi circuit overhead lines, Journal of Energy, vol. 60 Number 1–4 (2011) Special Issue, p. 75-80

4. CONCLUSIONS

1. Some utilities install on the same towers different voltage level circuits. Typical example is a case with the transmission and distribution circuits on the same tower. Insulation levels of the circuits are different. Lightning strokes hitting tower tops or shield wires will produce backflashovers on the lower level insulation distribution circuits.
2. Flashovers on the distribution circuit divert a fraction of the lightning current along its phase conductors, reducing current flowing thorough tower footing resistance. In addition, flashovers on the distribution circuit conductors transfer high tower top potential to these conductors (below transmission circuits) improving coupling conditions on the tower. Flashovers on the distribution circuits substantially improve transmission circuits lightning performance.
3. It is possible to improve transmission and distribution circuits lightning performance by the installation of the LSA on the distribution circuits only.
4. LSA on the distribution circuit divert also lightning current along its phase conductors, reducing lightning through tower footing resistance. LSA also transfer tower top potential below transmission circuit, improving coupling between conductors. Improvement of the transmission circuit lightning performance is similar to that without LSA.
5. Installation of LSA on the distribution circuit only is very attractive solution: Transmission circuits lightning performance is substantially improved using cheaper LSA.

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ANNEX 1

Line conductor data is given in Table A.1.

Table A.1 - LINE CONDUCTOR DATA

No	Circuit	x (m)	y(m)	r (mm)	Sag (m)
1	C_1	-1,8	21	12,7	3
2	C_1	-1,8	19	12,7	3
3	C_1	-1,8	17	12,7	3
4	C_2	1,8	21	12,7	3
5	C_2	1,8	19	12,7	3
6	C_2	1,8	17	12,7	3
7	C_3	0,9	13	5	2
8	C_3	0,9	11,5	5	2
9	C_3	0,9	10	5	2
7 (10)	GW_1	0	24	4,6	2,5

For Line Design B

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Line Arrester Application on a 110 kV High Alpine Overhead Line to reduce Lightning-Caused Outages

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SUMMARY

This contribution discusses a project, which aims to increase the reliability in an existing 110 kV overhead transmission network by taking measures addressing lightning and grounding issues. Due to the fault statistic in the past, a single overhead line was identified as a main reason for the lightning-caused outages in the area. In this work a number of possibilities for the reduction of lightning-caused outages are discussed and the measures taken in the network are described. All considerations took the special geographical situation of 2300 meter above sea level, the grounding resistance of up to 1200 Ohm and the local lightning activity of more than 6 lightning strikes per km² and year into account (4 to 5 times higher than in other Austrian regions).
An analytical process was carried out to evaluate relevant parameters and to develop a concept of practical measures. Within these evaluations, the footing resistance, the effectiveness of the shielding angle of the shielding wires and the line arrester locations were analyzed. A multiplicity of numerical calculations were performed to assess the application of surge arresters regarding the insulation coordination for the system. To improve the line performance and to decrease the line outage rate, a number of practical measures were applied to the 110 kV line. In the past, the double three phase systems of the 110 kV overhead line was constructional converted into one active single three phase system with two additional earth wires. According to the numerical results, 18 surge arresters have been installed in a line section of 9 towers, located in a high alpine part and in an area of high lightning activity. Three years of field experiences have shown that the theoretical investigations and the practical measures led to a significant decrease of lightning caused outages.
In the year 2007 a new project was started to evaluate a reconstruction of the line into the original double three phase system. New numerical calculation routines were made to apply line arresters at this important 110 kV system in an Austrian extreme mountain region. Based on this results, a new application of line arresters and the constructional change of the system is planned.

KEYWORDS

Line surge arresters, 110 kV overhead line, high alpine region, lightning outages, backflash

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1. MOTIVATION

Because of the historic development and the geographical position, the 110 kV transmission network is of great importance in Austria. Especially in the mid and southern parts of the country, long sections of the 110 kV network are situated in alpine or high alpine regions. Such areas have a high lightning activity, especially when compared to other parts of the national territory.
Furthermore, the earthing conditions tend to be bad in such areas because of the rocky soil which is accompanied by a high specific electrical resistance. Hence, it is not surprising that such lines naturally have a bad performance.
The line which will be investigated within the scope of this paper has already been under study for more than seven years now. With innovative constructive measures and the installation of line arresters in 2003 it was possible to achieve a notable improvement of the line performance. New requirements for energy transport lead to a performance update of this specific line nowadays, which is again combined with a line reconfiguration.

2. INTRODUCTION

The studied line was originally constructed as a double system, 3-phase 110 kV overhead line with one shielding wire at the tower top. The system consists of 108 steel towers with a (median) span field length of about 266 meters. It has to be noted that the line is electrically operated in parallel for 15 kilometres at one line end, which is nearly half of the total line length. For the rest of the line, each 3 phase system is operated independently (see Figure 3) [1,2].
In 2001, the network operator decided to take actions to enhance the line performance. This led to a line reconfiguration from a double system to a single system (Figure 1). Because of this rearrangement, three phase wires could be "freed", where two of them (the two upper phases) have been used as additional shielding wires and the third wire has been kept as a standby phase conductor. Additionally two phase wires (the two middle ones) have been protected by line surge arresters in the section with the highest lightning activity along the line (nine towers totally) [3].

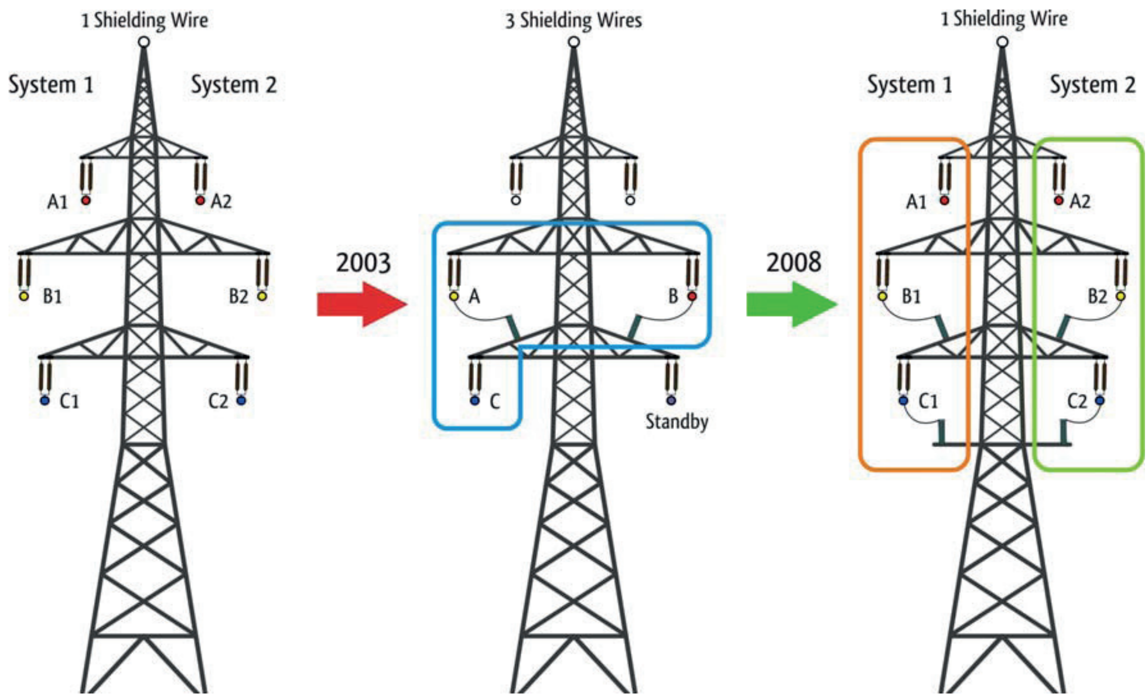

Figure 1: Original Double System without Protection (left); Present Situation: One Single System with Line Surge Arresters (middle); New Reconfiguration: Double System with Line Surge Arrester Protection in 2 Phases Each (right)

In 2007, the utility was forced to rebuild the system into the original double system on the proven condition with the good lightning performance.
Based on the line section and the towers respectively which have already been equipped with arresters, numerical simulation programs (ATP/EMTP) were used to evaluate a good solution of this specific task and to find optimized schemes for the additional placement of surge arresters.

3. MODELLING AND SIMULATION

Line Modelling

Despite the previous investigations which have been conducted, the modelling had to be started from scratch. In the past, the whole line was divided into 5 sections and these have then been modelled in ATP with different levels of detailedness. The most critical section and therefore the most important one in terms of research was Section 3 in the middle of the system (Figure 2). Studies of lightning data from ALDIS (*Austria Lightning Detection and Information System*) have confirmed the approach.

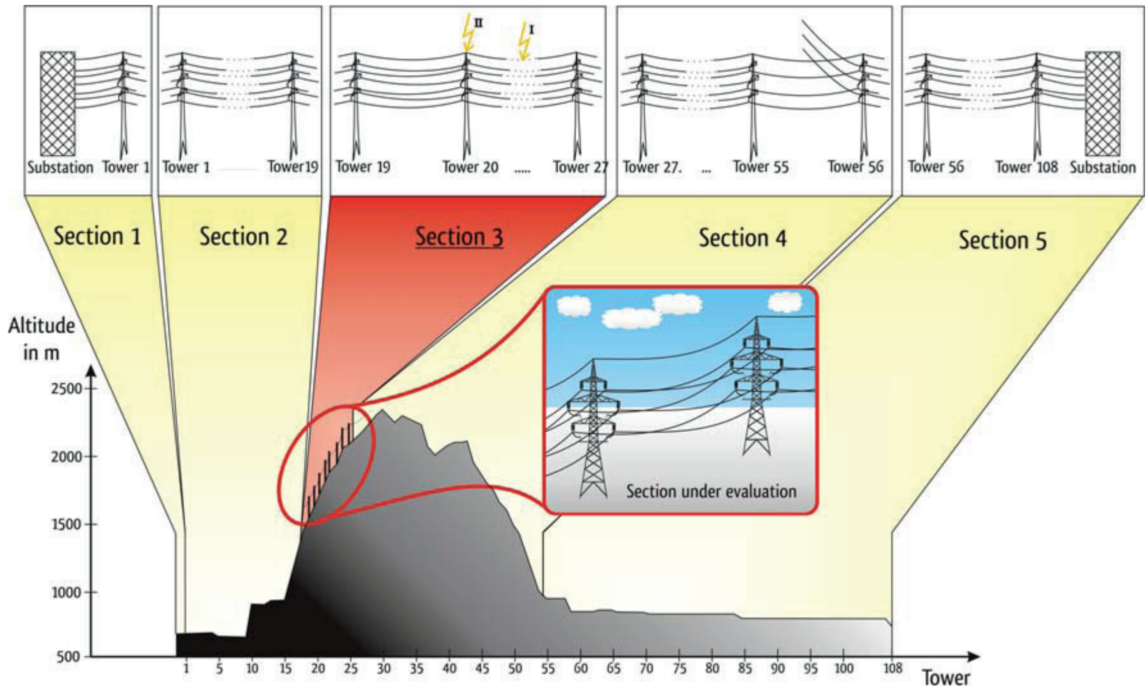

Figure 2: Line Sections and Altitude of the evaluated Line

Frequency dependent line models (LCC) have been used for the modelling of the whole line. Tower footing has been simulated for every tower where applicable. The power frequency voltage has not been taken into account. Section 3, consisting of 9 towers and also the two adjacent sections (Section 2 and 4) have been modelled detailed with single towers (transient tower model [4]) and the actual tower footing resistance. A direct discharge to one tower (Tower 25) with an injected lightning current of 15 kA is assumed for all of the simulations.

Mitigation of Lightning-Caused Outages

Before the first line reconfiguration in 2003, the double system was protected with one shielding wire at the top of the line and with arcing horns at the insulator strings as usual. With the re-fitting of 9 towers with surge arresters in Section 3 (Figure 3) and the acquisition of two additional shielding wires the overall line performance was increased dramatically.

Based on 3 years of operational experience, a new technical solution for the double system has also to guarantee the proven line performance. Therefore the additional application of line surge arresters and the numerical evaluation of the insulation coordination status was a central measure. Nevertheless, two additional topics have been simulated, namely the improvement of the earthing conditions (in particular the tower footing resistance) and the installation of a counterpoise wire in this section.

The improvement of the footing resistances is in fact quite impractical and inefficient in this special case because of the very high values of up to nearly 800 Ohms in Section 3 and even more in the adjacent sections. For example, a reduction of more than 80 percent of the actual resistances was studied. Such a theoretical reduction still implies a high risk for back flashovers and it should not be disregarded that it is not likely that such a reduction could be achieved in practice.

Counterpoise wires can be helpful for the equalisation of the earthing conditions along the line. For this specific situation the installation was not possible as the towers could not handle the additional load. Severe weather conditions like ice load or wind speed in this high alpine region have to be taken into account.

Figure 3: Tower with 2 Line Surge Arresters (Present Situation)

4. Solutions for Line Arrester Application

The application of line arresters at every phase and every tower of such an important overhead line within critical sections might be common practice sometimes but it is also the most cost intensive option [5,6]. The costs in this specific case can be divided into costs for research and evaluation work, unit costs for the arresters itself and costs for construction work and strengthening of the tower, if necessary. Additionally, the situation of the high voltage grid and the lightning activity was taken into account. Therefore separate costs for the grid monitoring and network analysis in the utility and costs for the lightning detection system influence the economic situation.
In this work a practicable and cost optimized solution has been worked out with the help of numerical simulations. Based on this process, a reduction of the number of line arresters is reasonable, still with respect to the insulation coordination and the utility specific operation demands.

<u>Standard Protection</u>

A double system overhead line is protected with one shielding wire at the top of the line and with arcing horns at the insulator strings usually. Theoretically without any protection devices, the peak values of the transient voltages can reach levels up to 2,2 and 2,5 MV, which exceeds the electrical withstand voltage of the insulation by far. With the standard integration of arcing horns at each insulator string (typical application in Austria), the voltage peaks can be reduced to values in the range of 550 to 850 kV.

<u>One Protected Phase Wire per System</u>

The protection of one single phase per system is a very economic one, but still two phases are not protected. In this case the voltage in the protected phase is limited to the residual voltage of the surge arrester. The voltage stress of the other two unprotected phases depends on the system arrangement including the surge arrester position. The insulation coordination studies have shown, that for an optimal protection the lower phase is preferred when using one arrester only (Table 1).

Table 1: Peak Values of the Transient Voltage Stress with only One Phase Wire protected

Voltages in kV of Phase:	Protected Phase A	Protected Phase B	Protected Phase C
A	325	900	957
B	1179	326	973
C	1344	1083	326

Two Protected Phases Wires per System

The protection of two phases can be seen as some sort of compromise between economics, protection and line performance. In this work several aspects have been studied to find out a efficient protection. The peak values of protected and unprotected phases are listed in Table 2.

Furthermore, it has to be taken into account, that one unprotected phase sometimes can be tolerated, if a single phase failure does not influence the system performance which is given by the operational structure of the utility.

Table 2: Peak Values of the Transient Voltage Stress with Two Phase Wires protected

Voltages in kV in Phase:	Protected Phase A, B	Protected Phase A, C	Protected Phase B, C
A	309	309	676
B	315	715	310
C	899	316	313

From the mechanical point of view it would be desirable to protect the top phases and the middle phases because the according surge arresters can be mounted on the subjacent tower crossarms. Electrically, the protection of the two lower phases in each system could be found as an optimal solution for minimising the transient voltage stress.

Three Protected Phase Wires per System

Some utilities run the strategy to apply arresters on each phase per system. The protection method can be stated as the most efficient one, but can also be seen as the most cost intensive method regarding the number of arresters and the mechanical tower dimensioning.

With respect to the evaluation in this specific transmission line, the maximum transient voltage stress per system could be calculated in the range of about 310 kV for all phases. To protect the lower phase with an surge arrester, an additional platform is necessary to be mounted at the tower.

Global Situation

A global overview of the peak values of the transient voltage stress is given in Figure 4. In this diagram the effectiveness of the surge arrester application can be seen, comparing different protection schemes.

Regarding to the line situation without arrester protection, the installed surge arresters in Section 3 solve the biggest issues concerning line outages. With two installed arresters on each system, the global situation of the whole line could be improved (see Figure 4). Nevertheless, the protection basically remains limited to the line section with the arresters installed. It has to be taken into account, that the adjacent sections of the line can be stressed by transient overvoltages (flashovers can occur).

Typical transient voltage time trends can be seen in Figure 5. In this figure, a protection scheme with 2 protected phases on each system is demonstrated. It is assumed that Tower 25 experiences a direct lightning strike with a 1,2/50 µs wave shape and a current of 15 kA as it is shown in the left picture. Furthermore it is assumed that the lower two phases of each system (Phase wires B (green) and wires

C (blue) in Figure 5) are protected. This would correspond to the arrester application as it is shown in Figure 1 in the very right picture.

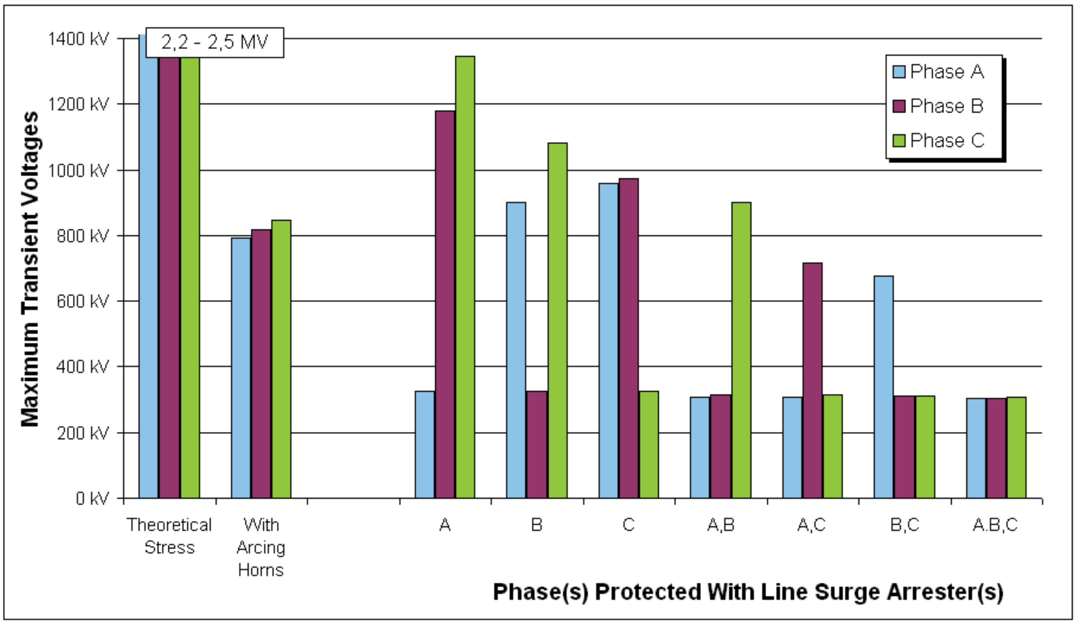

Figure 4: Peak Values of the Transient Voltage Stress in Section 3 for a 110 kV Transmission Line

The right picture in Figure 5 shows the transient voltages of one system on Tower 15. This tower is outside of Section 3 and is therefore not equipped with surge arresters. Because of the fact, that this tower is approximately 2500 meters away from the point of impact, the transient voltages are already lower than the voltages at Tower 25 but there are still oscillations.

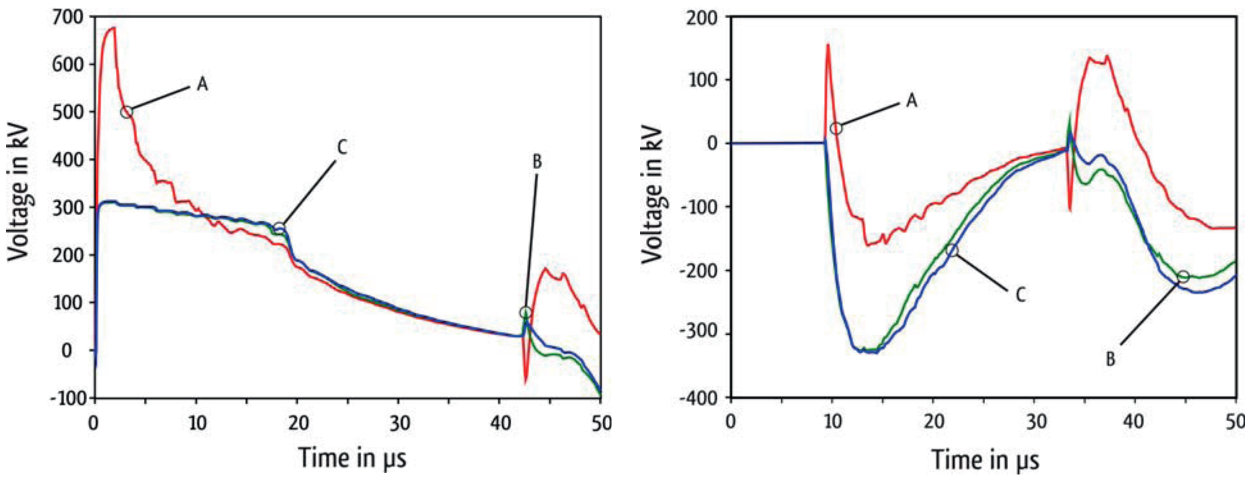

Figure 5: Transient Voltage Time Trends with Two Line Surge Arresters (placed at middle and bottom phases); Tower 25 (Left Graph) and Tower 15 (Section 2, Unprotected; Right Graph); Red – Top Phase (A), Green – Middle Phase (B), Blue – Bottom Phase (C)

5. CONCLUSION

The usage of line surge arresters for such an application has not been done before in Austria. Due to a registered high outage rate, one specific section of 8 spans within a high alpine transmission line was identified. A systematic evaluation of the local situation of the insulation coordination was done by using numerical calculation tools. Within a cooperation between an utility and Graz University of Technology, research projects covering this topic are running since 2001. It was also a novelty that a double system overhead line was reconfigured to a single system in 2003 to enhance line performance and also to increase the overall transmission network performance. In 2008, matters of energy transport necessitated the double system again. This further reconfiguration should be conducted with the maintenance of the upgraded line performance. As a result of the good operational experience, the usage of additional line arresters has been researched.

Line surge arresters are well suited for the mitigation of transient overvoltages and the related line outages. Especially in regions with poor earthing conditions and high lightning activity, line arresters can contribute very effectively to the line performance. Several years of operational experience of that special line are showing that. In this special case it is planned to equip a small but critical section of a double system overhead line with line surge arresters in Summer 2008.

6. ACKNOWLEDGEMENT

The authors would like to thank KELAG Netz GmbH for the cooperation and the assignment to conduct this research project respectively.

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PERFORMANCE OF PARALLEL SURGE ARRESTERS

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SUMMARY

The operation of parallel surge arresters can improve energy absorption capability if the arresters are similar and are installed close to each other. However, it has been reported that any small difference in the individual V-I characteristics can lead to unbalance in current sharing. When the arresters are installed some distance away from each other, travelling wave effects can modify the effectiveness of parallel arresters for surge overvoltage protection and, in this case, detailed simulations are required to ascertain the level of protection. Such a situation occurs in practice with large substations or short underground cable connections. Various studies have shown that a requirement for two-arrester protection is closely dependent upon the type and length of cable used.

In the case of overhead lines, the distances are much bigger and the main objective of line arresters is to reduce the flashover rates due to surge overvoltages. This is especially relevant to lines located in regions of high lightning activity, lines with compact/uprated design where the phase-to-phase and phase-to-earth air clearances are reduced.

In this paper, we present a study of parallel arresters considering the separation distance and their application to overhead lines. Various scenarios of overhead line configurations were considered and the overvoltage levels were calculated for each case. Assessment of flashover performance is also conducted for a number of conditions. A number of calculation techniques were used and compared.

KEYWORDS

Line arresters, protection distance, backflashover, lightning strikes, transient simulation, EMTP, cable protection, tower surge impedance.

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Introduction

Parallel sets of surge arresters can improve energy absorption capability if the arresters are similar and are installed close to each other. However, it has been reported that any small difference in the individual V-I characteristics can lead to unbalance in current sharing. When the arresters are installed some distance away from each other, travelling wave effects between the units can modify the effectiveness of parallel arresters for surge overvoltage protection and, in this case, detailed simulations are required to ascertain the level of protection. Such a situation occurs in practice with large substations or short underground cable connections. Various studies have shown that a requirement for two-arrester protection is closely dependent upon the type and length of cable used.

When using surge arresters in parallel within relatively short distances, the issues of protective level, current and energy sharing need careful consideration. Typical examples of how arresters are installed in parallel include:

(a) Multi-column arresters where the distance between the arrester columns is usually less than 0.5m,
(b) Multi-arrester protection of plant within large substations where the separation distances are up to few hundred meters,
(c) Protection on underground cable lengths, usually found at substation entries where the cables are used to connect the substation to the overhead line. In this case, the cable length can vary from a few tens of meters up to a kilometre or more,
(d) Line arresters to reduce flashover / backflashover rates on overhead lines exposed to lightning strike risk. Occasionally, protection against switching surges may be required, e.g. for compact line applications. The distance between arresters for this type of application can vary significantly from one to several span lengths.

In this paper, the above cases of arrester application were examined in order to quantify the effect of surge arresters and their separation distance on the protective levels offered to the system. In addition, the arrester voltages and currents were examined to assess the implications for energy absorption requirements. For the line arrester application, different modelling approaches to represent the towers and arresters with their connection leads were compared in order to identify optimised modelling approaches for such transient situations.

Multi-Column Arresters

In order to increase the energy absorption capability of arresters, multi-arrester column designs were developed. Usually, the V-I characteristic of the parallel column are matched at two points around the rated voltage V_r and nominal current I_r. Such designs have an increased energy absorption capability and, after a high energy operation duty, they exhibit a better temperature recovery time which is facilitated by the increased outside surface area available for cooling the complete multi-column arrester. In addition, the residual voltage at nominal current is lower compared with a single–column arrester due to discharge current sharing between columns.

One difficulty with the construction of the multi column design, however, relates to matching all columns for all points along the V-I curve. High current laboratory impulse tests [1] on two matched arresters connected in parallel have revealed that, even for closely matched arrester units, as much as 6% current sharing mismatch can occur between the two parallel arresters. This difference is enhanced in the highly non-linear region of the V-I characteristic where exact matching is difficult.

Impulse tests on an aged four-column arrester [2] have also shown that up to 17% difference existed between the currents in the four columns. The main consequence of unmatched columns in a multicolumn arrester design is non-uniform ageing. Relatively to the others, the column that conducts most current will undergo an accelerated ageing process which could lead to premature failure of the arrester. Despite this shortfall, the superior residual voltage, increased energy absorption capability and temperature properties of multi-column arresters makes them attractive for high energy applications. To reduce the effect of current sharing mismatch in multi-column designs, series parallel arrester designs are now used by several utilities. In this way, if mismatch occurs on a short section of the arrester, complete failure is avoided and the failed section can be replaced quickly.

Separation Distance Effects

In practice, location of the arrester very close to the high voltage plant to be protected against overvoltages is not always feasible. The separation distance between the two devices and the length of the arrester connection leads is known to affect the surge voltage level at the protected equipment.
Such a voltage increase is caused by travelling waves and inductance effects of the connecting conductors. Simplified equations have been suggested for the assessment of the protective voltage level at the equipment to be protected by a surge arrester located a distance away from the equipment. However, it must be stressed that the accuracy of the equations is limited. For substation applications, a detailed transient simulation study is required. Mitigation of the separation distance effect on surge overvoltage protection requires that the arrester is located as close as possible to the equipment to be protected, and that short connection leads are used to bond the earth terminals of the arrester and equipment. For high frequency applications, use of an extra earth rod at the arrester location helps better impulse current dissipation through access to deeper low-resistivity soil. Additionally, this earth electrode practice contributes the desirable safety benefit in mitigating the rise of earth potential at the arrester location. Recent developments introduced integrated designs of surge arresters with high voltage plant, which provide optimised overvoltage protection. However, issues of reliability and field distribution consequences are yet to be quantified and resolved satisfactorily.

Arrester protection of Line-Cable Junction: Effect of Cable Length

In this section, we consider the separation effect of cables on surge arrester performance, compared with that typically experienced on overhead lines. The effectiveness of the surge arrester is determined by the surge impedance of the network between the surge arrester and the item which it is protecting. Cables offer better protection due to the low surge impedance typically 20-40Ω compared with 300-450Ω for an overhead line. Air insulated busbar systems are in between, typically 100-150Ω, while GIS busbars are slightly lower 80-90Ω. In this investigation, a simplified model of a line terminated with an underground cable is considered (see Fig. 1).

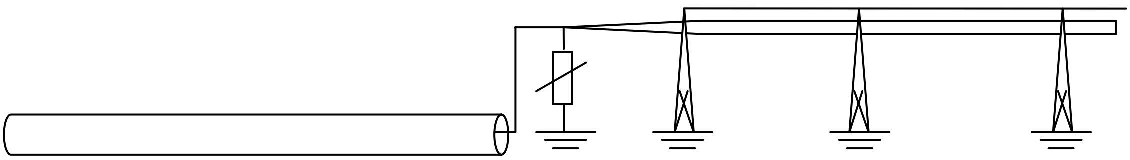
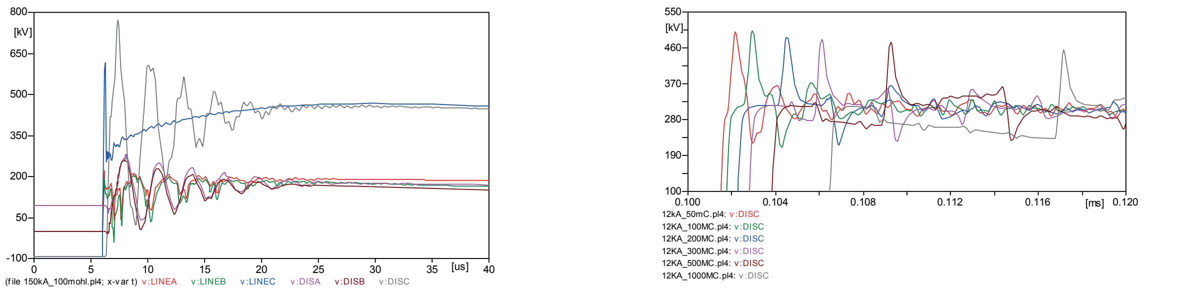


Figure 1: schematic of studied line cable system.

EMTP simulations were used to determine the effect of cable length on the voltage seen at the remote end. The results suggest that there is little effect for the case of shielding failures on the overhead line, while the issue is more pronounced at higher frequencies where the reflections associated with back-flashovers generate higher differential voltages at the remote end of the conductor system. Figure 2 shows typical voltage shapes computed for a 132kV system, and Table 1 summarises the results for the cable length effect. The key observation from the studies (Table 1) suggests that, for shielding failures, the cable further attenuates the travelling wave to a value below the control level of the surge arrester. Backflashovers, however, do not attenuate and higher voltages appear at the remote end, thus requiring an additional arrester [3].



(a) Voltage at sending and receiving end of 100m of 132kV overhead line -150kA back-flashover

(b)Variation of voltage (receiving end) with cable length (132kV) -12kA shielding failure

Figure 2: Computed voltage for cable-line junction model.

Table 1: Voltages calculated on 132kV XLPE cable with a line end arrester exposed to lighting impulses through an overhead line

XLPE Cable length (m)	Voltage (kV_{pk})					
	Shielding failure			Backflashover		
	SA end	Remote end	LIPM %	Surge arrester end	Remote end	LIPM %
50	388	500	23	388	400	39
100	350	502	23	388	390	40
200	372	486	25	389	430	34
300	371	481	26	390	470	28
500	370	474	27	385	520	20
1000	360	450	31	400	620	5

From the above results, it can be said that the presence of cable sections in the overhead line entry to a substation does impact on the nature of overvoltages transferred into the substation. A surge arrester located at the line entry side will control all but the worst case transients. These are typically caused by backflashovers which have fast rise times and generate voltage reflections at high surge impedance boundaries e.g. open disconnectors or unloaded transformers.

Effect of Line Arresters Models on Predicted Flashover Performance of Lines

In regions of high lightning activity and for compact or uprated overhead line designs, line arresters are commonly adopted by utilities to control overvoltage levels and reduce flashover rates on overhead lines.

Several studies have been performed to investigate the optimisation of line arrester applications to improve the line's flashover performance. Specialised software programs to carry out such studies have been developed and a number of approaches were developed and used for the flashover studies.

Statistical approaches were used to account for the parameters of the lightning phenomenon to include impulse shape and magnitude. However, it is worth emphasising the impact on results of the simulation models used for the line towers and arresters in carrying out the flashover studies.

In this work, a number of modelling options for the line towers and arresters connections were investigated to identify the controlling factors of the voltage appearing at towers following a lightning strike. Two types of 132kV lines were considered to illustrate the findings of this investigation; (a) an unshielded line having a portal type pole design and horizontal phase-conductor configuration, similar to those used in UK rural areas (Figure 3.a), and (b) a shielded double circuit "PL16" steel-tower line (Figure 3.b). In order to simulate practical lines, a total length of 20 km was considered. In both cases, the lines were terminated with transformers represented by their capacitance of C=5nF.

Unshielded Portal-type overhead line

A wood pole portal type tower, with horizontal conductors was used for the studies of unshielded line. The span length used was 300m and several combinations of surge arrester locations were studied. As expected, the simulations show voltages in the megavolt region if no line arresters were used, these voltages would cause a flashover for most lightning strike magnitudes. In contrast, if line arresters are used at every pole, the voltages will be limited by the surge arresters to safe levels below the flashover overvoltage. However, if a strike occurs at mid-span, a risk of interphase flashover may happen before the lightning surge arrives to the adjacent poles.

Several combinations of arrester locations were studied by previous investigators [4] and these have established some general facts about which phases have a flashover/backflashover risk and also some optimised arrester locations and distribution along the lines. However, very little information was given on the details and effects of the modelling approaches used for their studies. In particular, the study of tower models and surge arresters with their connections require further clarification. In this paper, we have selected a line configuration with an arrester every 4 spans to illustrate the effect of arrester/tower modelling on the computed results. Figure 3.a shows a section of the EMTP model used for the Portal line. The section depicts the lightning injection point and the two surge arrester separated by four line spans. The simulation results showed that most of the lightning current passes through the two arresters nearest to the strike, only a relatively small proportion is absorbed by arresters located further away down the line. When the effect of arrester connections leads was ignored, much higher current magnitudes were calculated through the two arresters nearest to the lightning strike point. The current magnitudes are more than 12% higher compared with the case with leads. This, of course, could have energy and cost implications, in which the simplified model overestimates the energy demand on the line surge arresters. As expected, the voltage across the insulation will change accordingly for the two models. For an injection of a 32kA lightning current, voltages close to the line BIL of 650kV were calculated when the arrester connection leads were not included in the model (Figure 4.b). The other case predicted much lower voltages and, hence, no risk of flashover (Figure 4.a).

Shielded lines

As can be seen in Figure 3.b, the arrester connection can be achieved either through the tower (represented by its surge impedance and footing resistance) or directly to ground; these alternative modelling approaches were evaluated for the backflashover and shielding failure determination.

(i) Shielding failure: For the shielding failure case, a 12kA strike was applied to the top phase as can be predicted by the shielding angle. As expected, the first two arresters next to the strike point absorb the majority of the lightning strike current.

(ii) Backflashover: For this case, a 100kA strike was used at the mid-line tower to illustrate the effect of tower and surge arrester models on the developed voltages at various nodes on the line. The surge arrester is represented by a non linear resistor (MOV model) and its connection with a series LR equivalent. The tower is represented by its surge impedance, Z=120Ω, in series with a footing resistance R=20Ω. Four different models were used for the arrester - tower combinations with varying degrees of simplification:

a) The surge arrester is connected to the top of the tower, (full model)
b) The surge arrester is earthed directly neglecting its connection lead,
c) The tower is represented by its footing resistance only and the arrester is earthed directly ignoring the effect of its connection leads
d) The surge arrester is earthed directly, and no tower model was used.

For model (a) above, it was found that the voltage at the tower tops along the line decreases exponentially with distance, d, from the strike point. An empirical trend for the tower voltage V_{tower} on phase C (bottom phase) was derived for this case, and is given by

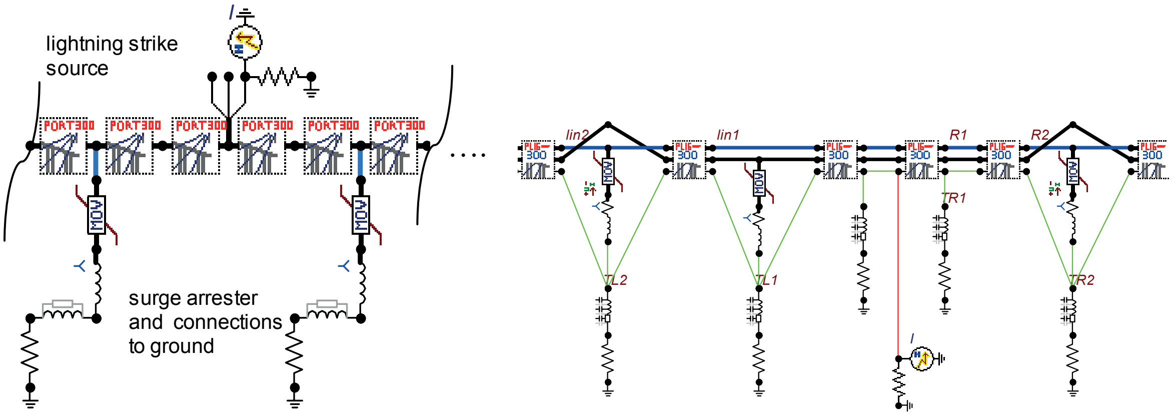
$$V_{tower} = 846.9\, e^{-3.992\, d} \qquad (1)$$

The voltage across the arresters also decreases away from the strike point for all models. However, as can be seen in Figure 5, there is a less steep change in magnitude. The voltage magnitude and shape also change significantly for the different models. Table 2 summarises the magnitudes of voltages across the first arrester for the four models above.

Table 2: Peak voltage at nearest arrester for various models.

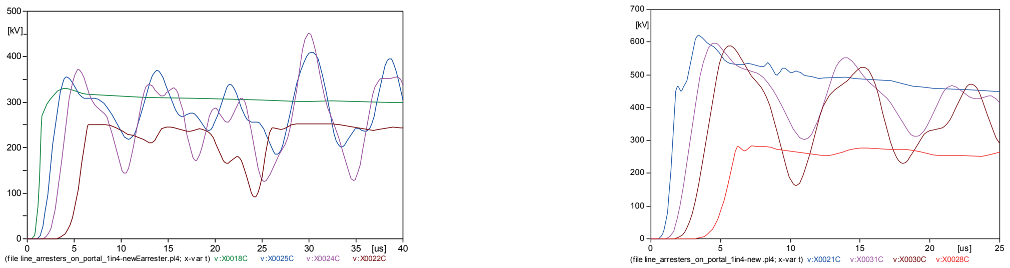
Simulation Model	Case (a)	Case (b)	Case (b)	Case (b)
Voltage across first arrester [kV]	76.2	56	52	252

From these simulations, it is shown that the modelling of arrester and tower affect the predicted results which, in turn, have implications for back-flashover determination and arrester current/energy. Further refinement of the arrester/tower connection model was found to have slightly different results. Figure 6 shows the proposed refined model.



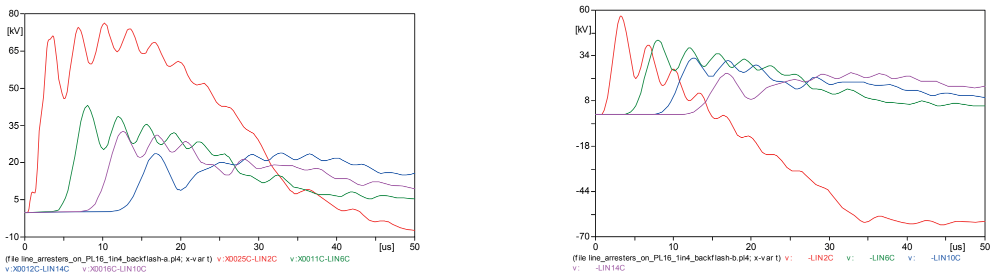
a) Section of Portal-type overhead model b) *Section of shielded line model*

Figure 3: sections of line models showing surge arresters every 4 spans and injection point.



a) voltages at arresters (with connection leads) b) voltages at arresters (without leads)

Figure 4: Effect of arrester model on voltages at arrester locations away from the injection point.



a) Tower model (a)- b) Tower model (b)

Figure 5: Examples of voltage shapes across line arresters for two different tower modelling techniques.

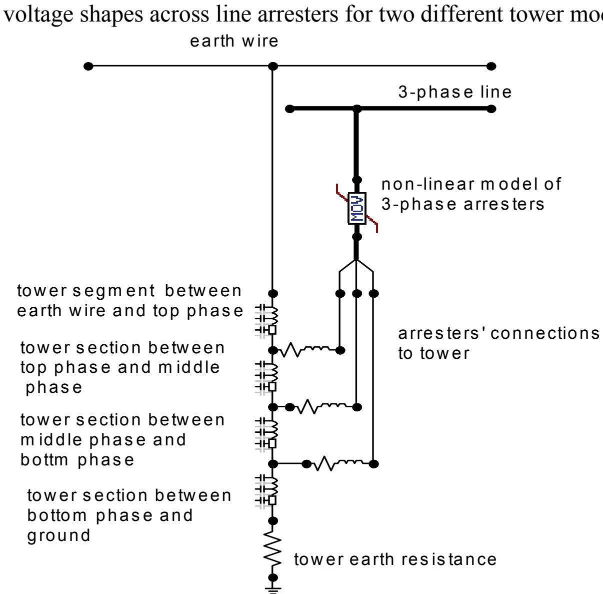


Figure 6: Proposed refined circuit model for tower-arrester assembly for a vertical phase configuration

Discussion and Conclusions

This analysis has considered a number of different scenarios. The nature of the incident lightning is a key. Obviously, the system voltage will have a major effect on the suitability of arrester application. Transmission is typical solidly grounded with very high BIL, while distribution systems will be impedance earthed with a much lower BIL. Therefore, trying to apply common guidelines is impractical. Coupled with this is the different electromagnetic nature between the two types of system, these effects are much more significant at transmission, although the design and security criteria may be quite different.

This paper has presented the results from a number of studies examining the degree of protection afforded from parallel surge arresters and their impact on the proximity effect for nearby equipment. There are many factors in the studies which can affect the results, variation between models being a major one. The main aim of this paper was to illustrate some of the general trends, but reinforces the case that this is a complex problem and for regional applications local design, operational, and topological factors must be incorporated into the model.

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Calculations of lightning-induced voltages in distribution lines with LSA

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SUMMARY

In this paper the results of the calculation of the effect of the surge arresters, placed in one of the conductors of a distribution line, are shown.
The calculations were made using a new computer program, written in MatLab environment, which is based in a new coupling model in order to take into account the presence of a lossy ground under the line. Other important feature of the new program is that, after a discretization only in space, the resulting system of ordinary differential equations (ODE) is solved using the powerful ODE solvers actually existing.
It is shown that a surge arrester protects the points behind it (seen from the strike point of the lightning discharge), but, it will only protect the points in front of it within a certain "effective distance", which depends on the risetime of the induced voltages.
It is also shown that, in general, the line span in front of the strike location is not protected, and, the protection afforded to the line span in front of the strike location, when it exists, is dependent on the risetime of the induced voltages.

KEYWORDS

Surge arresters, induced voltages, lightning protection, modeling.

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INTRODUCTION

Most of the calculations of lightning induced voltages, in lines with discontinuities (such as surge arresters), presented in the literature assume a perfectly conducting ground [1],[2]. One important exception is Reference [3] that presents a computer program to calculate induced voltages in lines with discontinuities, over a lossy ground. That program is based on the coupling model of Agrawal et al. [4], to take into account the lossy ground, and on the point-centered finite difference technique in the time domain, to integrate the resulting equations.
In this paper, the results of a new computer program are presented. The program takes into account the lossy ground using a new coupling model [5], and, to integrate the resulting equations, after a discretization only in space, the resulting system of ordinary differential equations (ODE) is solved using the powerful ODE solvers actually existing [6].

COUPLING MODEL

The problem of the coupling of an electromagnetic field to a transmission line consists of describing the voltages and currents induced in the conductors of the line in terms of the inducing fields.
The current *i(x,t)* at a point along a line conductor is defined, as usual, as the charge flow across the cross section of the conductor at that point.
Considering that the voltages are quantities that are not associated with a point but with a trajectory in space; in the case of a horizontal line, the induced voltage *u(x,t)* at a point of the line is defined as the integral of the electric field along a vertical trajectory from that point on the conductor to some reference point in the ground, usually ground level:

$$u^j(x,t) = \int_{h_j}^{0} \vec{E} \cdot d\vec{l} = -\int_{0}^{h_j} E_z dz \tag{1}$$

The model used in this paper is based on the application, for all conductors, of a formulation of Faraday's law in terms of the magnetic potential vector field *A* (*x*, *y*, *z*, *t*) and the scalar potential field ϕ(*x*, *y*, *z*, *t*):

$$\oint (\vec{E} + \frac{\partial \vec{A}}{\partial t}) \cdot d\vec{l} = 0 \Rightarrow \vec{E} = -\nabla \phi - \frac{\partial \vec{A}}{\partial t} \tag{2}$$

The application of Faraday's law applied to a conductor placed along the "x" direction can be written as:

$$-\frac{\partial \phi_j}{\partial x} - \frac{\partial A_{jx}}{\partial t} = E_x(x) \tag{3}$$

Assuming, as usual, that it is possible to define "indutances" and resistances" per unit length as:

$$A_{jx}^s(x,t) = \sum_k L_{jk} i^k(x,t) \tag{4}$$

$$E_x(x,t) = R_j i^j(x,t) \tag{5}$$

Where the suffix "s" denotes the potential due only to the currents in the line (scattered).
Introducing equations (4) and (5) into equation (3) a relation among scalar potentials and currents is obtained, that can be written as:

$$\frac{\partial i^k}{\partial t} = -L_{jk}^{-1} \{ R_j i^j + \frac{\partial A_{jx}^i}{\partial t} + \frac{\partial \phi_j}{\partial x} \} \tag{6}$$

Where the suffix "i" denotes the potential due to the currents external to the line (induzing).
On the other hand, the charge conservation law (or continuity equation) can be written as:

$$\frac{\partial \lambda^j(x,t)}{\partial t} = -\frac{\partial i^j(x,t)}{\partial x} \tag{7}$$

Where "λ" is the linear charge density along the conductor "j".
Assuming again that it is possible to define "capacitances" per unit length as:

$$\lambda^j(x,t) = C_{jk}\phi_k^s(x,t) = C_{jk}(\phi_k - \phi_k^i) \tag{8}$$

Introducing equation (8) into equation (7) a second relation among scalar potentials and currents is obtained, that can be written as:

$$\frac{\partial \phi_j}{\partial t} = \frac{\partial \phi_j^i}{\partial t} - C_{jk}^{-1}\frac{\partial i^k}{\partial x} \tag{9}$$

After a discretization in space of equations (6) and (9), the potential at potential nodes and the current at current nodes were considered as time evolving states of the system. The resulting system of ordinary differential equations (ODE) was then solved using the powerful ODE solvers actually existing [6].

This form of considering the vertical conductors permits, for example, to represent the grounding wire of a shielding wire or of a surge arrester not as a connection to ground, but, as a connection to the ground electrodes whose potential is then considered as more one state of the system.

INDUCED VOLTAGE CALCULATIONS

The induced voltage calculations presented in this paper will refer to a line with the geometry shown in Figure 1. In order to avoid the effect of imperfectly matched line terminations, the induced voltages calculated during the first 20 μs, for a 9 km line, will be presented.

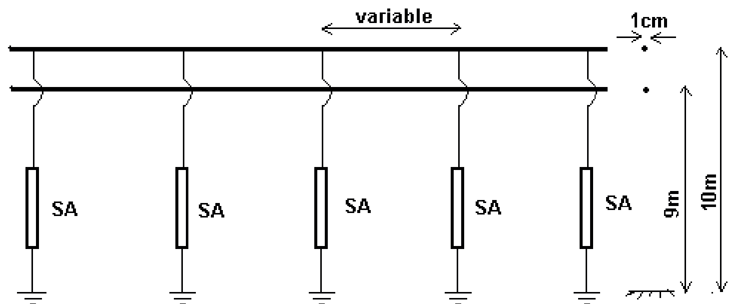


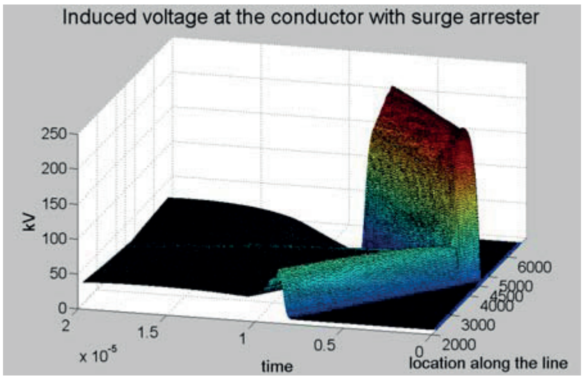
Figure 1 – Line geometry adopted in the calculations.

First, the effect of an isolated surge arrester placed at the middle of the line (z = 4500 m), grounded with a grounding resistance Rg = 10 Ohms, will be shown. The calculations will be done for the case of a 45 kA return stroke propagating with a velocity v = 0.3 c, with a lightning current of triangular waveshape 2x40 μs, that strikes at a distance of 70 m from the line, at the location along the line z = 4800 m.

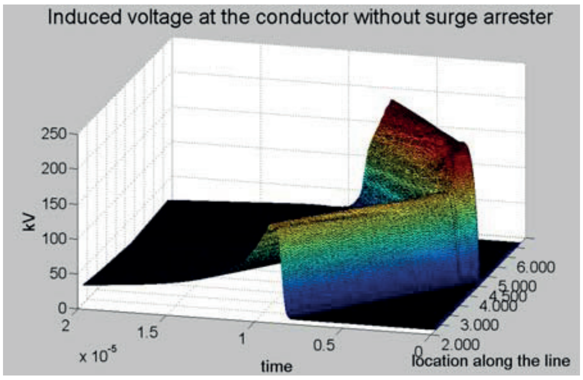
Figure 2 shows the profile of the induced voltage both in the conductor with surge arrester and in the conductor without surge arrester and, also, the voltage at the grounding electrode (that is proportional to the grounding current) and the arrester voltage.

From figures 2a and 2b it can be clearly seen that the effect of the arrester operation is perceived by the other points of the line with a certain time delay. The mitigating effect of the arrester, both on the conductor with surge arrester and on the conductor without surge arrester, is clearly seen for the points that are behind it (seen from the strike point of the lightning discharge), but, for the points in front of it the mitigating effect only exist within a certain "effective distance" that depends on the risetime of the induced voltages. Beyond that distance, the maximum value of the induced voltage is of the same value than for the case with no arrester, because the effect of the operation of the arrester arrives after the maximum of the induced voltage had already occurred.

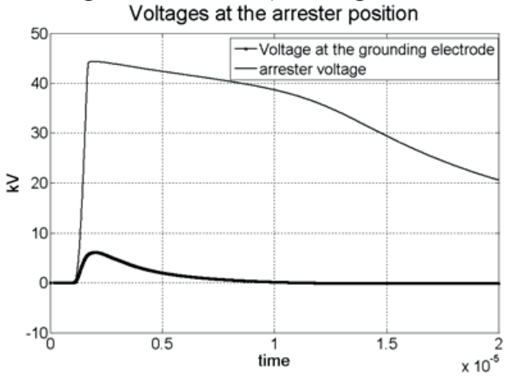
Next, the effect of multiple surge arresters, placed at a certain interval along the line and each of them grounded with a grounding resistance Rg = 10 Ohms, for the same lightning discharge previously considered will be shown. Figure 3 shows the profile of the induced voltage both in the conductor with surge arresters and in the conductor without surge arresters and, also, the voltage at the grounding electrode (that is proportional to the grounding current) and the arrester voltage at the same pole of the previous case.



a) Voltage at the conductor with surge arrester.

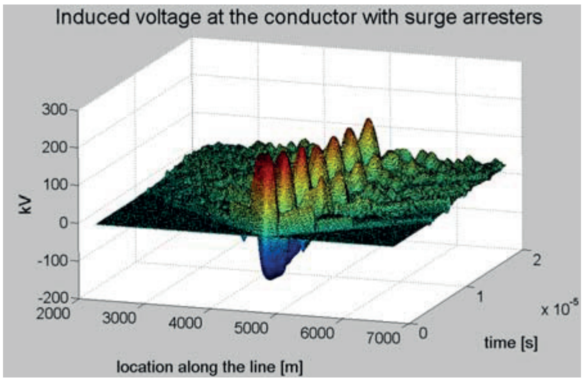


b) Voltage at the conductor without surge arrester.

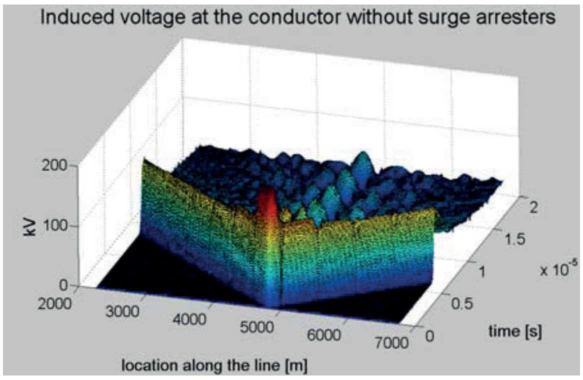


c) Voltages at the pole where the arrester is located (z = 4500 m).

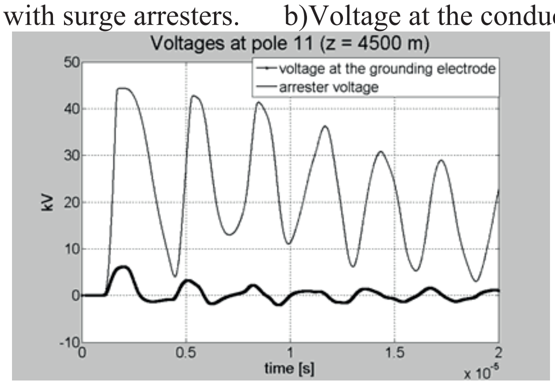
Figure 2– Voltages along a line with one surge arrester (Rg = 10 Ohms), placed at z =4500m, produced by a 45 kA lightning discharge (2x40 μs), propagating with a velocity v = 0.3 c, that strikes at z =4800 m, at a distance of 70 m from the line.



a) Voltage at the conductor with surge arresters.



b)Voltage at the conductor without surge arresters.



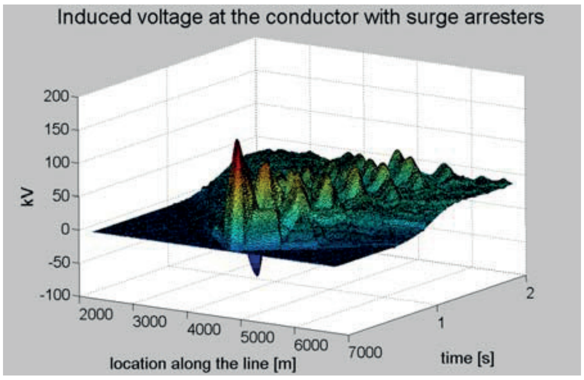
c) Voltages at the pole No.11 (z = 4500 m).

Figure 3– Voltages along a line with surge arresters each 450 m (Rg = 10 Ohms), produced by a 45 kA lightning discharge (2x40 μs), propagating with a velocity v = 0.3 c, that strikes at z =4800 m, at a distance of 70 m from the line.

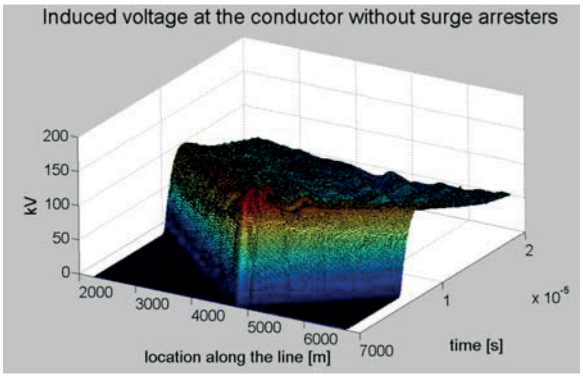
Comparing figure 3c with figure 2c, the effect of the operation of the arresters, which are placed in the neighboring poles, on the current through the arrester and also on the grounding current can be clearly seen.

From figures 3a and 3b it can be seen that the span in front of the strike location, in this case, is not protected by the arresters, in the sense that there are points within that span where the maximum value of the induced voltage is practically the same value than for the case with no arresters. It must be emphasized that all points within this span are in front of the arresters (seen from the strike point of the lightning discharge).

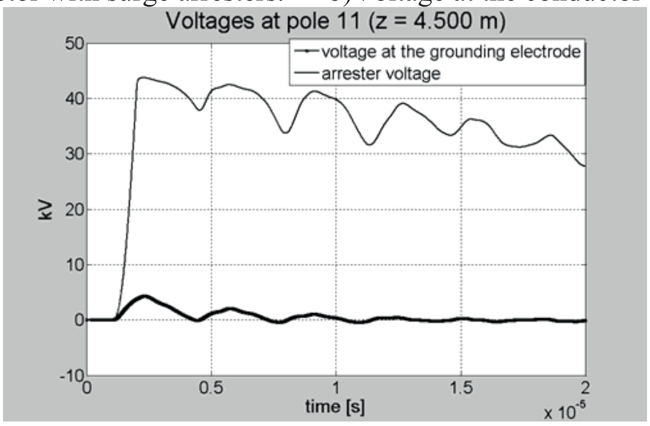
To show that the protection effectiveness of a certain interval between arresters depends on the risetime of the induced voltages, a new calculation was done with the same parameters of the previous calculation (the same discharge, the same interval between arresters, the same grounding resistance, etc.) except that now the propagating velocity of the return stroke is v = 0.1 c. Figure 4 shows the results in this case.



a) Voltage at the conductor with surge arresters.



b)Voltage at the conductor without surge arresters.



c) Voltages at the pole No.11 (z = 4500 m).

Figure 4– Voltages along a line with surge arresters each 450 m (Rg = 10 Ohms), produced by a 45 kA lightning discharge (2x40 μs), propagating with a velocity v = 0.1 c, that strikes at z =4800 m, at a distance of 70 m from the line.

From figures 4a and 4b it can be clearly seen that now the span in front of the strike location is protected by the arresters, in the sense that there the maximum value of the induced voltage is less than the maximum value for the case with no arresters.

CONCLUSIONS

In this paper the results of a new computer program to calculate lightning induced voltages on distribution lines, placed over a lossy ground, are presented. Concerning the conclusions that can be obtained from these results, referent to the protective effect of surge arresters against lightning induced overvoltages, we can mention the following ones (some of these facts are very well known others not so well known):

- The surge arresters act as a local protective device and the effect of its operation is perceived by the other points of the line with a certain time delay. So, there is a clear protective effect on the points behind it (seen from the strike point of the lightning discharge), but, for the points in front of it the mitigating effect only exist within a certain "effective distance" that depends on the risetime of the induced voltages.
- Multiple surge arresters, placed at a certain interval along the line, protect the region of the line outside the span in front of the strike location. The protection afforded to the line span in front of the strike location depends on the risetime of the induced voltages. Consequently, any statement about the effectiveness of a certain interval between arresters should be qualified by a certain risetime for which it is valid or by a probability that such risetime occurs.

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Lightning Protection of Electric Power Overhead Distribution Lines by Long-Flashover Arresters in Russia

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SUMMARY

A simple and effective method for lightning protection of power overhead distribution lines by long flashover arresters (LFAs) is presented. Even large lightning currents do not pose any threat to these arresters because the discharge develops in the air and not inside the device.

LFAs, which are based on the creeping discharge effect, increase the lightning flashover length significantly and thus eliminate Power Arc Follow (PAF). To protect a line against induced overvoltages, a single arrester should be mounted on a pole. To protect a line against direct lightning strokes, LFA-M arresters should be mounted in parallel with each insulator.

For covered-conductor overhead lines (CCL) using conductors with three-layer insulation a new lightning protection approach is suggested, involving use of antenna-type long flashover arresters whose essential component is the protected conductor itself. The essence of antenna-type long flashover arresters (LFA-A) is that the arrester which is connected to the antenna gets flashed over well before the lightning leader comes in immediate contact with the line.

The toroid-shaped antenna made of a metal tube is mounted on the covered conductor's surface midway between the protector's edge and the piercing clamp with the help of the toroid fixation unit. As the lightning leader progresses from a thunderstorm cloud to the CCL a high potential gets induced on the LFA antenna. A voltage drop that develops between the electrode and the zero-potential conductor core gives rise to development of a creeping discharge. Even before the lightning leader hits the line the creeping discharge channel flashes over the covered conductor's surface Thereby the conductor insulation get bypassed by the discharge channel and thus protected against puncture.

LFA's main applications and field experience are presented.

KEYWORDS

Lightning overvoltage, power arc follow, long flashover arrester

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1. INTRODUCTION

Outages of overhead power lines due to lightning strokes are one of the main causes of shortages of electric supplies and economic losses of power utilities. Widely separated pole-top metal oxide arresters can protect a distribution line against induced overvoltages. The main problem of using pole-top metal-oxide arresters is that they can be destroyed at direct lightning stroke to an overhead line [1].

In many countries, covered conductors are used for MV overhead lines. Such conductors have multiple benefits compared to bare conductors but there is a problem of conductor burndowns by Power Arc Follow (PAF), which occurs after lightning overvoltage and flashover of insulator. Arcing horns or similar devices that are used in some countries for protection of covered conductors against conductor burndowns do not protect overhead lines from lightning outages and have to be replaced after several operations.

In Russia [2], long flashover arresters (LFAs) developed by Streamer Electric Company are used for lightning overvoltage and conductor burn protection of 10 kV overhead lines [3-5]. The operating principle is based on extending the impulse flashover channel on the arrester surface through the creeping discharge effect. Owing to a long flashover length, the power arc gets extinguished and the overhead line continues operation without tripout. The main advantage of LFA is that the current passes outside the device and flows along the arrester surface. Therefore, the arrester cannot be destroyed by excessive current, even at direct lightning stroke. LFA’s construction is reliable and relatively simple. There are several LFA types.

2. MAIN APPLICATIONS

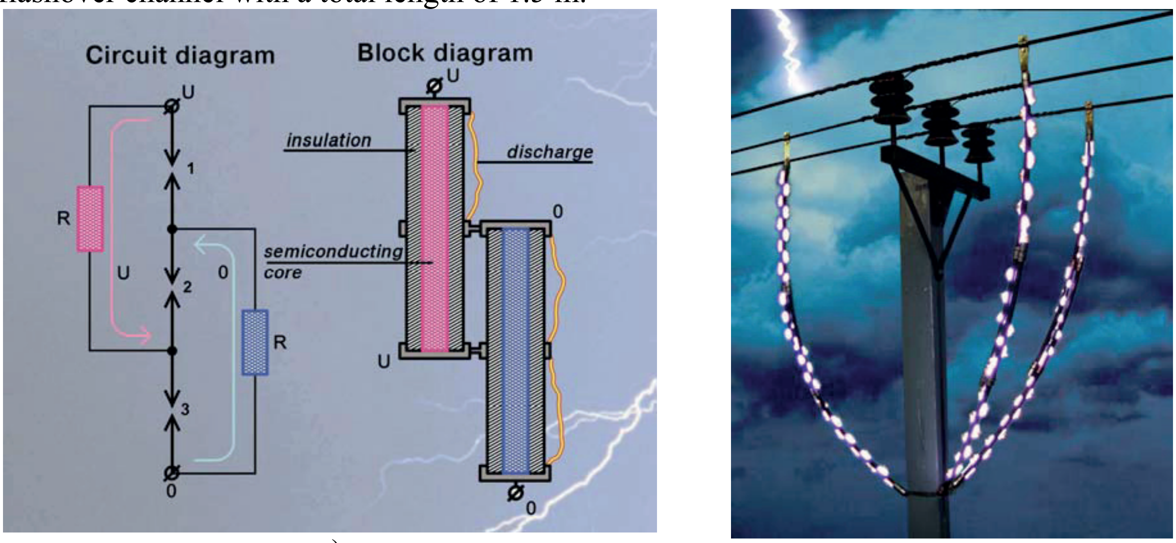
The Loop type LFA (LFA-L) consists of a piece of cable with steel cord inside, which is bent in a loop and connected to the pole with a clamp (Fig. 1). A metal tube is placed over the insulated loop in its middle part forming, together with the line conductor, a sparkover air gap. At one arm of the loop intermediate ring electrodes are installed. The loop is at the same potential as the structure. Due to a relatively big capacitance between the metallic tube and the steel cord inside the cable, the tube is practically at the same potential as the pole.

a) b)

Fig. 1. Loop-shaped LFA: a – sketch; b- photo of tests.

Therefore an overvoltage occurring between the line conductor and the pole will also occur between the metal tube and the line conductor. If the overvoltage is large enough, the sparkover gap will break down and the overvoltage will occur between the metal tube and the steel cord inside the cable to its insulation. Due to the overvoltage, a creeping flashover develops from the metal tube to a clamp of the insulated loop passing intermediate ring electrodes to the structure, thus completing the discharge circuit. The flashover length of a 10 kV LFA-L is 0.8 m. The intermediate electrodes have protrusions at opposite ends. Therefore, the flashover channel is broken into serially connected pieces of channels and due to this reason arc quenching is facilitated.

The Modular type LFA (LFA-M) arrester consists of two cable-like pieces with a resistive core (Fig. 2). There are also intermediate ring electrodes on its surface for the same purpose as for LFA-L (see above). The cable pieces are arranged so as to form three flashover modules 1 – 3, as shown in figure a below. The resistive core of the upper piece, whose resistance equals *R*, applies the high potential *U* to the surface of the lower piece at its middle. Similarly, the resistive core of the lower piece of the same resistance *R* applies the low potential *0* to the surface of the upper piece, also at its center. In this way, the total voltage *U* is applied to each flashover module at the same moment, and all three modules are assured conditions for simultaneous initiation of creeping discharges developing into a single long flashover channel with a total length of 1.5 m.



a) b)

Fig. 2. LFA-M arrester for protection of 10 kV overhead lines
a) circuit and block diagrams; b) arresters testing.

3. PROTECTION AGAINST INDUCED OVERVOLTAGES

For overhead 10 kV distribution lines with insulated neutral (a three-conductor ungrounded system), which are used in Russia, single phase to ground fault currents are quite low (1 to 30A). Thus PAFs are effectively prevented by LFAs.

To eliminate high short circuit currents associated with two- or three-phase lightning flashovers to ground, LFA-Ls are recommended to be installed one arrester per pole with phase interlacing (Fig. 3). With such an arrangement, a flashover to ground results in a circuit comprising two phases, two arresters and two grounding resistors that limit the fault current and ease arc quenching. The higher are the values of the grounding resistance, the more effective is the LFA-L operation. A 10 kV LFA-L with flashover length of 0.8 m quenches fault currents up to 500 A. LFA-Ls can be also used for protection of power grids with neutral grounded via resistor.

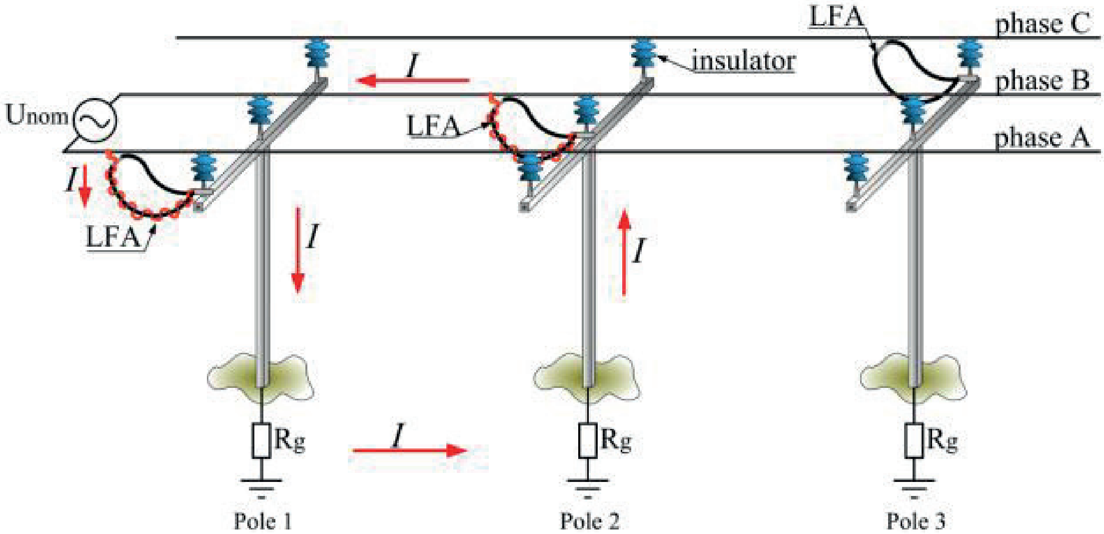


Fig. 3. LFA-L installation diagram on a distribution line

Four conductor overhead lines with grounded neutral have one phase to ground fault currents about several kiloamperes. In this case, the LFA-Ms with flashover length much greater than that of LFA-Ls can be used. They should be installed similarly, i. e. one unit per pole with phase interlacing.

4. PROTECTION AGAINST DIRECT LIGHTNING STROKES

A direct lightning stroke causes flashover of all the insulators on the affected pole. Therefore, in order to protect the line against a direct lightning stroke, LFA-Ms should be mounted on the pole in parallel with each line insulator. Phase-to-phase faults on a pole can give rise to follow-up current in the order of 10 kA or more. To quench such currents, flashover length of the LFA-M should be 1.5 m, i.e. much higher than that of LFA-L (0.8 m) which is intended to protect overhead lines against induced overvoltages.

5. FIELD EXPERIENCE

LFA-L and LFA-M are certified to meet the requirements of technical specifications and safety conditions of the Russian Government Standards.

Experimental exploitation of LFA-Ls started in 1999 and in the past three years more than 120 thousand arresters have been installed on various utilities including gas and oil companies equipment. As field experience has proved to be exceptionally successful, LFA-Ls are recommended by National guide for lightning protection of overhead MV lines as a main lightning protective means [2].

In October 2005, thirty arresters LFA-M were installed for experimental exploitation in St. Petersburg utility and in May 2006, 145 arresters were installed at an overhead line at Kuban utility (Southern Russia). Although the time is too brief to make sound conclusions, as of the present moment there have been no problems with the arresters exploitation.

Fig. 4. Installation of first experimental arresters (LFA-Ls) in St. Petersburg utility (Russia) in 1999.

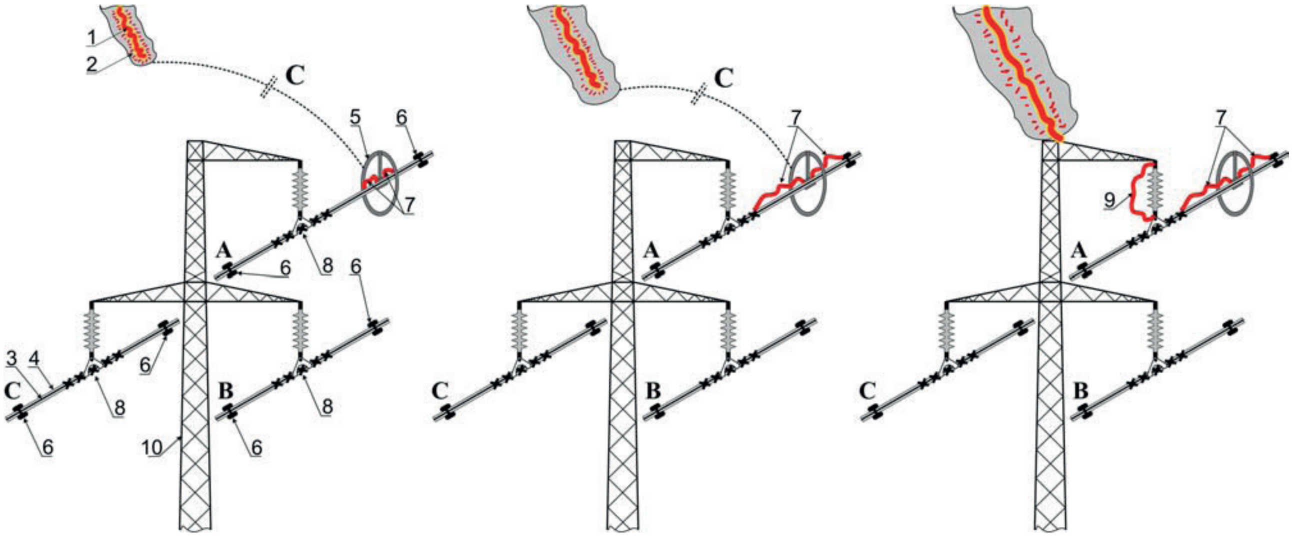
Fig. 5. 6 kV overhead line in Kuban utility (Russia) equipped with LFA-Ms.

6. LIGHTNING PROTECTION SYSTEM OF 35 kV LINES WITH COVERED CONDUCTORS

Reliability of electric power supply over 35 kV overhead lines can be enhanced through application of covered conductors, which are capable to rule line trip-outs due to brief electric crosses under effect of wind and ice loads and prevent ground faults because of contacts with tree branches. A lightning protection system of 35 kV CCL, which would be capable of protecting conductors against burns as well, can be implemented through use of LFAs.

Application of a three-layer covered conductor with excellent insulating performance, makes it possible to make the conductor an essential component of the LFA. Covered conductors are suspended on a tangent tower in a manner that rules out damage to their insulation at points of their fixation to an insulator. This is achieved through use of a supporting clamp with a protector and a conducting polymeric grip at conductor fixation points.

Six piercing clamps (two to a phase) are mounted on all the three phase conductors at a distance of about 1.4 m either side of the edges of conductor-supporting metal protectors (see Fig. 6). High voltage laboratory tests with 1.2/50 μs lightning overvoltage impulses showed the impulse strength of a composite insulator to be $U_{50\%\ \mathrm{ins}}$ = 250 kV; however, by using the insulating properties of the three layer covered conductor, as shown in Fig. 6, the impulse strength of the suspension set becomes as high as $U_{50\%\ \mathrm{ins\text{-}cov.\ cond}}$ = 400 kV. Thus the impulse strength of line insulation of all the three phases is raised to 400 kV.



a) b) c)

Fig. 6. Lightning protection of a 35 kV overhead line with covered conductors

a) The lightning is high above the ground, discharge channels start developing from the antenna fixation unit;

b) The lightning is close to the line, the covered conductor's section between a grip and a piercing clamp gets flashed over totally;

c) The lightning strikes the line, an insulator gets flashed over:

1 – lightning channel; 2 – space charge; 3 – conductor core; 4 – protective insulation; 5 – toroid-type antenna; 6 – piercing clamp;

7 – flashover channel over insulation surface; 8 – supporting clamp with protector; 9 – insulator flashover channel; 10 – tower.

The essence of antenna-type long flashover arresters (LFA-A) is that the arrester which is connected to the antenna gets flashed over well before the lightning leader comes in immediate contact with the line [6]. The toroid-shaped antenna made of a metal tube is mounted on the covered conductor's surface midway between the protector's edge and the piercing clamp with the help of the toroid fixation unit, which is further referred to as electrode. As the lightning leader progresses from a thunderstorm cloud to the CCL a high potential gets induced on the LFA antenna. A voltage drop that develops between the electrode and the zero-potential conductor core gives rise to development of a creeping discharge (Fig. 6, a). Even before the lightning leader hits the line the creeping discharge channel flashes over the covered conductor's surface (Fig. 6, b). Thereby the conductor insulation get bypassed by the discharge channel and thus protected against puncture.

A lightning stroke on a tower (Fig. 6, c) or on a line conductor results in an overvoltage on the conductor and on the protector, which is connected to the conductor via the discharge channel. The insulator gets flashed over as soon as overvoltage attains its flashover level. During a tower stroke most of the lightning overvoltage current flows first via the lightning flashover channel and next, via the tower to the ground (see Fig. 6, c). A part of the current flows by the creeping discharge channel over the conductor's surface to the piercing clamp and on over the line conductor.

When the lightning strikes a conductor the lightning overvoltage current flows by the lightning flashover channel over the conductor, across the piercing clamp and on by the insulator's lightning flashover channel and the tower body to the ground. The lightning overvoltage current is followed in the flashover channel by the power frequency current. As the follow-up current crosses zero the power arc gets extinguished, and the line maintains uninterrupted supply of power without an outage.

Attention is drawn to the fact that an antenna on the covered conductor's surface warrants that the covered conductor's section between the piercing clamp and the protector (see Fig. 6) is flashed over its surface with voltage rising smoothly and thus presenting no hazard for the covered conductor's insulation.

Without an antenna, the flashover pattern for the insulator-covered conductor system is totally different, with no discharges on the covered conductor's surface before the lightning strikes a tower or a line conductor. By way of example, a lightning stroke on a conductor results first in an insulator flashover, the voltage being abruptly applied to the covered conductor's insulation in a steep impulse resulting in a puncture.

The combined flashover length over the affected insulator and covered conductor (Fig. 6) needed to assure extinction of the follow-up arc can be found from the following equation [7]:

$$L = \frac{U}{70 I^{-0,41}} \quad \text{(at } 20 \le I \le 600 \text{ A)}, \qquad (1)$$

where U is the applied AC voltage, kV, and I , the follow-up current, A.

In isolated neutral grids, the follow-up current is capacitive single-phase fault current rarely in excess of 50 A. It follows from Eq. 1 that with the highest permissible phase voltage U=$U_{\text{ph, max}}$= 1.15·35/√3 = 23.3 kV and the follow-up current I = 50 A the total flashover length that warrants quenching of the arc is $L \approx 1.7$ m. The flashover length of a 35 kV insulator is about 0.5 m. Thus the needed flashover length over the covered conductor's surface is about 1.2 m.

The antenna voltage at the instant of an approaching lightning leader was calculated with the help of the procedure described in [6] for the overhead line alternative shown in Fig. 6, the minimum lightning current I_l being assumed to be 5 kA. If the arrester gets actuated at this minimum, there is even less doubt about its operation at any larger lightning current.

Both a conductor and a tower can be struck by a lightning. The farther from the antenna the lightning is, the lower is the induced voltage on the antenna [6]. Computations were made for the worst-case LFA-A scenario, viz., for the mid-span stroke on a conductor, with the lightning channel offset by about 75 m toward a tower along the line. A successful operation of the LFA-A at a mid-span stroke guarantees its good performance with a lightning striking a tower.

Shown in Fig. 7 are the calculated antenna potentials versus time for the antenna toroid radius R_{ant} of 30 cm at different toroid pipe radii. It can be seen from Fig. 7 that the antenna potential goes up as the above-ground height of the lightning decreases, i. e., as the lightning approaches the overhead line. With the lightning at some 50 m above ground, the antenna potential is about 100 kV, which exceeds the flashover voltage of a 0.7 m long creeping discharge (the distance between the electrode and the piercing clamp, see Fig. 1). At this voltage level creeping discharges start developing both sides of the electrode, which connect the grip to the piercing clamp. Fig. 7 also makes it clear that the antenna potential increases, although insignificantly, with the pipe radius owing to a growing capacitance between the lightning channel and the antenna. For the same reason the antenna potential grows with the toroid radius; this appears to be optimum at 30 cm.

The 100 kV antenna potential is attained even at the most unfavourable combination of various factors, such as a 5 kA minimum lightning current I_l, a 75 m distance between the lightning stroke point and the tower, and a low 1 Mohm leakage impedance. The antenna potential increases with a heavier lightning current, a larger leakage impedancey a smaller stroke-tower distance, so the quoted estimates can be considered to have a certain safety margin.

Fig. 8 presents a pilot commercial 35 kV CCL, which was built in Komi Republic (North of Russia) for power supply of an oil field. The line is 60 km length and passes through forest and uninhabited region. In order to decrease maintenance cost the line three layers covered conductor was used, which insures reliable operation of the line even in case of a tree fall on the conductors. Lightning protection system for the line by LFA-A was used. At uppermost phase a toroid antenna can be seen.

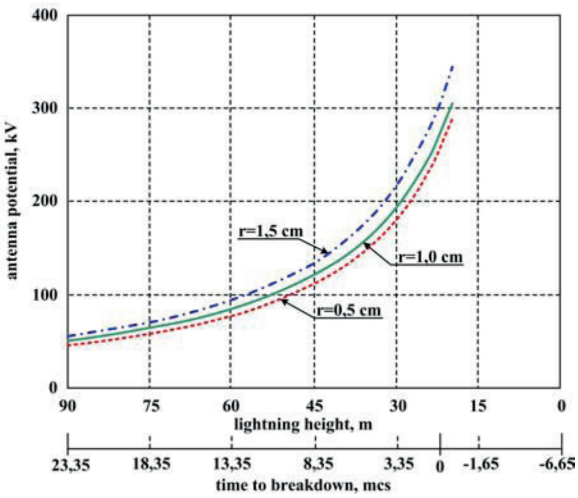


Fig. 7. Antenna potential vs. time to breakdown of the gap between the lightning and the line and vs. lightning height above ground at the toroid radius R_{Top} =30 cm and different pipe radii r

Fig. 8. 35 kV covered-conductor overhead line with Long Flashover Arresters of Antenna type.

7. CONCLUSIONS

1. A simple and effective method for lightning protection of power overhead distribution lines by long flashover arresters (LFAs) is presented. Even large lightning currents do not pose any threat to these arresters because the discharge develops in the air and not inside the device.
2. LFAs, which are based on the creeping discharge effect, increase the lightning flashover length significantly and thus eliminate Power Arc Follow (PAF). To protect a line against induced overvoltages, a single arrester should be mounted on a pole. To protect a line against direct lightning strokes, LFA-M arresters should be mounted in parallel with each insulator.
3. Lightning protection of a 35 kV overhead line with three-layers covered conductors can be feasibly implemented with the help of antenna-type long flashover arresters LFA-A. To this end, tangent towers of a covered-conductor line should be fitted with: 1) toroid-shaped antennas on the uppermost phase (one per tower) and 2) piercing clamps (two per phase, viz. six per tower). Conductors are suspended with the help of special supporting clamps with protectors assuring integrity of the covered conductors' insulation.

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First Experience in Monitoring of Line Surge Arresters Installed on 110 kV Transmission Line Ston – Komolac in Croatia

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SUMMARY

In paper are presented some first results and experience in real time monitoring of line surge arresters installed on 110 kV transmission line Ston – Komolac in southern part of Croatia. Mentioned line is the first line in Croatian transmission network equipped with line surge arresters (LSA).

The line with its length of 43,95 km is situated in region with high soil resistance, exposed to one of the highest level of lightning activity in Croatia. At the same time it is the most important line in connecting HPP Dubrovnik (240 MVA) to the main part of 110 kV transmission network.

Due to all mentioned reasons and great number of annual outages, it was decided to equip the line with LSA for improving the lightning performance and the availability of line. As result of performed numerical simulations on simulation line model it was decided to install 110 kV gapless, IEC Class II line arresters. Also, to improve analysis of expected results the 61 line arresters were equipped with Excount-II type of monitoring sensors. The main goal was to determine the behaviour of line arresters arrangement across the line during overvoltage events on towers. This installed "real-time" monitoring system enables remote control and wireless exchange the collected data from local data logger installed on LSA. Line arresters activity is monitoring through numbers, date and time and level of surges and the condition state of LSA, through the measuring of leakage current.

First results in application of LSA are showing significant reduction of line outages with registered relatively strong activity of monitored line arresters. Also, as it was expected some particular part of line is espied to be exposed to higher frequency and higher level of registered arresters surge current. During collecting the data of LSA activity, some practical problems were encountered with time synchronization between monitoring devices and it is mentioned and discussed in paper, too.

Although the analysed time period of eight months with LSA application is too short to allow strong final conclusions, obtained first experience will be very helpful in assessment of further LSA application in Croatian transmission network.

KEYWORDS

Line surge arrester, Line outages, Monitoring, Line surge arrester monitoring, Arrester activity, Arrester surge current, Collected data base.

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1. INTRODUCTION

Today metal oxide arresters (MOA) in polymer housing take a part more and more in line application because of low weight and simplicity in installation, high efficiency, long time of availability and finally, because of acceptable prices. They offer several possibilities to improve availability of transmission lines, spatially on double or multi-systems lines to solve the problem of back flashovers on insulators, in line up-rating, in insulation coordination etc. [1], [2], [3].

There were several reasons for application of line surge arresters (LSA) on transmission line 110 kV Ston – Komolac. This line is the shortest connection of HPP Dubrovnik (2x120 MVA) to the other part of transmission network in south of Croatia (Fig. 1). The line was constructed in 1961 and a big reconstruction has been done in 1994 with increasing transmission power capability installing TACSR/ACS conductors [4]. Further, it is crossing the region with high soil resistance and it is often exposed to strong lightning-storms. Outages due to lightning usually stopped down the generators of HPP and finally cause black out in region of town of Dubrovnik.

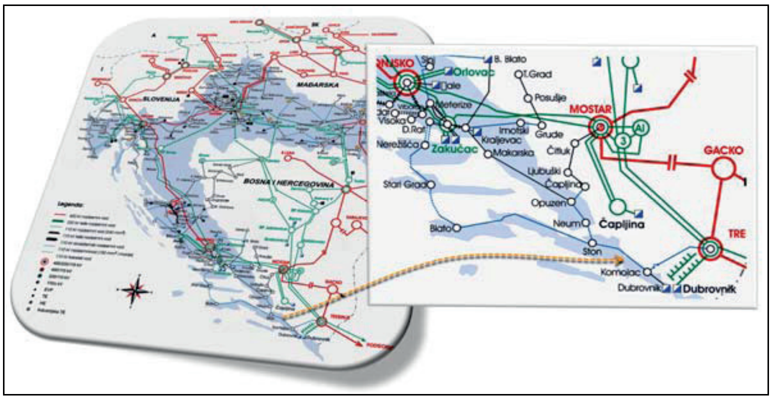


Figure 1-View to 110 kV transmission network in southern part of Croatia (blue lines)

Due to that reasons it was decided to improve lightning performance of line with application of 110 pieces of gapless, IEC Class II line surge arresters [5], [6], [10]. Also, due to improving the analysis of expected results it was planned to equip the 61 line arresters with Excount-II type of monitoring sensors (Fig. 2).

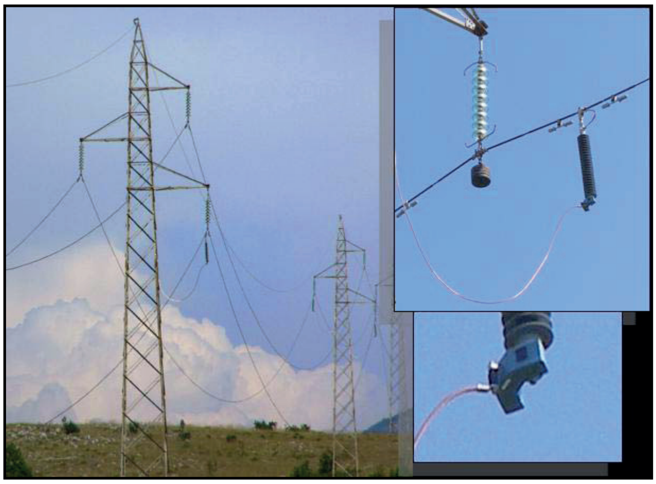


Figure 2-LSA on transmission line equipped with Excount II monitoring sensor

The main goal was to determine the behaviour of line arresters arrangement across the line during overvoltage events on towers. This installed "real-time" monitoring system enables remote control and wireless data exchange from local data logger installed on LSA. The LSA activity is monitoring through numbers, date and time and level of surges. The condition state of LSA is assessing by measuring the leakage currents [7], [8], [9]. The whole system has been installed at the end of June 2007, but only 49 monitoring sensors were put in service.

2. ARRESTERS ARRANGEMENT AND FIRST RESULTS OF MONITORING

2.1 Arresters arrangement

The installation and LSA arrangement on 110 kV line Ston-Komolac was based on performed study and computation on line simulation model [10], [11]. It was studied the lightning performance of line for different arresters arrangement along the line, also as a function of different tower earthing resistance. The goal was to find the optimal LSA arrangement to decrease a great number of backflashovers on insulator strings and a number of annual outages of line [12], (Fig. 3).

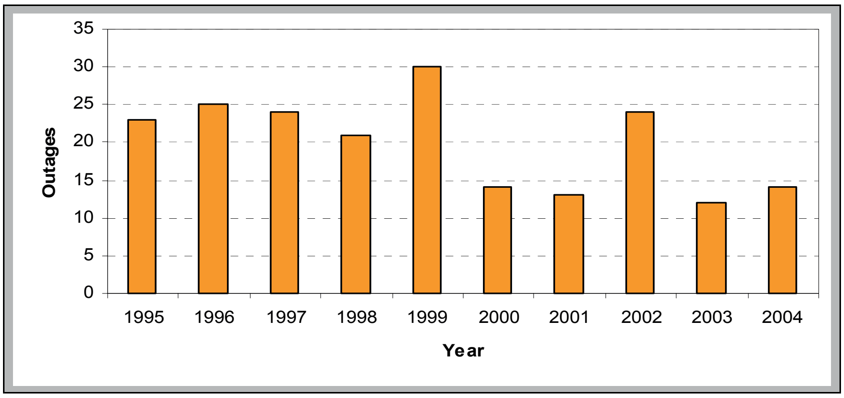


Figure 3-Number of annual outages during period of 10 years on 110 kV line Ston-Komolac (2004-up to June, 2 nd only)

As a result of computation it was chosen the LSA arrangement with one or two arresters per tower what is showed on schematic diagram on Fig. 4. In Table 1 are given the necessary numerical data. Also it is showed schematic phase arrangement on tower top.

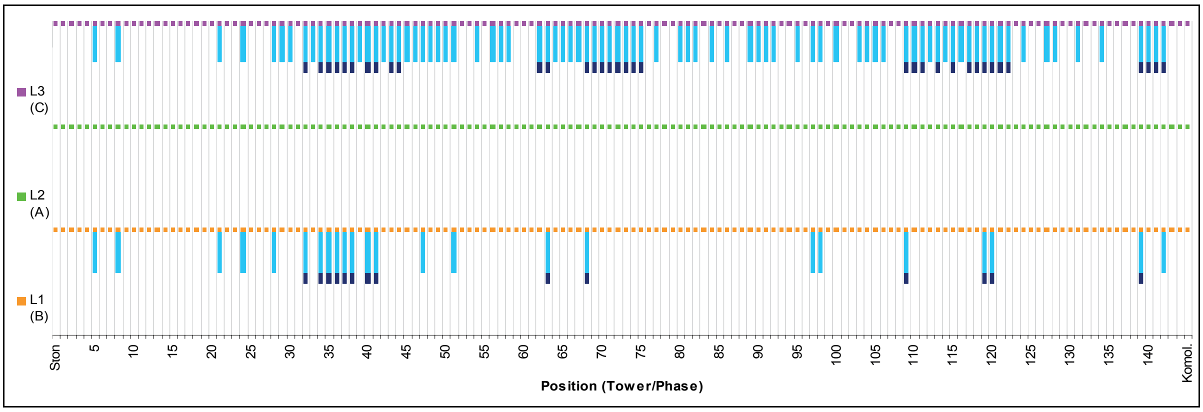
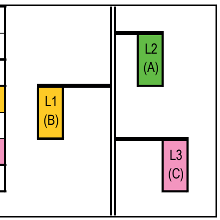


Figure 4-LSA arrangement along the line and installed Excount II monitoring sensors (dark blue or black)

Table 1-LSA and Excount II monitoring sensor arrangement data

Phase	Number of possible possitions	Mounted LSA			Mounted EXCOUNT II			Surges		
		pcs.	% of LSA	% of Towers	pcs.	%	% of Towers	registered	%	normalize to line
(1)	(2)	(3)	(4)	(5)=(3)/(2)*100	(6)	(7)	(8)=(6)/(2)*100	(9)	(10)	(11)=(2)/(6)*(9)
L1 (B)	145	24	21,8	16,6	14	28,6	9,7	37	32,5	383,2
L2 (A)	145	0	0	0,0	0	0	0,0	-	-	-
L3 (C)	145	86	78,2	59,3	35	71,4	24,1	77	67,5	319,0
Summa		**110**	**100**		**49**	**100**		**114**	**100,0**	



Further, expected reduction of number of annual outages of line - based on performed analyses on line simulation model - must be around 50 percent for chosen arrangement of LSA. For monitoring the LSA activity and for further analyses it was taken 49 Excount II sensors arranged and positioned on lightning exposed line structures what is also showed on Fig. 4 and in Table 1.

2.2 First results in monitoring of LSA activity

After the line surge arresters (LSA) installation have been completed on transmission line 110 kV Ston - Komolac in June 2007 started the “operation period” for so called “Pilot Project”.

First results after 9 months of application show that a number of line outages has been reduced (more than 50 percent during 6 months in 2007), particularly in summer time period (Fig. 5). Also, it is in expected range according to calculated values [10].

But, the observed period is not long enough to make appropriate statistical evaluation for sturdy conclusions. The real estimation of effects is possible to make after comparison and analysing longer time periods and bigger data collections. But the reduction in number of outages is very significant for taken protective measures on line even in the first short period.

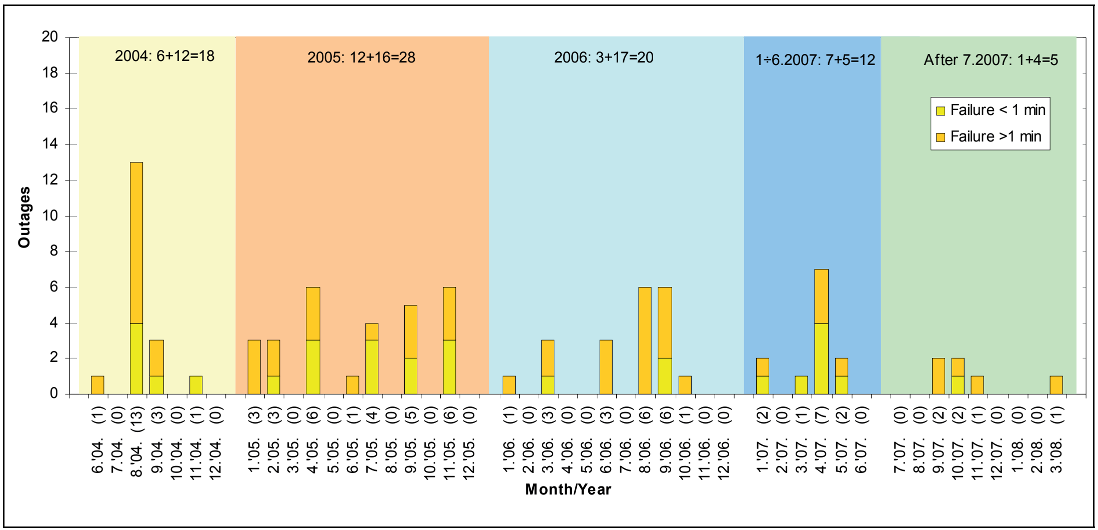


Figure 5-Review of outages on line 110 kV Ston-Komolac (before and after LSA application) (2007: 1-6 without LSA (blue), 2007: 1-12/2008:1-3 with LSA (green))

Further, the collected data from installed Excount II monitoring sensors exactly shows high level activity of LSA during observed time period. Additionally, it confirms the high level of the lightning in region of considered transmission line, because all of installed monitoring sensors have registered a lot of surges in their data loggers.

On Figures 6 and 7 it is shown the registered LSA surge current activity in accordance to sensor position (tower number) and corresponding phase. Additionally, it is shown the number of surges and level of surge current too.

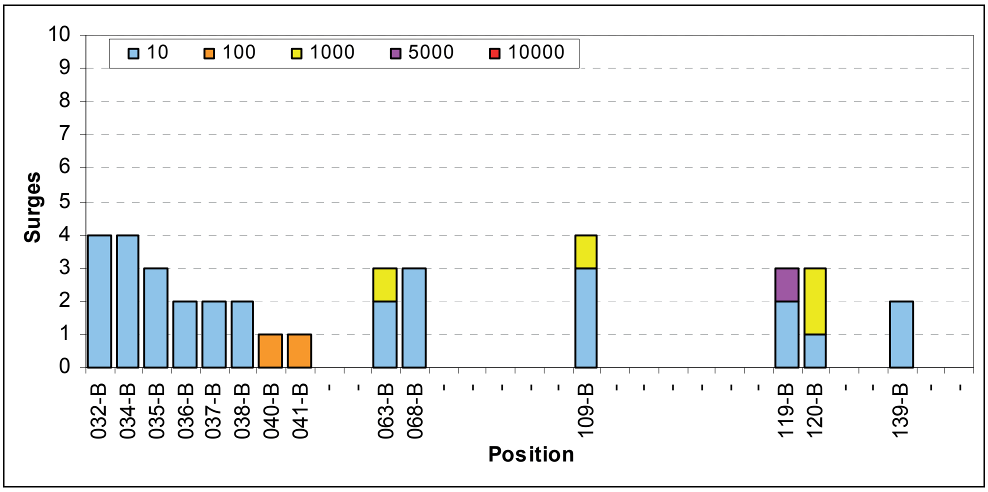


Figure 6-Review of LSA surges registered by Excount II monitoring sensors in Phase L1 (B)

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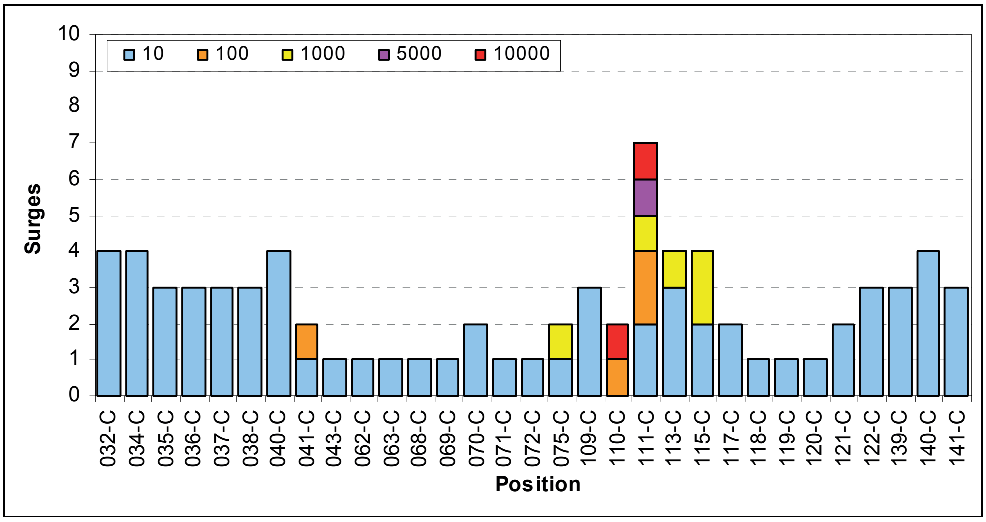

Figure 7- Review of LSA surges registered by Excount II monitoring sensors in Phase L3 (C)

In comparison the LSA activity in phase L1(B) with activity in phase L3(C) it can be concluded that the maximum number and level of surges are registered in phase L3(C). More intensive LSA activity was noticed in phase L3(C) on line tower No. 111 and on several neighbouring towers, too.

But, relating the installed number of monitoring sensors (monitored LSA) per phase and line length a little higher relative values can be calculated for LSA activity in phase L1(B), (see Table 1).

Of course, those are only the first results given in relatively short time of monitoring. In that sense on Fig. 8 is shown simple statistic review of failures due to events on line registered by distant relay protection during long time period. A portion of three-phase events is very significant.

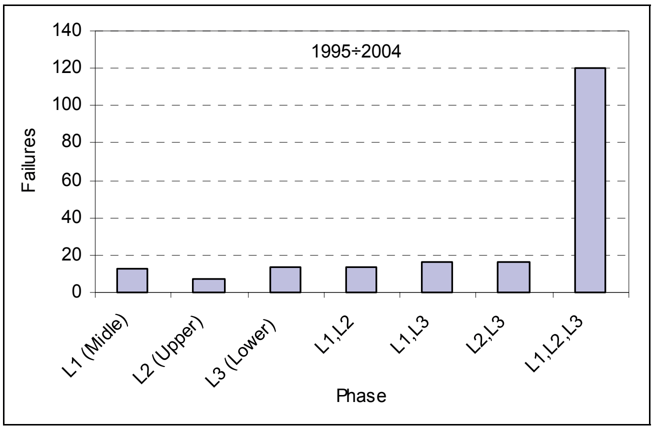

Figure 8- Review of events on line registered by distant relay protection

3. SOME PRACTICAL FIELD EXPERIENCES

First experience with installed monitoring system based on EXCOUNT II type of sensors showed good and practical basic system for wireless collecting the data of LSA activities on related transmission line. System makes possible to record surges on surge arresters including the data such as date, time and surge amplitude. Using that data it is possible to make advanced analyses of surges and overvoltage events on line and also in network.

In order to get good and reliable data from the system it is necessary to take into consideration some practical notes from equipment producers [8], [13]. The most important is the precise time synchronisation between sensors, transceiver and PC device with installed data base software.

Also, some problems could appear with “real time data” during practical work because of winter-summer time difference between the clocks of monitoring system devices, particularly in cases when collecting the data from all of system sensors is not “simultaneous”.

4. CONCLUSIONS

In the first application of line surge arresters (LSA) in Croatian transmission network on 110 kV line Ston-Komolac were installed 110 polymer housed LSA in order to improve line lightning performance. As a part of project a number of arresters were equipped with current sensors for real time monitoring of arresters current activity (49 sensors).

After 9 months of LSA application first results shown that a number of line outages have been significantly reduced according to expected and calculated estimation. Using the data collected from the whole system it is possible to make advanced analyses of surges and overvoltage events on line insulator strings, towers and their earthing system. In that sense the first analyses show that several line towers are much more exposed to lightning than others.

Experiences so far in application of installed monitoring system based on Excount II type of sensors also showed the advantages of wireless collecting data of LSA activities on related transmission line.

Due to short period of only 9 months of monitoring system field application, now it is too short time to achieve much more reliable estimations of all final effects and possibilities.

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