Abstract

A long flashover arrester (LFA), which comprises of three flashover modules using the creeping discharge effect, is described in this paper. In this design, the total arrester stressing voltage is applied simultaneously to all of the three modules so that the voltage-time characteristics of the arresters are improved. It assured reliable protection of medium voltage (e.g., 10kv) over head power line against both induced over voltages and direct lightning strokes. A single LFA per support or pole is found to be sufficient to protect an over head line against induced over voltages. An LFA should be arranged in parallel with each insulator in order to protect a line against direct lightning strokes.

**INTRODUCTION**   
A new simple, effective and inexpensive method for lightning protection of medium voltage overhead distribution line is using long flashover arresters (LFA). A new long flashover arrester model has been developed. It is designated as LFA-M. It offers great number of technical and economical advantages. The important feature of this modular long flashover arrester (LFA-M) is that it can be applied for lightning protection of overhead distribution line against both induced overvoltages and direct lightning strokes. The induced over voltages can be counteracted by installing a single arrester on an overhead line support (pole). For the protection of lines against direct lightning strokes, the arresters are connected between the poles and all of the phase conductors in parallel with the insulators.   
  
**LIGHTNING**  
WHAT IS LIGHTNING Lightning is an electrical discharge between cloud and the earth, between clouds or between the charge centers of the same cloud. Lightning is a huge spark and that take place when clouds are charged to at a high potential with respect to earth object (e.g. overhead lines) or neighboring cloud that the dielectric strength of the neighboring medium(air) is destroyed.   
TYPES OF LIGHTNING STROKES  
There are two main ways in which the lightning may strike the power system . They are  
1. Direct stroke  
2. Indirect stroke  
  
**DIRECT STROKE**   
In direct stroke, the lightning discharge is directly from the cloud to the an overhead line. From the line, current path may be over the insulators down to the pole to the ground. The over voltage set up due to the stroke may be large enough to flashover this path directly to the ground. The direct stroke can be of two types   
1. stroke A  
2. stroke B  
In stroke A, the lightning discharge is from the cloud to the subject equipment(e.g. overhead lines). The cloud will induce a charge of opposite sign on the tall object. When the potential between the cloud and line exceed the breakdown value of air, the lightning discharge occurs between the cloud and the line.   
In stroke B the lightning discharge occurs on the overhead line as the result of stroke A between the clouds. There are three clouds P,Q and R having positive, negative and positive charge respectively. Charge on the cloud Q is bound by cloud R.If the cloud P shift too nearer to cloud Q,Then lightning discharge will occur between them and charges on both these cloud disappear quickly. The result is that charge on cloud R suddenly become free and it then discharges rapidly to earth, ignoring tall object.   
**INDIRECT STROKE**   
Indirect stroke result from eletrostatically induced charges on the conductors due to the presence of charged cloud. If a positively charged cloud is above the line and induces a negative charge on the line by electrostatic induction. This negative charge however will be only on that portion on the line right under the cloud and the portion of the line away from it will be positively charged. The induced positive charge leaks slowly to earth. When the cloud discharges to earth or to another cloud, negative charge on the wire is isolated as it can not flow quickly to earth over the insulator. The result is that negative charge rushes along the line is both directions in the form of traveling wave. Majority of the surges in a transmission lines are caused by indirect lightning stroke.   
**THE LFA PRINCIPLE**   
When a lightning surge gets to an insulator, the insulator may flashover depending on the overvoltage value and insulation level of the line. Probability of power arc flow (PAF) depends on many parameters: nominal voltage of the line Unom, length of the flashover path L, moment at which lightning stroke occurred, lightning current magnitude, line parameters, etc. It was found that the main factor, which determines the probability of PAF, is the mean gradient of operational voltage along the flashover path.   
E = Uph/L  
Where Uph = Unom /3 =phase voltage, kV;  
L = length of flashover,   
The probability of PAF sharply decreases with a decrease in E. An analysis of available data on spark over discharge transition to PAF concluded that for E=7 to 10 kV/m probability of PAF is practically zero. The flashover length, L is greater for lines with wooden structures rather than steel or concrete structures, because wooden Cross-arm increases the flashover path. As a result probability of PAF for wooden structures is sufficiently lower than for steel or concrete supports. From the short analysis presented above, it is clear that it is possible to improve the protection against lightning by increasing the length of lightning flashover path. The suggested LFA accomplishes this principle. The LFA's length may be several times greater than that of an insulator (string, etc.). Due to a special inner structure the LFA impulse flashover voltage is lower than that of the insulator and when subjected to lightning overvoltage the LFA will flashover before the insulator.   
**DESIGN OF LFA-M**  
An LFA-M arrester consists of two cables like pieces. Each cable piece has a semi conductive core of resistance R. The cable pieces are arranged so as to form three flashover modules 1,2,3 as shown in figure1.Semiconductive core of upper piece, whose resistance is R ,applies the high potential U to the surface of the lower piece at its middle.Similiarly,the semi conductive core of the lower piece of the same rÃƒÂ©sistance R applies the low potential 0 to the surfaces of the upper piece, also at its center. Therefore 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 in to a single long flashover channel.   
Tests have been shown that, as the line conductor is stressed by lightning over voltage impulse, flash over channel develop at different rates.Modules1 and 3 flashover first, followed by module 2 ,and thus, forming a rather long flashover channel along the LFA.   
Due to long flashover path, a flashover does not give rise to a power arc as the arc extinguishes when the power frequency current crosses zero. This assures uninterrupted power supply of a LFA protected over head line.   
**FLASHOVER PERFORMANCES**   
The flashover performance of modular long-flashover arresters(LFA-M) arresters of two different flashover lengths and the voltage-time characteristics of LFA loop arresters, as well as those of the most common Russian insulators ShF 10-G and ShF 20-G with lengths 17 and 23 cm,respectively,were studied. The 50% flashover voltages of these units are 130 and 160 KV when stressed by 1.2/50 lightning impulses of negative polarity. therefore, these units will be referred hereafter as INS 130 and INS 160,respectively.   
The voltage-time characteristics of the arresters and insulators can be approximated by the expression  
U=a tb  
Where, U=flashover voltage in kilovolt.  
t=time to crest in microseconds.  
a,b are empirical coefficients whose values are given in the table  
test object impulse polarity A b  
insulator ins130 + 190 -0.352  
insulator ins 130 - 185 -0.285  
insulator ins160 + 243 -0.407  
insulator ins160 - 280 -0.28  
LFA-M,L=1m +,- 109 -0.784  
LFA-M,L =2 m +,- 173 -1.05  
LFA-M,L=0.8m + 159 -0.5  
LFA-M,L =0.8m - 107 -1.64  
  
**PROTECTION AGAINST DIRECT LIGHTING STROKES  
GENERAL PATTERN OF DIRECT LIGHTNING STROKES**  
The physical phenomena associated with a direct lighting stroke on an unprotected power line causing line tripping. The general pattern is as follows. For an overhead line in delta configuration shown in fig2, the top center face is the most vulnerable. For a lightning stoke on a phase conductor, the lighting current propagates both ways from the stroke point overcoming the surge impedance Zs of the line. A fairly high voltage drop develops at the points where the lines equivalent resistance equals half of the surge impedance Zs/2; this point is the closest to insulator unit of the lightning struck phase conductor. The voltage causes the insulator to flashover. A heavy impulse current flows through the flashover channel, the pole, and the pole footing resistance resulting into a large sharp voltage rise at the cross-arm.. Due to electromagnetic coupling between phases, the potential of the healthy outer phases also increases and it can be assessed from the conductor coupling factor. This voltage, however, is not as high as that for the lightning struck-conductor. Thus, the insulators of the healthy phases are stressed and flashed over by a voltage equal to the potential difference between the cross arm and the phase conductor. Phase to phase lightning flashover is also highly probable to occur resulting to a power arc accompanied by heavy short circuit currents, which causes immediate line tripping.  
  
  
**PROTECTION USING LFA-M**  
It follows from the previously described sequence of events that direct lightning stroke causes flashover of all the insulators on the affected pole. Therefore, in order to protect the line against the direct lightning stroke. LFAs should be mounted on the pole in parallel with each line insulator. A delta arrangement of conductors maximizes direct lightning strokes on the top (center) phase, which acts as shielding wire for the bottom (outer) phases. The shielding failure of the outer phases is reduced and it is given by the following equation.   
Pfail = exp   
Where, =protection angle between the top and bottom phases in degrees  
ho= the pole height in meters.  
  
For example, for ho = 10 m and = 300, the probability of a lightning stroke on the outer phases can be as slow as 0.001.   
An LFA mounted on the top phase must flash over before the top phase insulator. It is stressed by fairly steep over voltage impulses associated with direct lightning strokes on a conductor. Therefore, this arrester should be relatively short.   
  
After a top phase LFA flashes over, lightning current will flow, through the affected conductor and through the pole to the ground. Thus, the voltage on the cross arm increases at a much slower rate than it does on the lightning struck conductor before the flashover of the top phase LFA . On the other hand, the potential of the adjacent phases also increases due to electromagnetic coupling between conductors but at much slower rate than that applied to the top phase insulator consequently, an outer phase arrester operates under much easier coordination conditions than a top phase arrester. With one or both outer phase arresters activated, a two or three phase lightning flashover is initiated. To prevent transition of an impulse flash over to a PAF, the total flashover path L must be long. It can be calculated from the formula.   
L= Ul/Ecr  
Where Ul is the maximum operating line voltage; Ecr is the critical gradient of the power frequency voltage that rules out PAF.   
  
**CRITICAL GRADIENT AND LENGTH OF LFA-M**  
  
  
Some results of published experimental studies on the critical gradient are shown . As seen the critical gradient depends greatly on the line fault current. As the fault current increases from 20 â€œ 300A, the critical gradient drops abruptly from 20 â€œ 7kV/m.The rate of decrease of the critical gradient slows down for larger fault currents. Over the 1000-10000A fault current range, the critical gradient decreases from 5-4kV/m.   
Phase-to-phase faults on a pole can give rise to fault current in order of a few kiloampers. Therefore the critical gradient can be assumed to be 4kV/m. for a 10kV power line operating at maximum voltage (20% higher than nominal), the total flash over length is equal to L=12/4=3m. With 1-m flash over length of the top center phase LFA, the length of the LFA protecting an outer phase must be 2m.   
  
**PERFORMANCE ANALYSIS OF DIRECT LIGHTNING STROKE PROTECTION**  
The direct lightning performance of the modular arresters was carried out using the equivalent circuits.The arresters are connected between the pole and all of the phase conductors in parallel with the insulators. The arresters are assumed to be variable resistors whose resistance changes step wise from infinity to zero, in steps of , R , R/2, 0.   
As illustration, let us consider the operation of phase A arrester. Due to different propagation rates of flashover channels for lightning impulses of positive and negative polarity, the first module to flashover is module 1 with a flashover length of l1. Before flash over, the total resistance of the arrester can be assumed to   
be infinitely large . After module 1 flasheover at time t1, the arrester resistance RA is equal to that of one cable piece RAO, that is RA = RAo = LAoRA where LA o is the length of one cable piece of phase A arrester, LFA A, and Rl is the per-unit- length resistance of the cable.   
As tests have shown, module 3 of phase a arrester will usually flash over after module 1. At this instant t2, the resistance RAO of the second cable piece gets connected in parallel with the resistance of first piece and the total equivalent resistance of the arrester becomes RA =RAO/2. When the central part of the arrester flashes over at instant t3, the arrester sparks over through a single spark channel of very low resistance. Since the resistance of the flash over channel is low compared to other resistance affecting lightning over voltages (surge impedance of the conductor and of the lightning channel, etc.) It was assumed to be equal to zero. Therefore, starting from instant t3 the arrester resistance RA is zero a lightning stroke on the phase A include voltages on the outer phases B & C . However, as shown by calculations, until arrester LFAA flashes over, none of the modules of phase B arrester, LFAB, flash over. In other words , in time interval t3 < t t4 when LFAA flashes over completely, none of the LFABâ„¢s modules are affected. As the voltage keeps rising, module 1 of LFAB flashes over, and the flash over development and resistance change for the LFAB follow the same pattern described for the LFAA .   
The effect of the power frequency voltage of a 10-kV line on discharge process on the arrester surface is negligible. Since phases B and C and their arresters operate under identical conditions, it is practical to combine them in an overvoltage analysis.   
Phase B and C arresters are represented by a variable resistance RB/2 while the surge impedance of phases B and C on both sides of their arresters are represented by resistance ZS/4 where ZS is the line conductor surge impedance. The pole inductance is replaced by the concentrated inductance Xpole = Lohpole ,where LoÃ‚Â¬=1H/m is the per-unit-length inductance of the pole and hpole is the pole height   
  
**FLOW CHART OF LIGHTNING OVERVOLTAGE PROTECTION**  
  
A flowchart of the calculations is shown in fig6. First, the line parameters are entered, including the arrangement and radius of the conductors, the pole height, the grounding resistance, etc. Next, the insulators and arresters voltage-time characteristics (VTCs) are entered in an analytical form. Finally, the overvoltage calculations are performed for a given lightning current steepness in order to determine the lightning protection performance. The calculation is carried out for a linear increase of the lightning current, that is   
I1=Il 1t  
Where Il 1t is the lightning current steepness and it is the time   
Time is incremented in equal steps t. The equivalent EMF e is calculated as follows   
e = I1Z1  
where Z1 is the surge impedance of the lightning channel (Z1 = 300).  
The equivalent circuit for this time interval is elementary comprising e, Z1 and Zs/2.It is shown in the figure(5)  
The next step is to calculate flashover voltages for the individual discharge components or modules. Initially, for tt1, the equivalent resistance of phase A and B arresters (LFAA and LFAB, respectively) is infinitely large.   
  
The voltage and its rate of rise on arrester LFAA and insulator InsA are calculated. Equation (A4) of the Appendix is used to find the rate of propagation of discharge channels in modules 1 and 3 of arrester LFAA and the distance covered by these channels over time t.It is given below   
  
V = lt-1 =l   
Next, the channel lengths in the LFAAâ„¢s modules are compared to the modules lengths. If the channel length is greater or equal to the module length, a flashover is assumed to have occurred for that particular module and the equivalent arrester resistance abruptly becomes equal to the resistance of the respective semi conductive cable section. Furthermore, the arresters and insulators are checked for flashover based on their voltage-time characteristics. Flashover of insulator InsA indicates lightning protection failure. At this point, the calculation is stopped and the output is printed, including the steepness of the lightning current I11 at which the insulator flashed over. If insulator InsA does not flashover, the calculation restarts at a new time step of ti+1 = ti+t, where ti and ti+1 are the instants of iterations i and i+1, respectively. After a module of the LFAA flashes over across resistance RA, the pole reactance Xpole and Rg get involved, and the voltage and the rate of voltage rise on InsA, LFAA, InsB, and LFAB are calculated. The rate of channel propagation on arrester modules is determined, and the modules are checked for flashovers. In case of a flashover, the respective resistance RA and/or RB is changed. Finally, the calculation is checked for completion. If both the LFAA and LFAB arresters flashed over the lightning protection system performed successfully: If a flashover occurred on at least one of the insulators InsA or InsB. The lightning protection failed. Both results put an end to the calculation, and printout is produced. If only a partial flashover of the arrester occurred. The calculation is restarted as a new time step t.   
**VOLTAGE-TIME CHARATERISTICS OF ARRESTERS AND INSULATORS**  
typical voltage versus time curves for phase A and B insulators and arresters. It is seen that until module 1 of the LFAA arrester flashes over (t t1) the rate of rise for phase A voltage is quite high. When module 1 flashes over at instant t1, the voltage first drops abruptly but insignificantly and then it starts increasing but at a slower rate in the t1< t t2 interval. When module 3 flashers over at instant t2, the voltage drops abruptly again and then, over the t 2 < t t3 interval. It keeps increasing at a still slower rate until time t3. At t 3. Phase A voltage curve crosses the VTC curve of the LFAA arrester and the second (middle) module of the LFAA flashes over. (i.e., the arrester is now fully flashed over and the voltage drops on both the insulator and phase A arrester). At instant t3 an opposite polarity surge takes rise on insulator Ins B and arrester LFAB of phase B. After the LFAA fully flashed over, the lightning current travels through the pole and its footing. Thus, the voltage on phase B rises at a much slower rate than on phase A before the LFAAÃ‚Â¬ flashed over. The pattern of voltage rise on the LFAB is similar to that on the LFAA but features a slower rate of rise. At instants t4, t5, and t6 the first, third, and second modules of arrester LFA B flash over, respectively, changing the resistance of the arrester.   
  
the VTC of insulators and arresters cross at relatively small times to crests tcr. For a line using INS160 insulators and phase A LEFs with a flashover length lA= 1m. the critical time is tcr.AÃ‚Â¬ = t3 0.3 s. The average span length Ispan of a 10-kV line is usually about 70m. The travel time of a reflected wave from the nearest pole to the lightning-struck pole is given by ttr = (lspan + lspan)/ s (70+70)/300 0.5 s   
Where s 300m/s is the speed of propagation of an electromagnetic surge along the line. Thus, ttr is larger than tcr. ttr and a voltage surge reflected from the nearest pole comes to the lightning struck pole only after the arrester has operated or the insulator flashed over. Therefore, the nearest pole is not to be taken into account in the coordination analysis of the LFAA.   
For a line using phase B arresters with a flashover length lB = 2 m, the critical time is tcrB = t6 0.8 s (i.e., a voltage surge reflected from the nearest pole will be able to reach the lightning â€œ struck pole and lower the voltage applied to insulator InsB and arrester LFAB). The above calculation does not take into account the effect of near-by poise: thus, the calculated lightning performance of LFA-protected overhead lines can be regarded to have a certain margin.   
in evidence a lightning protection hazard of steep lightning over voltages. The voltage rate of rise Ul is proportional to steepness of the lightning current. This is the reason why the calculation takes into account the critical values of the lightning current steepness Ill,cr at which the insulator flashes over for a given set of parameters.   
  
**EFFICIENCY OF LFA-M**  
the critical lightning current steepness Ill,cr decreases versus grounding resistance Rg for a line with INS160 insulators. It can be clearly seen that as the grounding resistance increases, the critical lightning current steepness Ill,cr decreases.   
  
The number of lightning outages n o caused by direct lightning strokes (DLS) on conductors of an unprotected line can be estimated by the following equation   
n0=NDLS P( Il)Parc(1-Prc)   
Where NDLS is the number of direct lightning stroke(DLS) on a line; P (Il) is the probability of lightning current likely to cause flashovers of the line insulation; Parc is the probability of a power are caused by an impulse flashover an insulator; and Prc is the probability of successful line breakers enclosures   
It is shown that the steepness and not the magnitude of lightning current Il l Il is the important factor in the performance if a LFA protected line thus(1) can be written in the following form.   
Where n|0 is the number of lightning outages on an LFA protected line caused by direct lightning strokes on the phase conductors and P (Il,cr) is probability of a lightning current with steepness greater or equal to Il,cr   
The efficiency of LFA lightning protection against direct lightning strokes can be expressed as the ratio of the number of lightning outages n0 for unprotected line to n|0 for lines protected by LFA arresters .   
K = =   
Where k is the outage reduction factor of lightning outages caused by direct lightning strokes.  
  
**GROUNDING RESISTANCE AND REDUCTION FACTOR**  
the outage reduction factor of a line protected by LFA 10-M arresters (IA=1M; LB=LC=2M), versus the grounding resistance for the INS 160 and INS 130 insulators. A line with LFA arresters and INS 160 insulators is shown to have a good lightning protection performance for direct lightning strokes. For grounding resistance Rg = 10, LFA 10-M arresters assure a 200-fold decrease of lightning outages, virtually ruling them out. As the grounding resistance increases, the outage reduction factor k decreases faster up to Rg = 50 and then more slowly . for Rg = 50 . K is approximately equal to 20 and for Rg = 80 , k= 10. Thus, the number of outages caused by direct lightning strokes can be lowered with the use of LFA arresters by an order of magnitude or more even for high values of grounding resistance.   
As shown by calculations, in the case of INS 160 insulators, it is important to coordinate the performance of phase B arrester and insulator because the voltage rate of rise, and thus, the lightning protection efficiency at direct lightning strokes depends heavily on the grounding resistance.   
With the INS130 insulators the number of lightning outages is lowered by a factor of five, the outage reduction factor KDLS being practically independent of the grounding resistance. In the case, it is essential to coordinate the arrestors and the insulators on the lightning struck phase A. As indicated before, the coordination of arrester LFA A is not depend on the grounding resistance because the pole does not   
get involved in the path of the lightning current until the insulator or the arrestors have flashed over. It was shown by the calculation that a 1-m- long arrestors. LFA A is coordinate with an INS130 insulators at much lower values if the lightning current steepness than with an INS160 unit. It was also shown that, after the LFAA arrestors has successfully operated, the voltage rate of rise on phase B insulator and its arrestor becomes low and this facilities successful operation of the LFAB arrestor, at least, over the 10 to 100- grounding range.   
It should also be remembered that even large lightning currents do not present any hazards to these arrestors because the discharge develops in the air and not inside the device. Therefore, this new lightning protection system is thought to feature simple design, low cost, and high reliability.   
  
**FUTURE EXPANSION**  
The LFA-M described here consists of three flashover modules. We can increases the flashover modules. If the number of flashover modules increases by increasing the cable pieces this LFA-M can be used for lightning protection of very high voltage lines. When the modules increases the total arrester stressing is distributed these modules also. Then it can withstand very high over voltages.   
  
**CONCLUSIONS**  
1. A long flashover arrestor (LFA) comprising three flashover modules using the creeping discharge effect was presented in this report. Its resistors assure application of the total arrestor-stressing voltage simultaneously to all the modules.  
2. The voltage-time characteristics of this modular arrestor assure reliable protection of medium voltage overhead lines against both induced over voltages and direct lightning strokes.   
3. To protect a line against induced over voltages; a single arrestor must be mounted on a pole.  
4. The conditions for the efficient protection of a medium voltage (e.g. 10-kv) overhead line against direct lightning strokes, are as follows:  
o Delta phase configuration of phase conductors  
o Mounting of LFA-M arresters on all poles in parallel with each insulators ;  
o A relatively short flashover path (for example, 1 m for a 10-kv line) for the top phase LFA-M arrester  
o A longer flashover path (for example 2 m for a 10-kv line) for the bottom phase LFA-M arrester