Lightning and Lightning Arrester Simulation in Electrical Power Distribution Systems

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***Abstract*--this paper presents an overview of how ATP/EMTP can be used to model lightning strikes and their effects on power distribution systems. Emphasis is given on lightning arrester action and deployment. This work is the result of a two graduate students at the University of Puerto Rico-Mayagüez**

***Index Terms*—lightning, power system lightning effects, surge arresters, ATP, ATPDraw, power system transients, distribution feeder.**

I. NOMENCLATURE

PCC- Point of common coupling
LA-lightning arrester
BIL-basic insulation level
MOV-metal oxide varistor
ATP-Alternative Transient program
EMTP-Electromagnetic Transients Program
LLS-Lightning locating systems

II. INTRODUCTION

Lightning is a very impressive phenomenon that occurs in nature. The amount of energy contained in a lightning stroke is very high and it can be extremely destructive.

Electric distribution networks are particularly vulnerable to lightning strokes. A single stroke to a distribution line can be sufficient to cause a blackout throughout a feeder. To prevent this, power systems are protected with lightning rods, ground wires and lightning arresters.

This paper presents the results of simulations completed in ATP/EMTP that quantify the effects of lightning strikes on a particular distribution feeder. The paper focuses on the impact of lightning on power systems and its mitigation by the use of appropriate surge suppressor deployment.

III. LITERATURE REVIEW

A. Lightning an overview

Lightning is a physical phenomenon that occurs when the clouds acquire charge or become polarized, so that the electric fields of considerable strength are created within the cloud and between the cloud and adjacent masses such as earth and other clouds, [1]. When these fields become excessive, to the extent that the dielectric (the air) of intervening space can no longer support the electrical stress, a breakdown or lightning flash occurs; this is usually a high-current discharge.

B. Lightning in power systems

Lightning is the main reason for outages in transmission and distribution lines [1]. The lightning problem is classified as a transient event. When lightning strikes a power line, it is like closing a “big switch” between a large current source and the power line circuit. The sudden closing of this “big switch” causes an abrupt change in the circuit conditions, creating a transient. There is also the case when the lightning strikes the vicinity of the power line and the large magnetic field generated from the lightning current cause mutual coupling between the power line and the lightning. The event alters the conditions of the power line circuit, as a result, produce an electrical transient.

The study of lightning strokes in power lines is very important because it is known that lightning does strike the same structure over and again. This can be a very serious problem for power lines, typically, the highest structures located in high incidence lightning regions [2]. Any structure, no matter its size, may be struck by lightning, but the probability of a structure been struck increases with its height.

Very close dart leaders can make as significant a contribution as return strokes in inducing voltages and currents on power systems [3].

C. Lightning Prevention and Suppression Mechanism

Lightning rods are used as prevention mechanisms to avoid lightning hitting tall buildings or houses where lightning incidence is high, but no lightning rod can offer absolute protection, [2]. A lightning rod protection system has three main parts:

- The rods on the top of the protected structure,
- The wires which connect the rods together and those which run down the sides of the structure to the grounding arrangement,
- The grounding arrangement.

Rods can be pointed or ball rounded at the top. The rod material should be a corrosion-resistance material such as a copper, aluminum, or galvanized iron.

The wires that connect the rod to the grounding arrangement have the function of carrying the lightning current to the ground. The wires in the top of the structure have the secondary function of intercepting lightning

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discharges which may have missed the rods, [2]. The wires must be well grounded otherwise the lightning current may jump from the wires into the protected structure in search of a better ground. Grounding is accomplished by connecting the wires to long rods which are driven into ground or by connecting the wires to large buried metallic conductors. The buried conductors have to be connected to all nearby gas pipes, water pipes, or other buried metallic pipes or cables.

To protect high voltage transmission lines from lightning, the metallic rods and wire conductors are replaced by a system of wires suspended between tall towers arranged around the structure. These grounded wires are strung above the high voltage lines to intercept strokes that would otherwise hit the power lines, [2].

If a lightning stroke hits a power line, the only way to protect it is using a lightning arrester (LA). The lightning arrester is a non-linear device that acts as an open circuit to low potentials, but conducts electrical current at very high potentials. When lightning strikes a line protected with a lightning arrester, the non-linear resistance draws the current to ground.

One of the most common lightning arresters is the MOV (metal oxide varistor) lightning arrester, [4]. The MOV has a piece of metal oxide that is joined to the power and grounding line by a pair of semiconductors. The semiconductors have a variable resistance dependent on voltage. When the voltage level in the power line is at the rated voltage for the arrester, the electrons in the semiconductors flow in a way that creates a very high resistance. If the voltage level in the power line exceeds the arrester rated voltage, the electrons behave differently and create a low resistance path that conducts the injected lightning current to the ground system.

D. Description of a Lightning Discharge

A lightning discharge is called a *flash*, [2]. The duration of a flash is only a few tenths of a second. Cloud to ground flashes are composed of a single stroke or a multiple number of component strokes. Multiple stroke flashes have 3 to 4 strokes. The strokes are typically 40 to 50 milliseconds apart.

The typical lightning peak currents measured at ground range from 10 kA to 20 kA, but occasionally they range up to hundreds of thousands of amperes, [2]. The peak current is reached in a few millionths of a second, and then it decreases terminating in a thousandth of a second or so unless continuing current flows. It is very common that first stokes have larger currents that subsequent strokes, but this is not always true.

Lightning flashes which contain continuing currents are called *hot lightning*, [2]. The continuing current lasts for one or two tenths of a second and have a typical peak value of 100 A. Hot lightning ignites fires. The lightning that does not contain a continuing current is called *cold lightning*, [2]. Cold lightning does not set fires, but it is very destructive.

E. Starting a Lightning

The usual flash between the cloud and the ground is initiated in the base of the cloud, [2]. The initiating discharge, a downward traveling spark, is called the *stepped leader*. The stepped leader is a low-luminosity traveling spark which moves from the cloud to the ground in rapid steps about 50 yards long, and lasts less than a millionth of a second. The formation of each step of a dart-stepped leader is associated with a charge of a few milli-coulombs and a current of a few kilo-amperes, [3]. The visible lightning flash occurs when the stepped leader contacts the ground. The usual stepped leader starts from the cloud without any “knowledge” of what structure or geography are present below. It is thought that the stepped leader is “unaware” of objects beneath it until it is some tens of yards from the eventual strike point. When “awareness” occurs, a traveling spark is initiated from the point to be struck and propagates upward to meet the downward-moving stepped leader, completing the path to ground. When the stepped leader reaches ground, the leader channel first becomes highly luminous at the ground and then at higher altitudes. The bright, visible channel, or so-called *return stroke*, is formed from the ground up, thus visible lightning moves from the ground to the cloud.

In very tall structures the lightning is result of the reverse process, [2]. They are initiated by stepped leaders which start at the building top and propagate upward to the cloud.

F. Characteristics of Lightning

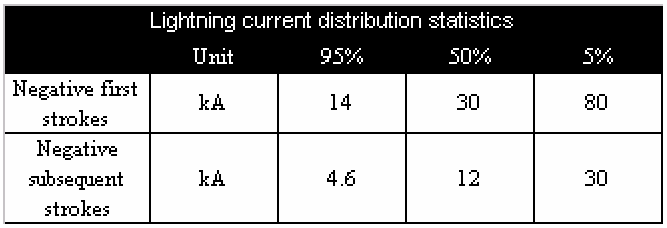
The usual ratio between the median values for field peaks of the first stroke and the subsequent stroke is 2:1, [5]. Larger strokes are preceded by longer inter-stroke intervals. The typical mean flash duration found in the literature is 175 ms. Since many lightning parameters show a large scatter for different thunderstorm days, long-term data from lighting locating systems are more representative of average lightning compared to data derived from electric field measurements typically performed during a few thunderstorms.

Lightning parameters are the basis for the design of lighting protection equipment and for the calculation of lightning radiated fields and their interaction with power lines, [5]. There are four different methods to measure lightning parameters:

- Direct current measurements in natural lightning
- Direct current measurements in triggered lightning
- Measurement of interferences from electric and magnetic fields
- Lightning locating systems

Lightning peak currents is one of the most important lightning parameters. Almost all of the national and international standards on lightning protection are based on lightning current measurements made in Switzerland. Lightning peak currents are lognormally distributed and usually described by median value and standard deviation or by 5, 50, and 95% values (see TABLE 1), [5].

TABLE 1. LIGHTNING CURRENT MAGNITUDE DISTRIBUTION



Lightning current distribution statistics				
	Unit	95%	50%	5%
Negative first strokes	kA	14	30	80
Negative subsequent strokes	kA	4.6	12	30

Typically, 51% of all flashes with more than one stroke contained at least one subsequent stroke with a peak greater than the peak of the first stroke, [5]. To quantify how much the peak of one of the subsequent strokes exceeds the peak of the first stroke in these flashes, the ratio of maximum subsequent stroke peak field to peak field of the first stroke is calculated.

Different percentages of single-stroke flashes are reported in literature. The values range from 14% to 40%. Percentage of single-strokes flashes vary significantly from storm to storm (from 30 to 80% with a mean of 40%) and probably depend on season, type of thunderstorm, etc, [5].

The number of strokes per flash varies due to the location, season and type of thunderstorm. In Florida, Rakov reported an average number of strokes per flash to be 4.6 [6]. The geometric mean of the time interval between strokes is about 33ms to 60 ms. Flash duration is reported to have a median duration of 180 ms for negative multiple-strokes flashes [7].

First strokes in Austria are different from those in Florida, consistent with the hypothesis that lightning parameters are specific for topographic and climatic regions, [5]. The percentage of single-stroke flashes and the number of strokes per flash exhibit a considerable variability for the individual storms even in the same region. Statistical evaluations based on data for a few storms may, therefore, may not be representative of the total lightning activity in a region. It is very important to be aware of possible bias, when data from only a single storm is analyzed.

G. Lightning Properties

Measurements reveal that the initial electric field peak (current peak) for the only strokes in single-stroke flashes was smaller than for first strokes in multiple-stroke flashes, [6]. Half of all flashes, single and multiple-stroke, contact ground at more than one point, with spatial separation between the channel terminations being up to many kilometers. One third of all multiple-stroke flashes had at least one subsequent stroke whose distance-normalized initial electric field peak exceeded that of the first stroke in the flash. Contrary to the implication of most lightning protection and lightning test standards such flashes are not unusual. Leaders of lower-order subsequent strokes following previously formed channels were more likely to show stepping, as opposed to continuous propagation (i.e., to be dart-stepped leaders rather than dart leaders), than were leaders of higher-order strokes.

Lower-order subsequent return strokes exhibited a larger initial electric field peak than did higher-order strokes. The second leader of the flash (the first subsequent leader) encounters the least favorable propagation conditions of all subsequent strokes: more than half of the second leaders either deflected from the previously formed path to ground or propagated in a stepped, as opposed to a continuous, fashion along the lowest part of that path. Inter-stroke intervals preceding second strokes are similar to or shorter than those preceding higher-order strokes.

A number of lightning properties derived from electric field records appear dependent on stroke order, [6].

The majority of long continuing currents (longer than 40 ms) are initiated by subsequent strokes of multiple-stroke flashes as opposed to either the first stroke in a multiple-stroke flash or the only stroke in a single-stroke flash, [6]. There appears to be a pattern in initiating long continuing currents.

Findings regarding the occurrence of single-stroke flashes, multiple ground strike points, and the relative stroke intensity within a flash, may have important implications for lightning protection and lightning test standards, [6].

H. Triggered lightning

Many aspects of the physics of the lightning discharge and of the interaction of lightning with the objects and systems can only be properly understood by way of measurements made on very close lightning, [3]. The probability for a lightning discharge to strike at or close to a given point of interest on the Earth’s surface is very low, even in areas of relatively high lightning activity. The study of the properties and the effects of close lightning have been made practical via the use of artificially initiated lightning, lightning stimulated to occur between a thundercloud and a designated point on the ground.

The most common technique for triggering lightning involves the launching of a small rocket attached to a trailing grounded copper wire in the presence of a sufficiently charged cloud overhead, [3]. The cloud charge is remotely sensed by measuring the electric field at ground level, with values of –4 to –10 kV/m usually being good indicators of favorable conditions for lightning initiations. When the rocket is typically 200 to 300 m high, the electric field enhancement near the upper end of the wire is sufficient to trigger a positively charged (in the most common case of predominantly negative charge at the bottom of the cloud) leader extending toward the cloud. The upward leader melts and vaporizes the trailing wire and establishes a so-called “initial continuous current” of the order of some hundred amperes along the wire trace, which effectively serves to transport negative charge from the cloud charge source to the ground via the instrumented triggering facility. After the cessation of the initial continuous current, several downward leader/upward return stroke sequences often traverse the same path to the triggering facility.

The return strokes in triggered lighting are similar to subsequent return strokes in natural lightning, although the initial processes in natural and classical triggered lightning are distinctly different: in natural lightning, a negative downward stepped leader and ground attachment followed by a first return stroke versus, in triggered lightning, an upward positive leader followed by an initial continuous current.

Lightning appears to be able to reduce the grounding impedance which it initially encounters at the strike point so that at the time of channel-base current peak the reduced grounding impedance is always much lower than the equivalent impedance of the channel, [3].

I. Positive Lightning

Positive lightning discharges have recently attracted considerable attention for the following reasons, [8]:

- The highest recorded lightning currents (up to 300 kA) and the largest charge transfers to ground (up to hundreds of coulombs) are associated to positive lightning
- Positive lightning can be the dominant type of cloud-to-ground lightning during the cold season and during the dissipating stage of a thunderstorm.
- Positive lightning has been recently identified as a major source of sprites and elves in the middle and upper atmosphere.
- Reliable identification of positive discharges by lightning locating systems (LLS) has important implications for various studies that depend on LLS data.

Positive flashes are usually composed of a single stroke. About 80 percent of negative flashes contain two or more strokes, [8]. Multiple-stroke positive flashes do occur but they are relatively rare.

Positive return strokes tend to be followed by continuing currents that typically last for tens to hundreds of milliseconds, [8]. Electric field measurements show that continuing currents in positive flashes are in excess of 10 kA, an order of magnitude larger than for negative flashes, for periods up to 10 ms. In the winter lightning in Japan directly measured positive continuing currents in the kilo-amperes to tens of kilo-amperes range in are seen following the initial current pulses. Such large continuing currents are probably responsible for the unusually large charge transfers by positive flashes.

From electric field records, positive return strokes often appear to be preceded by significant in-cloud discharge activity lasting, on average, in excess of 100 ms, [8]. This suggests that a positive discharge to ground can be initiated by a branch of an extensive cloud discharge.

LLS's data reveals that the median value of the positive lightning peak current is found to be greater in the winter than in the summer, [8]. Median positive peak currents exceeded 40 kA in the Midwest of the U.S., but were less than 10 kA in Louisiana and Florida. The positive peak current maximum in the winter lightning in Japan appears to vary during the storm life cycle reaching the largest value when the stratiform region is most intense.

It appears that positive cloud-to-ground discharges are intimately related to positive lightning discharges, [8]. Some cloud discharge processes are apparently capable of producing electric and magnetic field signatures resembling those characteristics of return strokes and of comparable amplitude. The polarity of these cloud-discharge pulses is probably more often the same as that expected for positive return strokes. As a result it is very difficult to identify positive return-stroke waveforms with confidence.

J. Bipolar Lightning

Lightning current waveforms exhibiting polarity reversals are denominated bipolar lightning, [8]. Many bipolar lightning current waveforms have been observed in winter lightning studies in Japan.

There are basically three types of bipolar lightning discharges, although some events may belong to more than one category, [8]:

- The first type of bipolar discharges is associated with a polarity reversal during a slowly-varying (millisecond-scale) current component, for example the initial continuous current in object-initiated lightning or in rocket-triggered lightning. The polarity reversal may occur one or more times and may involve an appreciable no-current interval between opposite polarity portions of the waveform.
- The second type of bipolar discharges is characterized by different polarities of the initial stage current and of the following return stroke or strokes. The initial stage current in this waveform is negative and the return stroke current, followed by a continuing current is positive.
- The third type of bipolar discharges involves return strokes of opposite polarity. All documented bipolar discharges in this category (return strokes of opposite polarity) are of the upward type.

Bipolar lightning discharges are usually initiated by upward leaders from tall objects, [8]. It appears that positive and negative charge sources in the cloud are tapped by different upward branches of the lightning channel.

IV. DEVELOPMENT OF SIMULATION

A. Test System

To assess the impact of lightning strikes on electric power systems, a test system was assembled using ATPDraw. The test system is based on the IEEE 34 bus test feeder system [9], which features three phase balanced and unbalanced loads and distributed single phase loads. The system's infinite bus is a 69kV connection from the utility. This bus becomes the point of common coupling (PCC) for a 24.9kV feeder. The original 34 bus IEEE test system featured a 2.5 MVA substation transformer; this transformer was adjusted to a higher value of 22 MVA, to compensate for additional loads that were going to be included in the simulation. Per unit impedance values were kept the same and internal transformer impedance values were adjusted to the new capacity. The 69kV to 24.9kV substation transformer and the 24.9kV to 4.16kV transformer at bus 832 were simulated as a saturable three phase delta-wye devices based on the standard ATP *GENTRAFO* model. Regulating transformers were not included in these simulations; their impact would be negligible in this kind of analysis and the added simulation complexity did not justify the extra precision. For the general system configuration see figure 1.

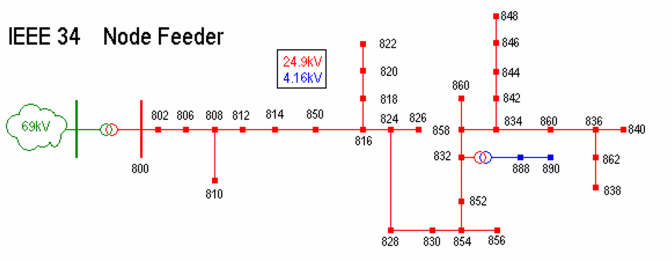


Fig. 1: General system configuration

System unbalances, including effects due to loads and unequal phase spacing were included in the simulation, since they had a noticeable impact on the system operation. All line parameters, except line 806-808, were included as lumped series or pi equivalents depending on the way it was established on the 34 bus IEEE test feeder specification. Line 806-808 was simulated using ATP Line and Cable Constants (LCC) subroutine using the line's physical configuration given. This line was simulated using the LCC to consider mutual inductance between phases. Two LCC modules were created to simulate the two half-lengths of the line and provide for a center node in the line. The center node was used to connect the simulated lightning strike.

All load values, three phase or single phase, were simulated as constant impedance loads instead of the load model specified in the IEEE test system specification. This was done for simulation efficiency and ease of convergence. Single phase loads were installed following the phase information stated in the standard. Distributed loads were included in the following way: distributed loads dispersed through several buses were divided in equal lump spot loads installed at each bus along the specified line; if the dispersed loads were located along a single line segment between two buses, a single equivalent lump spot load was installed on the far end of the line. These modifications provided for worst case formulation of the data. Single phase loads were simulated as constant impedance loads and integrated into the system as lumped passive RLC elements with the adequate R, L and C values for the real and reactive power requirements. Three phase loads were implemented using the *RLC-Y* or *RLC-)* ATP models. Unbalanced three phase loads were simulated as specified by the test feeder standard, including phase rotation and individual phase loading. The feeder configuration as implemented in ATPDraw is shown in figure 2.

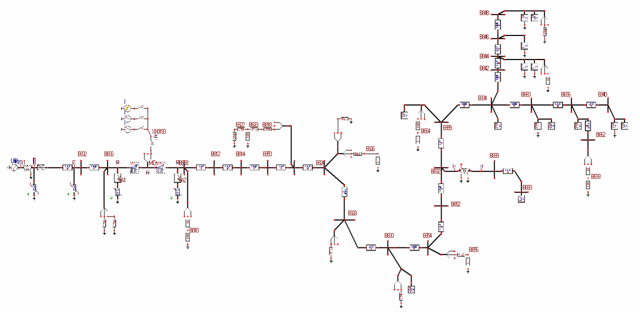


Fig. 2: ATPDraw system Configuration

B. Lightning flash

The lightning flash simulated in ATPDraw was based on the cold lightning flash characteristic described in [2]. The flash is composed of three sequential spikes of varying magnitudes. The first strike has a magnitude of 20kA, while subsequent strokes have magnitudes of 12kA and 9kA respectively. It was implemented in ATPDraw using three shunt connected ideal current sources. The first stroke has a duration of 0.6 ms and is presented figure 3.

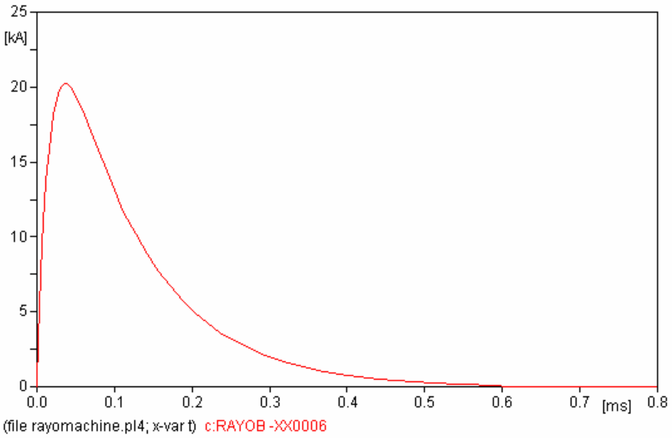


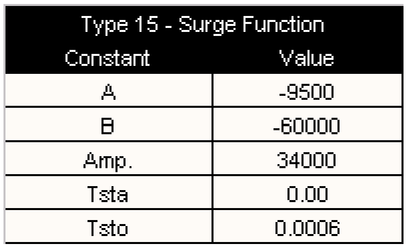
Fig. 3: First lightning stroke – 20kA for 0.6ms

This first stroke was simulated using a Type-15 Surge function. According to the ATP/EMTP Rule Book [10] the surge function is given by

$$f(t) = amplitude(e^{At} - e^{Bt}) \text{ ---- } (1)$$

The constants *amplitude, A* and *B* were selected to provide a surge value of 20kA for a duration of 0.6ms. Constants values are presented in Table 2.

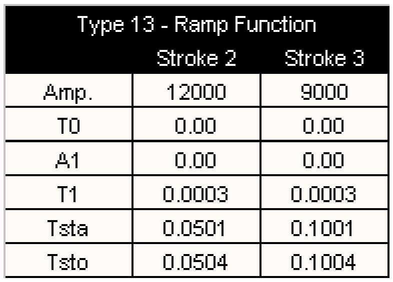
TABLE 2: TYPE 15 SURGE FUNCTION VALUES



Type 15 - Surge Function	
Constant	Value
A	-9500
B	-60000
Amp.	34000
Tsta	0.00
Tsto	0.0006

The second and third strokes were implemented using TYPE-13 ramp functions of 0.3ms duration with 12kA and 9kA magnitude, respectively. Table 3 summarizes the values used for the functions. Figure 4 shows the simulated lightning flash as implemented in ATPDraw.

TABLE 3: TYPE 13 RAMP FUNCTION VALUES



Type 13 - Ramp Function		
	Stroke 2	Stroke 3
Amp.	12000	9000
T0	0.00	0.00
A1	0.00	0.00
T1	0.0003	0.0003
Tsta	0.0501	0.1001
Tsto	0.0504	0.1004

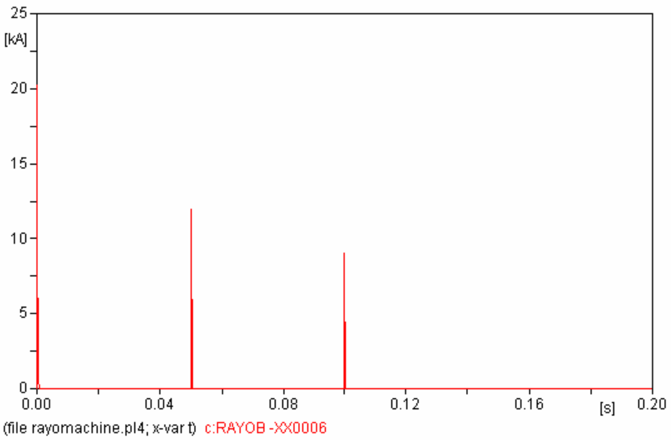


Fig. 4: Cold Lightning strike as implemented in ATPDraw

For the simulations, lightning makes direct contact with phase B of line 806-808 at varying locations depending on the specific case. Phase B was selected since it is the middle conductor on the line structures, which provides for the highest induction on the other two phases. Lightning arresters were simulated in typical locations including load PCCs and the substation transformers. Lightning arresters used for the simulation were 30kV, distribution class, rated units. Lightning arrester characteristics were taken from manufacturer datasheets [11]. Arrester residual voltage curve is shown in figure 5.

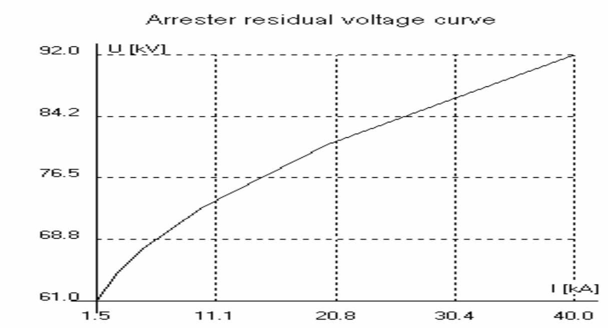
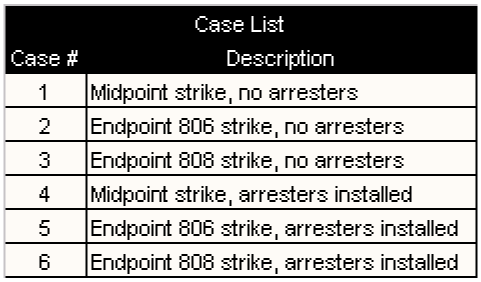


Fig. 5: Arrester residual voltage curve

C. Cases

Two different scenarios were analyzed for this study. Each scenario had several cases with varying contact locations. The first scenario included cases with no lightning arresters installed on the loads or on the substations, while the second scenario provided lightning arresters on the loads and substations, as typically found in distribution feeders. Three cases were defined for each scenario. Each scenario had a center strike case and two line end cases (node 806 and 808). Line end cases were added to see the effects of a lightning strike directly to the loads, while the center cases were designed to assess the propagation of the induced lightning surge across the line. Case numbers and descriptions are specified in table 4.

TABLE 4: CASE LIST AND CASE DESCRIPTIONS



Case List	
Case #	Description
1	Midpoint strike, no arresters
2	Endpoint 806 strike, no arresters
3	Endpoint 808 strike, no arresters
4	Midpoint strike, arresters installed
5	Endpoint 806 strike, arresters installed
6	Endpoint 808 strike, arresters installed

V. DISCUSSION

A. Scenario 1: No lightning arresters

The first scenario of the study simulated direct contact of the phase B conductor of line 806-808 without any lightning arresters. As will be presented later in this discussion, impact is severe. The severity of the lightning flash is enough to guarantee insulation failure on line structures and damage to connected equipment; equipment which include the substation transformer. The voltage levels at the strike point are in excess of 8000kV for cases without lightning arresters (cases 1-3). Due to limitations of space, only worst case events are plotted, other cases produced lower values unless otherwise noted. Voltage waveform at the strike point for case 1 is shown in figure 6.

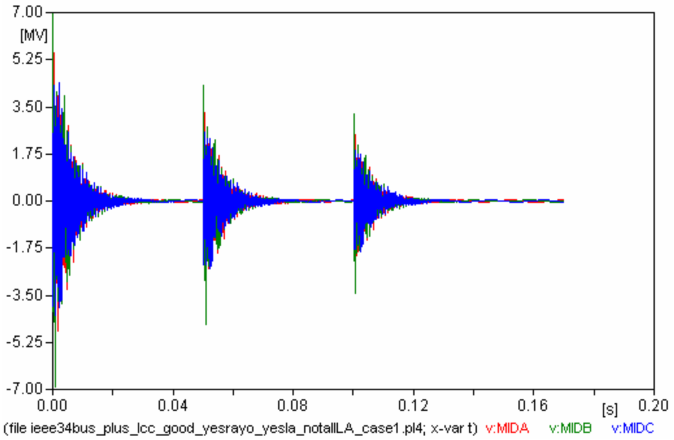


Fig. 6: Voltage at strike location for case 1

It can be observed from the above figure, that first stroke induced voltages are in the vicinity of 7000kV. Nonetheless, reflections along the feeder amplify the surge, producing higher voltages downstream into the feeder. Maximum voltages for cases 1 to 3 are: 8067kV, 9229kV, and 9231kV (B840/848, B808, and B806), respectively for phase B conductors. These values are clearly over insulation flashover levels for 24.9kV equipment. As expected, phase B conductors exhibit the worst overvoltages due to direct impact. One interesting detail that should be emphasized for these cases is that maximum voltages are present in the opposite ends of the line for endpoint cases (cases 2 and 3), but in branch buses 840/848 for the midpoint case 1. Voltages at the substation are also affected, enough to surpass BIL levels of the transformer (350kV BIL for 69kV) but lower than overall maximum overvoltages. Figure 7 presents the waveforms at the substation. Results from cases 1-3 clearly indicated that voltage surge mitigation is in order. Figure 8 presents the waveform for buses 840 and 848 for case one (only phase B shown for simplicity).

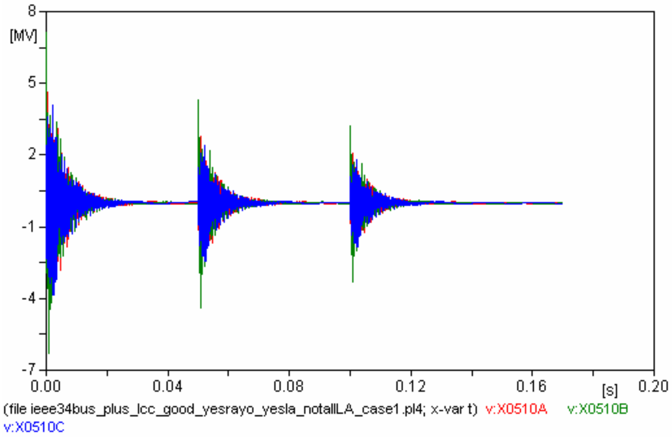


Fig. 7: Substation bus voltage after strike.

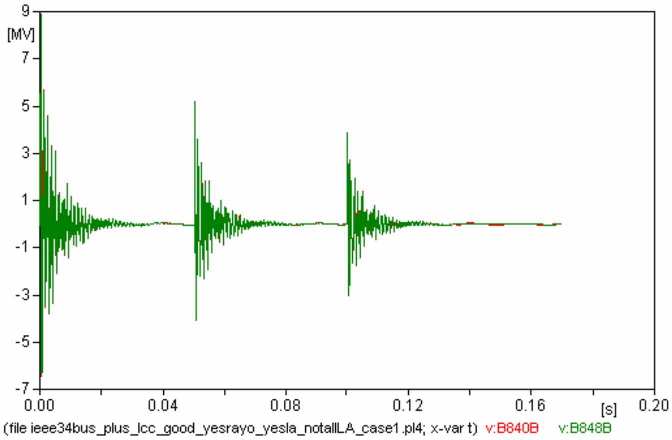


Fig. 7: Voltage at buses 840/848

Note that figure 8 presents two waveforms, but one traces identically the other. These are the worst case voltages for case 1, namely buses 840 and 848. Values will be used for comparison with lightning arrester cases.

B. Scenario 2: Lightning Arresters

Initially, simulations were intended to include all typical lightning arrester installations across a feeder. Unfortunately, one non-linear device per load across the whole feeder increased simulation complexity exponentially, as did its execution time. After several tries, convergence problems and excessive calculation delays forced the simplification of the model to allow completion of simulations within a tolerable time frame. Only lightning arresters in the endpoint buses (806 and 808), substations and buses 848 and 840 were left for subsequent simulations. Case 4 established the impact location in the midpoint of line 806-808; it is equivalent to case 1 but with lightning arresters. The use of lightning arresters immediately reduces lightning impact on the system. Overvoltages for case 4 are limited to values in the vicinity of 50kV for the endpoints of the line and 46kV for both substation and 832 buses. The most impacted buses of case 1, B848 and B840, show greatly decreased voltage peaks, with maximum voltage equal to 44.7kV (see figure 9).

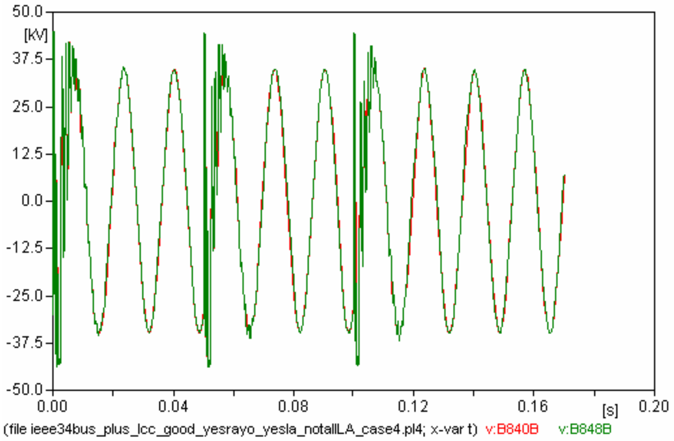


Fig. 9: Bus 840/848 waveforms with lightning arresters. Note: Only Phase B is displayed.

These values are well within flashover and BIL ratings of the feeder equipment (25kV/150kVBIL). Nevertheless, voltage magnitude at the point of impact is still of astronomical proportions, namely 5MV (see figure 11). Magnitudes of this proportion are still able to cause flashover and surely the destruction of the adjacent distribution poles. Energy dissipated by the arresters by bus 848 is shown in figure 12.

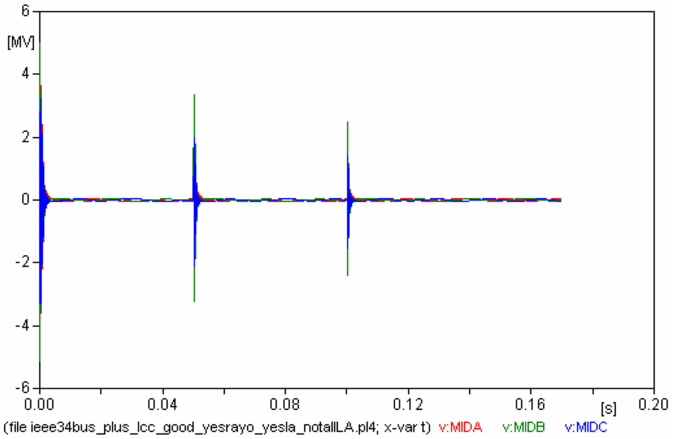


Fig. 11: Midline strike point voltages for case 4

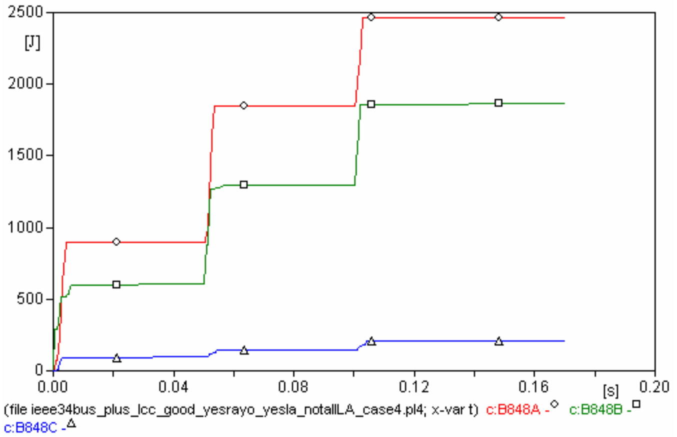


Fig. 12: Lightning arrester dissipated energy bus 848 case 4

As is illustrated in the above plot, maximum energy dissipation for bus 848 arresters peaks at 2.5kJ. This value is well within the maximum allowable energy dissipation for the arrester model [cooper], namely 74.8kJ (max. 3.4kJ/kVUc where Uc=22kV). A point of concern though, is the energy dissipation of the arresters in the end buses of the line (see figure 13).

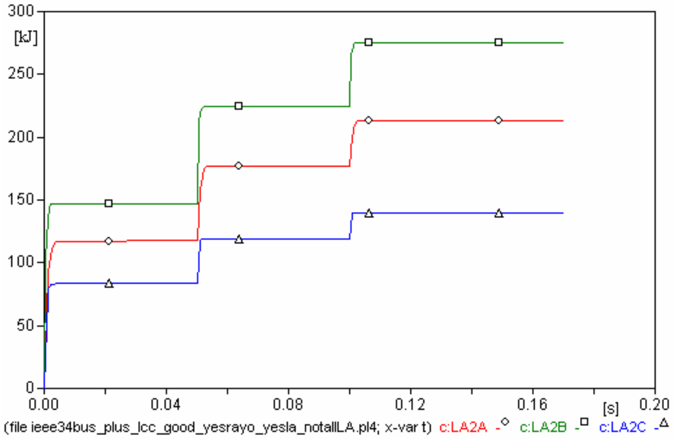


Fig 13: Lightning arrested dissipated energy bus 808 case 4

The plot shown above proves that even though voltages are being kept at acceptable levels at buses 808 and 806 (bus 806 LA plot not shown, but contain same values of bus 808), energy dissipation is exceeding maximum total capacity of the arresters. The plot does seem to indicate, that the arresters would remain operational until nearing completion the first stroke. Subsequent strokes most likely will cause arrester failure. Thus, even though simulations indicate maximum voltages of 52kV for buses 806/808, this value can be realistically much higher. This indicates that if such event could happen in the feeder, higher energy class rated arresters are required. Otherwise, the LA's must be replaced after an event of the simulated magnitude. Nevertheless, the arresters should have dissipated the first and most severe stroke before failure, most preventing propagation of the highest surges. It is not unlikely then, that adjacent arresters would dissipate the additional energy from lesser subsequent discharges without failure. Maximum voltages across the feeder metered buses and LA energy dissipation is presented at the end of the discussion in tables 5 and 6, respectively.

Cases 5 and 6 were failed attempts at simulating endpoint strikes on the line with arresters installed. Simulation of both cases led to convergence problems since voltage surges produced by direct contact exceeded the maximum operational voltage of the arresters. Thus, it can be concluded from this error that the arrester would not survive a direct impact of a lightning strike of the magnitude simulated (20kA). From case 4 and the partial execution of cases 5 and 6, it can be seen that a lightning of such magnitude will cause damage to equipment directly affected by contact but all adjacent equipment protected by arresters will survive. Thus, the purpose of the arrester is served for most cases. Realistically, a strike in an event such as the one simulated would with most probability be less severe than the strikes simulated in this study, like stated in table 1.

TABLE 5: MAXIMUM RECORDED VOLTAGES

Case #	Max. Volt. Bus	Max. Volt. Recorded
1	840/848	8882.5kV
2	808	9229.9kV
3	806	9231.8kV
4	808/806	51.95kV
5	N/A	N/A
6	N/A	N/A

TABLE 6: MAXIMUM RECORDED VOLTAGES WITH LA

Bus #	Max. Volt. Recorded	Occurred in Case #	Volt. With LA
Sub	8.5	3	46.9kV
806	9231.8kV	3	52kV
808	9229.9kV	2	52kV
832	8.25	3	45.6kV
840	8882.5	1	44.2kV
848	8882.5	1	44.7kV

VI. CONCLUSIONS

In this paper, the effects of a lightning strike is presented and analyzed. A multiple stoke lightning flash was successfully simulated in ATP. The lightning was used to investigate the impact of such transient phenomena in a distribution feeder based upon the IEEE 34 bus test-feeder configuration. Impact was mitigated using distribution level surge arresters.

Voltages on buses 806, 808, 832, 840, 848 and the substation bus were monitored to quantify the effect of a direct lightning stroke on line 806-808. Several contact points along line 806-808 were selected to discover the worst case event.

We can conclude that operating a feeder with no lightning protection, is very detrimental for system performance. Also, exposes loads and system devices to unnecessary overvoltages which may cause insulation flashovers and device failures.

The installation of lightning arresters helps decrease the adversarial effects resulting of the lightning strike in the feeder. Our study shows that for certain operating characteristics of the lightning arrester it can help mitigate one direct hit multiple-stroke lightning. Nevertheless, the lightning arresters have to be replaced for several cases, after operation, due to excessive energy dissipation.

The study successfully establishes the need for lightning protection systems in distribution feeders. Further research can be made to identify a different arrester model more suitable for this feeder.

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VIII. BIOGRAPHIES

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