Performance of Surge Arrester to Multiple Lightning Strokes on Nearby Distribution Transformer

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Abstract

Overhead distribution lines are prone to lightning overvoltages due to their configurations and characteristics. Metal Oxide Varistor (MOVs) arresters for many years have proven to be more advantageous than others arresters in lightning surge protection; therefore it is worthwhile to continually assess the behavior and performance of these arresters to different kind of overvoltages caused by lightning strokes for power system applications. This paper presents the performance of MOV arresters to multiple lightning strokes nearby a substation transformer. All simulations were performed with Alternative Transients Program/ Electromagnetic Transients Program (ATP/EMTP Program).

Key-words: Lightning strokes, surge arrester, ATPDraw, Transient Overvoltages.

1 Introduction

The study of lightning has been subjected of research for decades. It is regarded as a natural phenomenon which generates unidirectional double–exponential impulses, which usually have tendency to interact with power system networks [1]. Research has shown that lightning voltages are usually greater than many thousand of volts, but can be millions of volts in most cases [1], [2]. Detrimental effect of lightning on power system can be summarized as follows;

- It builds up an overvoltage across a struck equipment/device/object resulting into a sparkover that results into short circuit of the whole system or the voltage punctures through the equipment electrical insulation thereby causing a permanent damage
- Failure or defect of protective device can occur when the energy of the lightning stroke exceeds energy handling capability of the device.

2 A Multiple strokes Lightning

Research into lightning has being in existence for decades and a number of research institutions have investigated into this natural phenomenon through field studies, laboratory experiment and simulations based on the real natural lightning. For example, research done by *Rakov* confirmed that 80% of cloud-to-ground discharges contain more than one stroke per flash with up to eighteen strokes per flash as observed in Russia and Florida [4],[5]. In summer 2006, a total of 67,000 cloud-to-ground flashes were located by lightning sensors installed within Finland's borders with a mean of two strokes per flash, where a single flash contained one to fifteen strokes [6]. Other has also provided information that every cloud-to-ground flash has more than one stroke with an average of 3 to 4 strokes per flash and a multiple of strokes to ground flash is a sequence of multiple pulses with intervals of tens of milliseconds [7]. Other field studies and experiment survey by [7] on lightning parameters have also revealed that the natural characteristics of lightning are entirely different from testing procedures which focus only on a single impulse with a specified impulse wave shape. Moreover, in a single lightning flash, several strokes therein may be in form of positive or negative strokes [6]. The first stoke in most cases are greater than the two subsequent strokes, thus increasing the total energy injected to the struck object.

Any new equipment to be installed into an existing power network are usually subjected to standard lightning impulse test so as to be assured of its reliability and energy capability when exposed to lightning surge. The test procedures on lightning impulse test in the presently adopted standards require effectively only a single test, but this is completely different from the characteristics of natural lightning previously discussed, such as the multiple strokes formation, peak magnitude and waveshape. It is likely that these equipment respond differently during surge and other transient faults due to difference in these characteristics. Therefore the performance analysis of surge arresters such as Metal Oxide Varistors (MOVs) should be continually assessed with multiple impulses rather than an impulse test that had been reported in many previous studies.

3 MOV surge Arrester

The primary goal in surge arrester design is to develop an arrester that can provide the most reliable overvoltage protection for an electric power system network at most reasonable cost. MOV was first introduced for overvotage protection in the late 1960s, with small overvoltage handling capability for electronic equipment protection [8]. Presently this arrester has eliminated the need for a series gap in surge protections with higher overvoltage handling capability without gap. It also responds faster to overvoltage control than any gapped arrester, with much greater level of protection [9]. The following list gives of the capability features of MOV arrester valve element to performing overvoltage protection function;

- It can withstand the rated power frequency voltage without any additional point or devices
- Since the device is gapless, it goes into conduction and starts dissipating energy and limiting voltage as soon as an overvoltage commences
- Protective characteristics region is relatively insensitive to ambient condition. Power dissipation at operating power frequency voltage, however, it is very sensitive to temperature- a very important design variable.

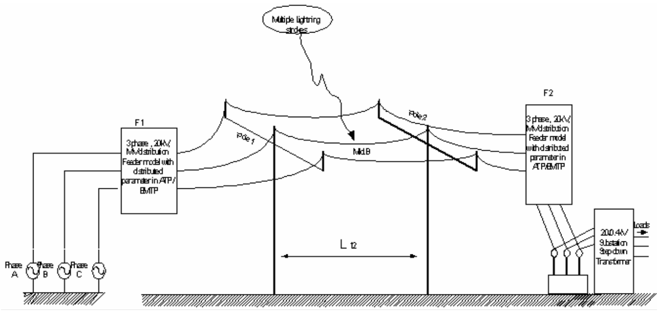

Fig. 1: Concept on MV distribution configuration

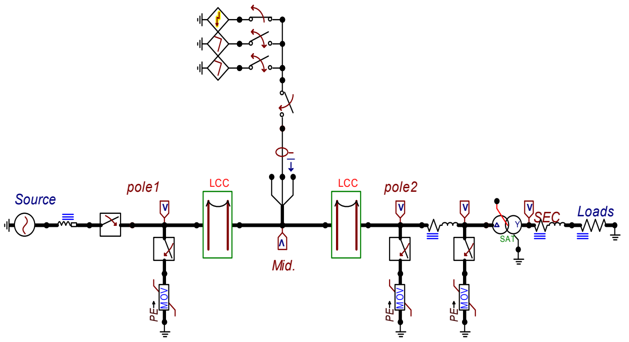

Fig.2: ATP/EMTP model of the MV distribution configuration

4. Simulations Procedure

4.1 System Configuration

Lightning surge studies are usually done with simplifying assumptions because of some unknown characteristics and quantities such as the lightning amplitude, waveshape e.t.c. In view of these unknown quantities, the implementation of lightning analysis with highly sophisticated model is not always justified [10]. Therefore, a power system network of Figure 1 was used in this work in order to expedite simulations and eliminate losses. The simulation of direct multiple strokes lightning and the test system were performed with ATPDraw.

The Parameters for the system configuration are as follows; Infinite source of 20kV, 50Hz; MV distribution Transformer is 10MVA, 20/0.4kV with resistance and reactance of 1% and 6% respectively. This was simulated based on ATP GENRAFO model as a saturated 3-phase Delta/Wye system; feeders F1 and F2 of distances 1000m and 50m respectively were modeled with distributed line parameters. The feeder F1 length was chosen long enough to prevent surge reflection from source. Only the line (L_{12}) was simulated with (LCC) subroutine using the line's physical configuration in ATP/EMTP theory book [10], considering 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. A 3-phase balanced load of 1800W and power factor of 0.9 lagging was modeled as impedance load at the low voltage side of the transformer.

4.1.1 Direct Multiple lightning strokes Model

Implementation of the model was done with ATPDraw adopting the characteristics of a cold lightning flash in [11] with sub-millisecond interstroke intervals of [2]. Authors have made use of three strokes in a flash with amplitudes 20kA, 12kA and 9kA for first, second and third strokes respectively, with 1ms interval. In the simulation, three ideal sources were used for the strokes, with time duration of 0.6ms for the first and 0.3ms for the second and the third stroke each. The first stroke was modeled with *Type 15* idea source of ATPDraw characterized by two exponentials with Amplitude and constant *A* and *B* as in the ATP rule book with function;

$$f(t) = Amplitude[e^{At} - e^{Bt}]..................(1)$$

The parameters of the stroke were selected as follows, in order to obtain a 20kA current for 0.6ms duration of the waveform (Figure 3)

Table 1: Surge parameters for type 15 [10]

Constant	Values
Current (Amp.)	34000
A	-9500
B	-60000
Tsta (sec)	0
Tsto (sec)	0.0006

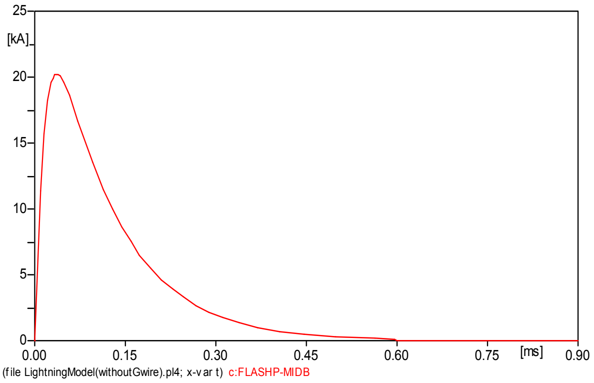

Fig.3: Waveform of the first injected lightning stroke with amplitude of 20kA.

The 2nd and 3rd strokes were modeled with two slope ramp *Type 13* of ATPDraw based on the characteristic of the subsequent lightning strokes in lightning literature [11]. Table 2 illustrates the parameters use for the simulation. Figure 4 gives the waveform of the multiple strokes simulated.

Table 2: Parameter of Ideal source Type 13 [10]

Parameters	Values	
Current (Amp.)	12000	9000
To	0	0
A1	0	0
T1 (sec)	0.0003	0.0003
Tsta (sec)	0.0016	0.0029
Tsto (sec)	0.0019	0.0032

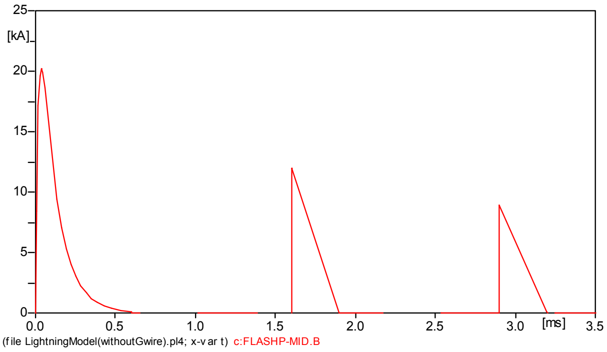

Fig. 4: Waveforms of the 1st, 2nd and 3rd lightning strokes modeled with ATPDraw

In this approach, *line B*, located at the center was considered as the line directly terminated by the lightning strokes. Further, an exclusion shield wire was made to fully access the performance of the MOV arresters at various points under this condition and also to have a maximum overvoltage induction at the other lines when the center *line B* is struck by direct lightning flash.

MOV arresters were employed for the protection of lightning surges at various locations of the test system. Obtained from the Manufacturer datasheet [12], the V-I characteristic curve of the arrester used for the simulation is shown in Figure 5;

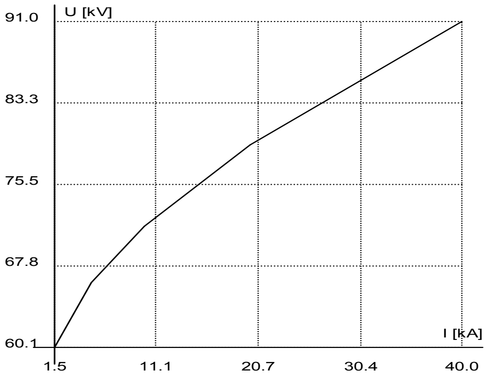

Fig. 5: V-I Characteristic curve of the 27kV MOV arrester (8/20 μ s) (V: Residual voltage and I: discharge current)

4.1.2 Cases Description

Six different cases were analyzed in order to study the effect of the multiple strokes on the performance of MOVs arresters distribution network. Lightning strokes termination are assumed on phase B in all cases considered. The further also presumed that the strategic location of MOV arresters would reveal the propagation effect of overvoltage due to these strokes and assessed their capability and reliability in suppressing the lightning surges even in such situations where any of the arresters fails in operation. Table three gives a summary of the cases.

Table 3: List and Descriptions of Cases for simulation

Case No.	Description of Case study
1	Strokes at Midpoint *MidB*, no arrester installed in the network
2	Strokes at Midpoint *MidB*, One arrester installed at transformer terminal.
3	Strokes at Midpoint *MidB*, arresters installed at Pole 1 and Pole 2
4	Strokes at Midpoint *MidB*, arresters installed at Pole 1, Pole 2 and transformer terminal
5	Strokes at Pole 1, arresters installed at Pole 1 and Pole 2 and transformer terminal
6	Strokes at Pole 2, arresters installed at Pole 1, Pole 2 and transformer terminal

4.2 Simulation Results

Six simulation cases are reported in this paper. The cases are divided into three scenario as follows; the first scenarios evaluated the effect of lightning overvoltages on power equipment and insulations with the strokes at the *MidB* with no arrester installed on the line and the transformer primary terminals. The second scenario analyzed the performance of lightning overvoltages with MOV arresters optimized installation along MV lines also with lightning contact at the *MidB* of the line was assumed, while the third scenario gave the responsiveness of these MOV arresters to lightning surges with assumption that the strokes were directly terminated on phase B at pole 1 and also at pole 2. Only the figures of worst events are presented because of limitation of space.

4.2.1 1st Scenario: An unprotected MV network

In Case 1, induced overvoltage of 780MV was recorded from the first stroke at the point of contact (Figure 6), this resulted into a sparkover to all the other phases of the line thereby causing a short circuit. The maximum overvoltages recorded at other phases are very close to this value and a maximum surge reflection trough feeder L2 to the transformer primary was in excess of 770MV (Figure 7) Overvoltages build-up in this case is sufficient to cause a serious hazard to line insulation and poles and electrical equipment installed adjacent to the line when they are left unprotected by surge arresters. All the overvoltages recorded are extremely above the insulation flashover (20kV) of the line and Basic Impulse Level (BIL of 150kV) of the transformer.

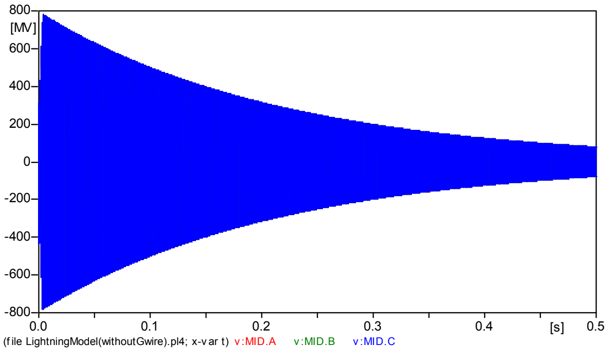

Fig. 6: Case1- Resulting overvoltages at the MidB of the line after lightning strokes observation at middle of the line (phase B)

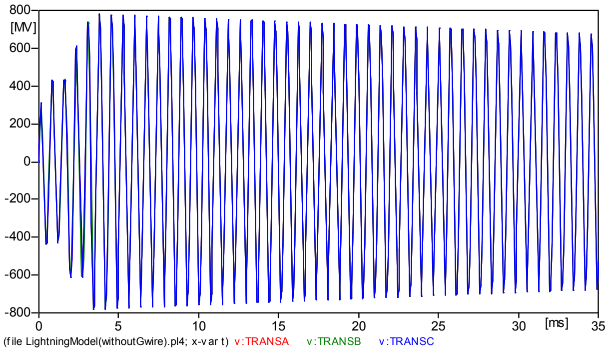

Fig. 7: Case1- Resulting overvoltages at the transformer primary after lightning strokes at the Middle of the line(phase B)

4.2.1 2nd Scenario: MOVs response to Overvoltage

In Case 2, with a surge arrester at the transformer primary, the overvoltages from the multiple strokes were intriguingly suppressed from the maximum values of 770MV to 76kV (Figure 8) after its conduction, all the residual voltages are within flashover and BIL ratings of the feeders and the transformer. However, the worst situation occurred as the maximum energy absorbed by this arrester on *phase B* (207kJ), was more than its maximum rated energy (Figure 9) (74.8kJ, 3.4kJ/kV where Uc= 22kV), a manifestation that the arrester might have suffered both physical and electrical damage after its successful operation after the first and two subsequent strokes. Therefore in reality, it may require replacement for future protection. In case 3, the arrester at the transformer primary was replaced with two arresters at pole 1 and pole 2 for further simulation. The overvoltages were also clamped below the BIL of the substation transformer as shown in Figure 10a and overvoltage was totally damped in less than 10ms, except at the Middle of the line, where the maximum overvoltage was up to 2.6MV. The energies absorbed by the arresters at pole 1 and 2 were 157kJ and 134kJ respectively (Figure 10 b &c); these also signaled physical and electrical defects and may require replacement for guaranteed protection in future.

In Case 4, installation of arrester at pole 1, pole 2 and transformer terminal yielded the best results when compare to the previous cases as shown in Figure 11(a &b), The overvoltages are clamped to 70kV, 69kV and 65kV for pole 1, pole 2 and transformer primary respectively. The energies absorbed are within the maximum energy handling capabilities at Pole 2 (61.2kJ) and transformer primary (48kJ), however subsequent strokes most likely will cause the arrester failure at pole 1 unless the higher energy rated class is installed. The arresters energies are shown in Figure 12(a & b)

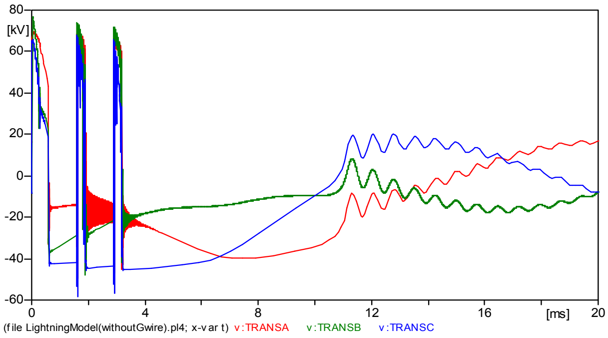

Fig. 8: Case 2- Remaining voltages at the transformer primary terminals after lightning strokes observation at the middle of the line (phase B)

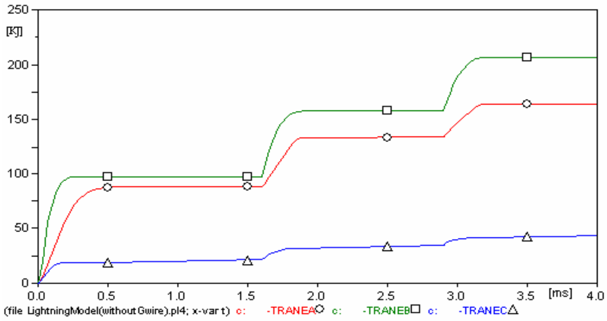

Fig. 9: Case 2-Energy absorbed by the arrester at transformer primary after the operation

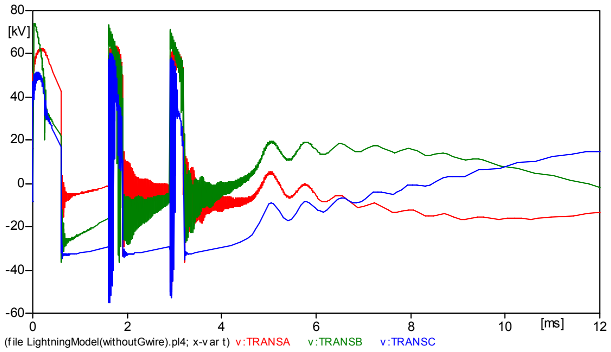

Fig. 10a: Case 3- Remaining voltages from 2nd stroke, measured at the transformer primary terminals after lightning strokes observation at the Middle of the line (phase B). Arresters installed only on pole 1 and 2.

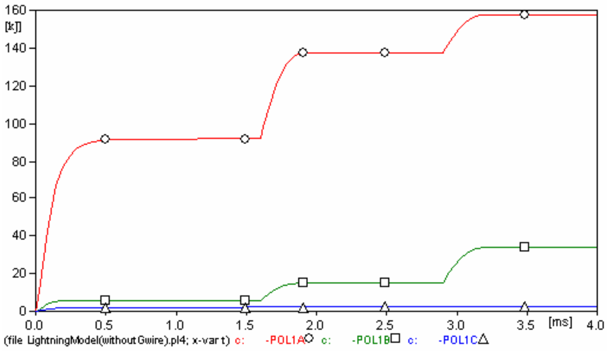

Fig.10b: Case 3-Energy absorbed by the arrester at pole 1 after the operation

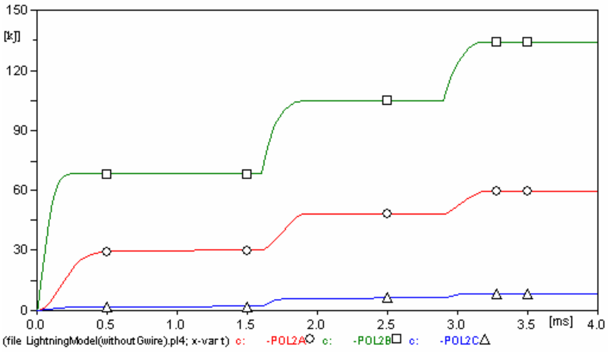

Fig. 10c: Case 3-Energy absorbed by the arrester at pole 2 after the operation

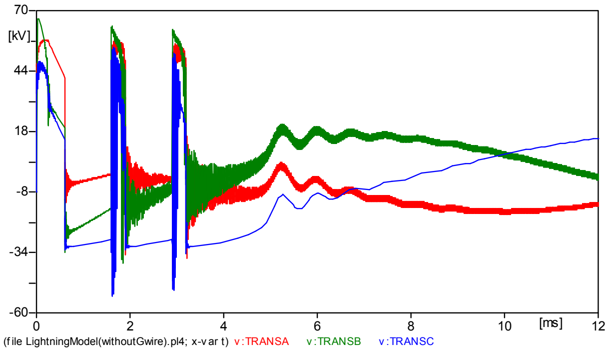

Fig. 11a: Case 4- Remaining voltages from Multiple stroke, measured at the transformer primary after lightning strokes observation at the Middle of the line (phase B). Arresters installed on pole 1, pole 2 and transformer primary

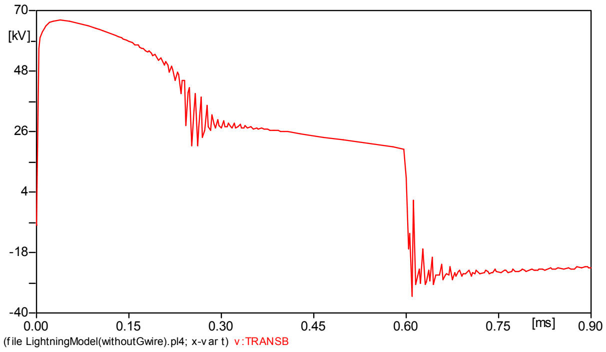

Fig. 11b: Case 4-Remaining Voltage from the 1st stroke clamped by arrester at the transformer primary (Only phase B is shown)

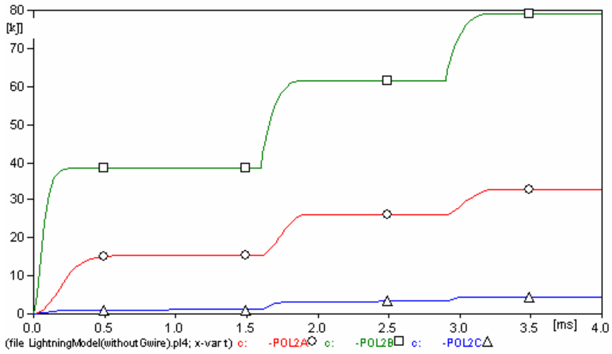

Fig. 12a: Case 4-Energy absorbed by the arrester at Pole 2 after the operation

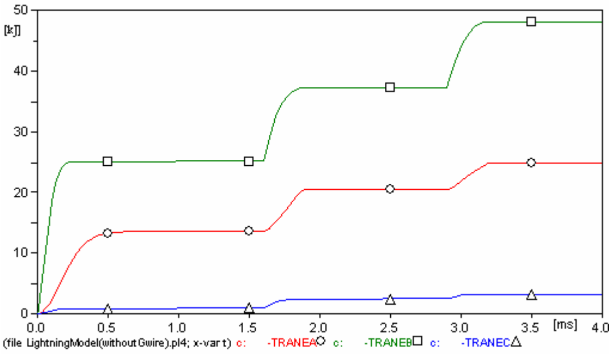

Fig. 12b: Case 4-Energy absorbed by the arrester at transformer primary after the operation

4.2.3 3rd Scenario: Variation of Lightning Terminations

An attempt was made to foresee the possibility of lightning strokes terminating on both sides of the poles, one after the other, with three arresters arrangement as in case 4. The lightning flash was directly on pole 1 in case 5, in very closed proximities to the arrester. The simulation results showed that none of the residual voltages clamped by these arresters terminal is harmful to the line and transformer (Figure 13). Moreover, the energy of MOV at pole 1 is 33.50kJ. This is much lower than the maximum arrester energy. However, MOV at pole 2 and the transformer terminal absorbed energy of 240kJ each which implies that they will need replacement if such operation occurred in reality. In case 6, the strokes were terminated on pole 2 as in previous case (case 5), but also closed to the substation transformer. The simulation results showed that each the residual overvoltage at transformer is less than 48kV (Figure 14). The energy absorbed about 35kJ each, but a different scene at the pole 1 with overvoltage lowered to 81kV and energy absorbed higher than its capability (218kJ).

Thus, the performance of MOV arresters in lightning surge protection has been carried out successfully in this study. Though, in all cases considered, the simulations have shown that one or more arresters may not survive the next operation if not replaced by new ones with higher energy handling capability, it is also worth emphasizing here that very few natural lightning strokes recorded in literature are up to the ones simulated in this work. Therefore, the arrangement of arresters in case 4 will serve best for lightning overvoltage protection.

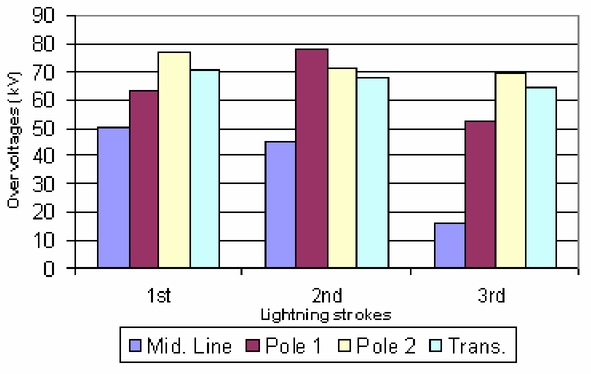

Fig. 13: Case 5- Arrester voltages measured at tranformer primary with Strokes on pole 1, arresters installed at Pole 1, pole 2 and transformer terminal (Flashover & BIL ratings of the feeder equipment =20kV/150kV)

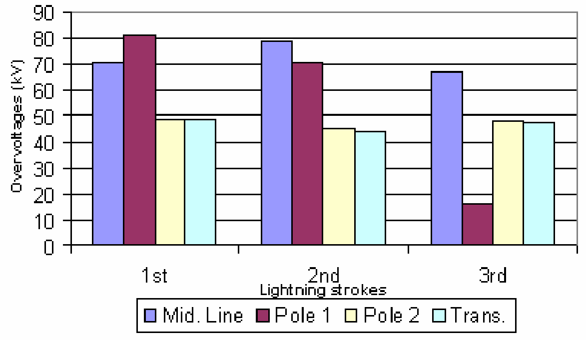

Fig. 14: Case 6- Arrester voltages measured at tranformer primary with Strokes on pole 2, arresters installed at Pole 1, pole 2 and transformer terminal (Flashover & BIL ratings of the feeder equipment =20kV/150kV)

5. Conclusion

The Performance of MOV arresters to lightning overvoltages from multiple strokes have been assessed on a simple radial distribution network. Voltages at the two ends of the poles and transformer primary were monitored in all the cases in order to quantify the effect of these overvoltages and to ascertain the worst case. With arresters energy capabilities shown, it has been observed in most of the cases considered that multiple strokes are more severe than single stroke lightning even in a situation where the arresters are adequately installed into the network. Further work is in progress to investigate the influence of nearby trees and tall objects on lightning overvoltage suppression in a distribution network.

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