Simulation of Combined Shield Wire and MOV Protection on Distribution Lines in Severe Lightning Areas

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***Abstract*—This paper presents the protective effects of shield wire coupled with Metal Oxide Varistor (MOV) arresters in a distribution network located in a severe lightning area. The presented test case is the IEEE 34-node radial distribution test feeder injected with multiple lightning strokes and simulated with the Alternative Transients Program/ Electromagnetic Transients program (ATP/EMTP). The response of the distribution line to lightning strokes was modeled with three different cases: no protection, protection with surge arresters and protection with a combination of shield wire and arresters. Simulations were made to compare the resulting overvoltages on the line for all the analyzed cases.**

***Index Terms*—Direct strokes, Lightning flash, MOV arresters, Lighnting Overvoltages, ATP/EMTP, ATPDraw, Test feeder.**

I. INTRODUCTION

Overhead distribution lines for all system voltage levels are exposed to lightning, and outage and damage occur frequently due to this natural phenomenon. More than 80% of cloud-to-ground lightning flashes contain more than one stroke [1]-[3]. In Finland, lightning flash counter results in 2006 (April-October) was about 65,000 cloud-to-ground flashes [4]. Multiple strokes from these flashes range from 1-15 strokes. In both northern and coastal Finland, fewer flashes are detected than in the inland parts of southern Finland (Fig. 1) where lightning incidence is most severe. Within this area, many distribution utilities deliver electricity to several thousands of consumers, through radial distribution networks. Therefore, the assessment and augmentation of surge protection in this kind of area is the subject of this paper.

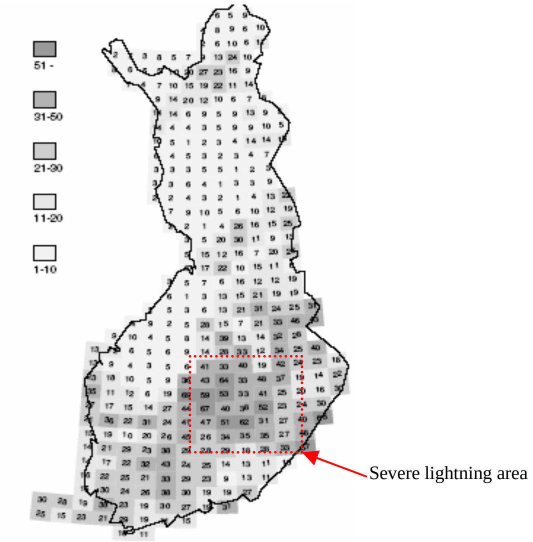

Fig.1: Densities of located lightning flashes per 100 km^2 in Finland in 2006. Inset is the area with highest flash densities since 1998. [4]

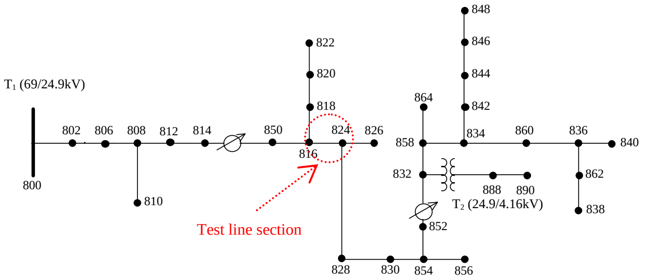

Fig.2: IEEE 34-node Test Feeder

II. SIMULATION PROCEDURE

A. Test system

In this study, the IEEE 34-node radial distribution test feeder was tested with direct multiple strokes with the test data in [5]. The test feeder diagram is shown in Fig. 2. It was modeled with ATPDraw, as shown in Fig. 3, and all data available in [5] were used for the simulations with slight modifications. Brief descriptions of the model are as follows;

1) The test system has an ac source of 69kV, 60Hz from the utility. It was model with a 3-phase infinite source.

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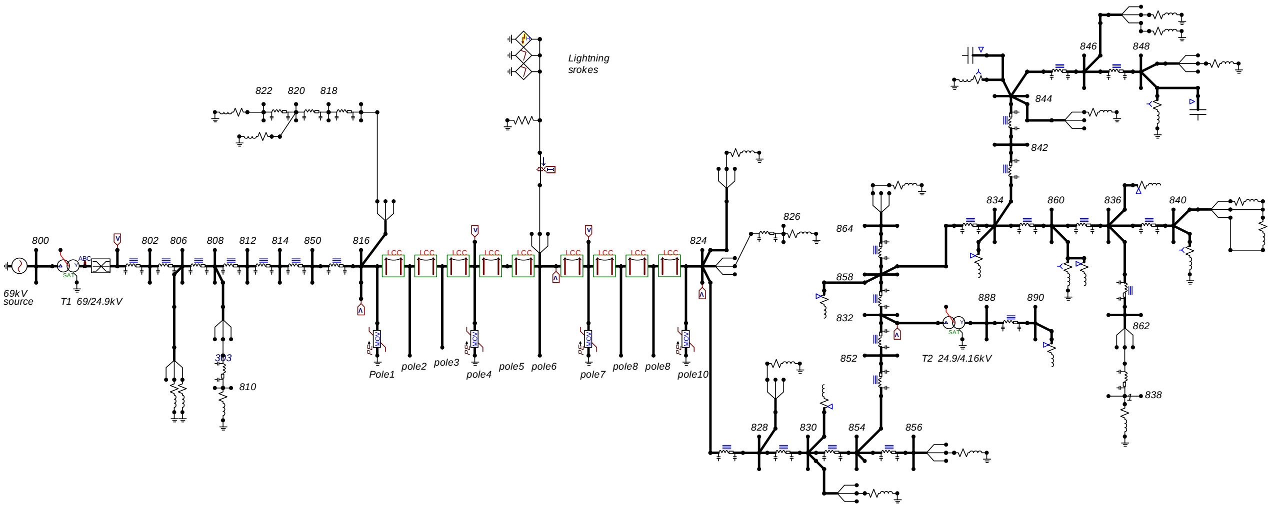

Fig. 3: ATPDraw Model of the IEEE 34-node Test Feeder with line model modification from 816 to 824

2) The 2.5MVA (69/24.9kV) substation transformer (T_1) was increased to 25MVA with its per unit impedance, in order to compensate for losses due to the inclusion of additional loads. The 5kVA in-line transformer (T_2) (24.9/4.16kV) was used with its original parameters. The transformers were simulated in a saturable 3-phase delta-wye format based on the standard ATP GENTRAFO model.
3) The two regulating transformers at bus feeder points 814 and 856 were excluded from the simulation as their impact would be negligible in this kind of analysis.
4) All line parameters except line 816-824 were included as lumped or pi equivalents based on the IEEE 34-node specifications.
5) A set of 20 distributed and unbalanced loads together with 6 spot and balanced loads were modeled as constant impedance loads.
6) Line 816-824 of length 3.112 km, was modeled as a 10 pole distribution line of 9 equal spans. The whole line was simulated with the ATP line and cable constant (LCC) subroutine using the physical configuration of Finnish distribution lines, shown in Fig. 4.
7) A lightning flash of multiple strokes was assumed to terminate on phase B (the middle conductor) at pole number 6 along line 816- 824

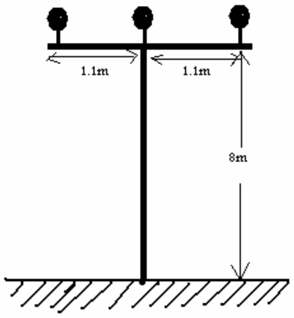

Fig. 4: Finnish Overhead Distribution Line configuration (diameter - 12.7mm)

B. Multiple Lightning Strokes

A selection of multiple lightning strokes of Fig. 6 was based on the mean values of positive lightning strokes observed in Finland in 2006 [4] with amplitudes of 18.6kA, 15kA and 12kA for the 1^{st}, 2^{nd} and 3^{rd} strokes, with 1ms intervals. In the simulation, three ideal sources were used for the strokes, with time durations of 0.6ms for the 1^{st} and 0.3ms for the 2^{nd} and 3^{rd} strokes. The 1^{st} stroke was modeled with a *Heidler* ideal source (1.2/50 μs), Fig. 5, and the 2^{nd} and 3^{rd} strokes were modeled with the two slope ramp *Type 13* of ATPDraw, based on the characteristic of the lightning strokes in the lightning literature [6]. Fig. 6 gives the waveform of the multiple strokes simulated.

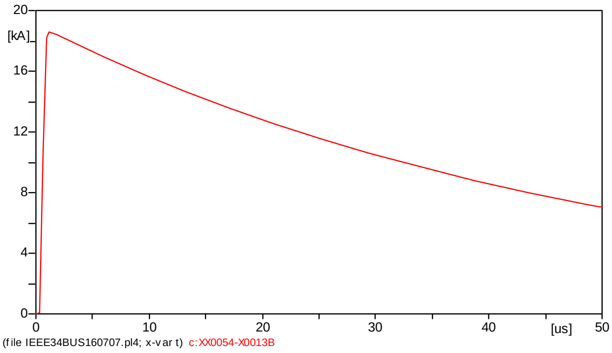

Fig.5: Waveform of the 1^{st} injected lightning stroke with amplitude of 20kA (1.2/50 μs)

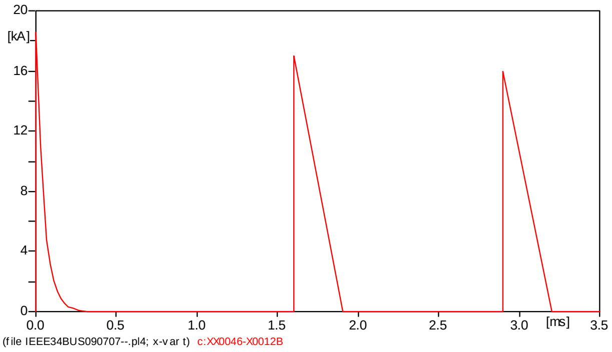

Fig. 6: Waveforms of the 1^{st}, 2^{nd} and 3^{rd} positive lightning strokes modeled with ATPDraw

MOV arresters were employed for the protection of lightning surges at various locations on the test system. Obtained from the manufacturer's datasheet [**7**], the V-I characteristic curve of the arrester used for the simulation is shown in Fig. 7.

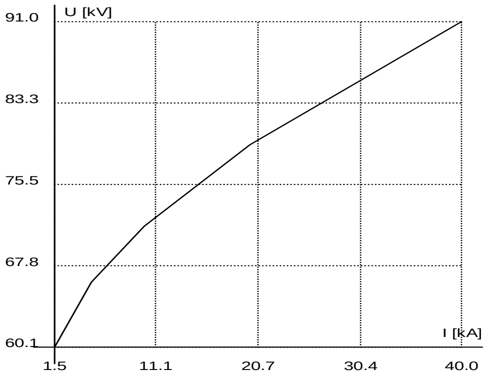

Fig. 7: V-I Characteristic curve of the 30kV MOV arrester (8/20 μ s) (V: Residual voltage and I: discharge current)

C. Case Descriptions and Simulation Results

All cases considered in this study were analyzed with the ATP/EMTP program based on fast transient studies of lightning surges [6]. Three cases were studied to observe the suppressing effect of lightning overvoltages from direct strokes due to the combination of shield wire and surge arresters. As shown in Fig. 3, direct strokes were terminated on phase B, at pole number 6

Case 1

No protection was considered on feeder 816-824. The strokes terminated on phase B of pole number 6. Table 1 summarizes the result obtained from the simulations. Overvoltages obtained at points of observation are far above the flashover voltage and Basic Impulse Level (BIL) ratings of the feeder equipment (25kV/150kV BIL). Overvoltages at the terminals of the two transformers surpassed their BILs (350kV for 69kV & 150kV for 24.9kV). Fig. 8 shows the overvoltages on all the phases at pole number 6. It can be observed here that the overvoltages in phase B resulted in induced overvoltages to the other phases due to mutual coupling effect of the line, with phase C's overvoltage more than half of the overvoltage in phase B and phase A's overvoltage slightly higher than the overvoltage in phase C at pole number 6. Overvoltages recorded at others poles and the transformers follow almost the same pattern.

Table 1: Peak Overvoltages at Poles -No Protection, Direct Multiple Strokes on Phase B, at Pole 6

	Phase A (MV)	Phase B (MV)	Phase C (MV)
Pole 1	**1.86**	**4.25**	**1.46**
Pole 4	**3.31**	**7.16**	**3.49**
Pole 6	**5.92**	**9.01**	**5.80**
Pole 7	**4.92**	**8.00**	**4.67**
Pole 10	**3.39**	**4.18**	**2.14**
Transformer 1	**1.52**	**2.74**	**0.93**
Transformer 2	**2.22**	**1.59**	**2.16**

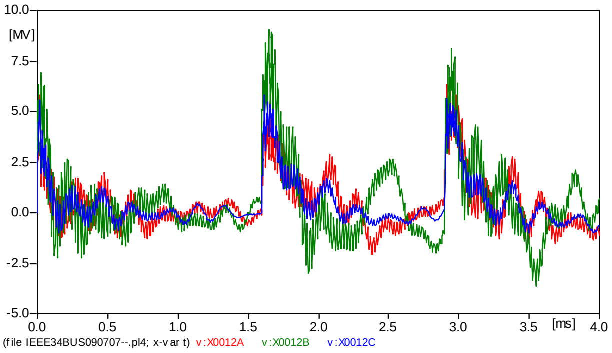

Fig. 8: Case 1- Overvoltage Waveshape at pole number 6 - No protection on the line

Case 2

Three MOV surge arresters were installed on phases A, B and C on each of poles 1, 4, 7 and 10, but no arresters were installed at the terminals of the substation transformer terminal (T_1) and the in-line transformer terminal (T_2) transformers. It was assumed here that the strategic location of surge arresters at three pole intervals, starting from pole 1, would suppress the overvoltages due to the strokes simulated in this study. Table 2 summarizes the results and Fig. 9 shows the remaining overvoltages clamped by the arresters at pole number 6. Only the highest peak overvoltages from multiple strokes are displayed for clarity. Also shown in Fig. 10 and 11 are the overvoltages at the terminals of the two transformers, from the whole flash. Only the energies absorbed by the arresters at poles 4 and 7 are displayed in Fig.s 12 and 13 due to space limitation.

Table 2: Peak Overvoltages at Poles –With Arresters, Direct Multiple Strokes on Phase B, at Pole 6

	Phase A (kV)	Phase B (kV)	Phase C (kV)
Pole 1	**43.50**	**54.90**	**31.70**
Pole 4	**67.87**	**79.36**	**66.74**
Pole 6	**2910**	**5230**	**3000**
Pole 7	**69.33**	**80.11**	**68.22**
Pole 10	**46.60**	**59.05**	**47.09**
Transformer 1	**20.32**	**73.73**	**56.40**
Transformer 2	**43.00**	**33.46**	**32.92**

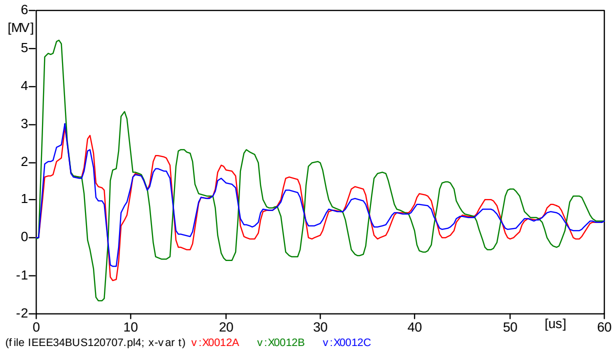

Fig.9: Case 2- Remaining overvoltages from 1st stroke measured at Pole 6. Phase B has the maximum overvoltage from the multiple strokes

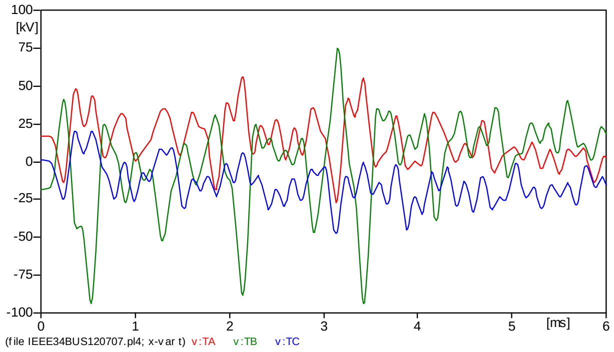

Fig 10: Case 2- Remaining overvoltages from the strokes measured at substation transformer (T_1). Phase B has the maximum overvoltage from the multiple strokes

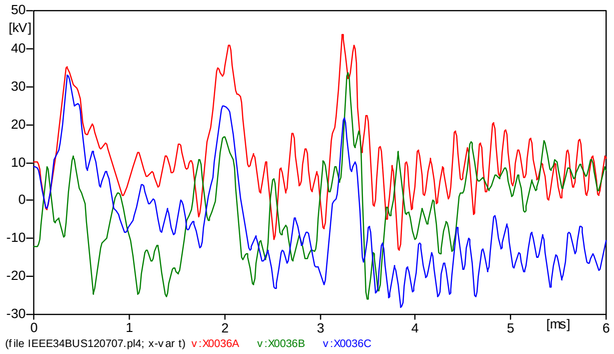

Fig 11: Case 2- Remaining overvoltages from the strokes measured at in-line transformer (T_2). Phase A has the maximum overvoltage from the multiple strokes

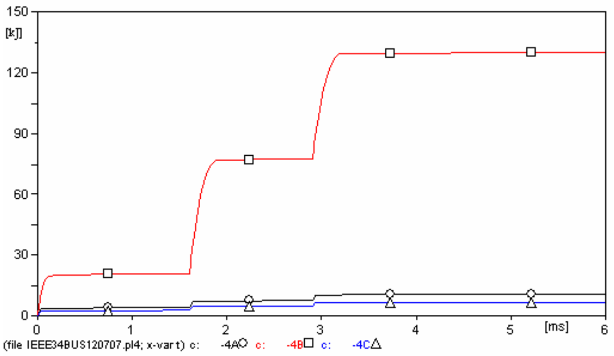

Fig. 12: Case 2-Energy absorbed by arresters at pole 4 after operation.

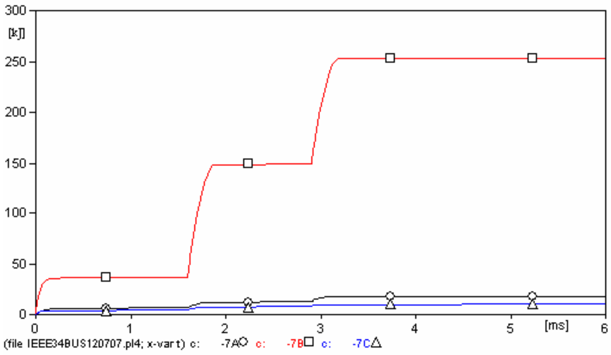

Fig. 13: Case 2- Energy absorbed by arresters at pole 7 after operation

Case 3

The shield wire was augmented with surge arresters, therefore the pole configuration of Fig. 4 was modified with the inclusion of a shield wire 1.5m above phase B on line 816-824. It was assumed that both the shield wire and phase B were directly hit by the strokes as they were positioned in the same vertical plane as the lightning flash. The arresters were installed on all phases as in *Case 2*, and the shield wire was grounded at the poles where the arresters were installed. Table 3 summarizes the results of the simulation and Figs. 14, 15 and 16 show the remaining overvoltages at pole number 6 and the transformers. The energies absorbed by the surge arresters at pole numbers 4 and 7 are also shown in Figs. 17 and 18.

Table 3: Peak Overvoltages at Poles –with Arresters & Shield wire, Direct Multiple Strokes on Phase B, at Pole 6

	Phase A (kV)	Phase B (kV)	Phase C (kV)
Pole 1	**43.29**	**56.52**	**33.29**
Pole 4	**60.50**	**79.64**	**58.70**
Pole 6	**900**	**4090**	**1170**
Pole 7	**62.27**	**80.46**	**60.50**
Pole 10	**47.79**	**57.82**	**49.53**
Transformer 1	**45.70**	**54.36**	**16.46**
Transformer 2	**75.71**	**50.75**	**51.99**

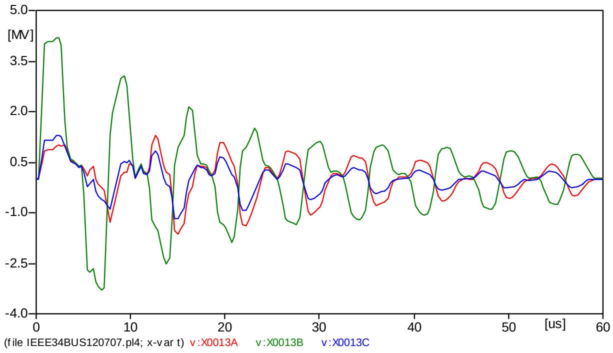

Fig.14: Case 3- Remaining overvoltages from 1st stroke measured at Pole 6. Phase B has the maximum overvoltage from the multiple strokes.

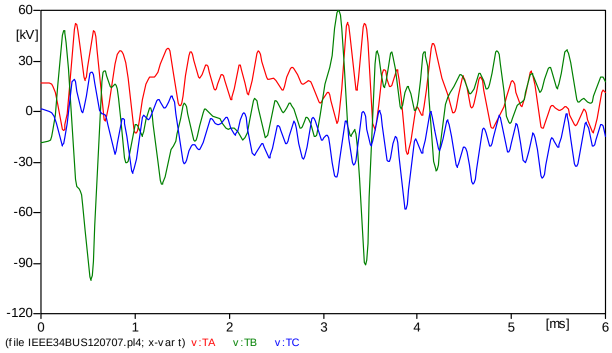

Fig 15.: Case 2- Remaining overvoltages from the strokes measured at substation transformer (T_1). Phase B has the maximum overvoltage from the multiple strokes

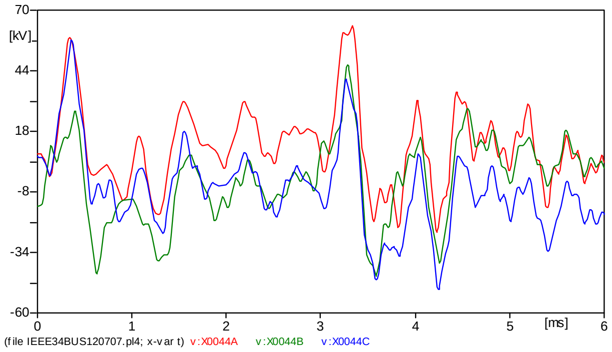

Fig 16.: Case 3- Remaining overvoltages from the strokes measured at in-line transformer (T_2). Phase A has the maximum overvoltage from the multiple strokes.

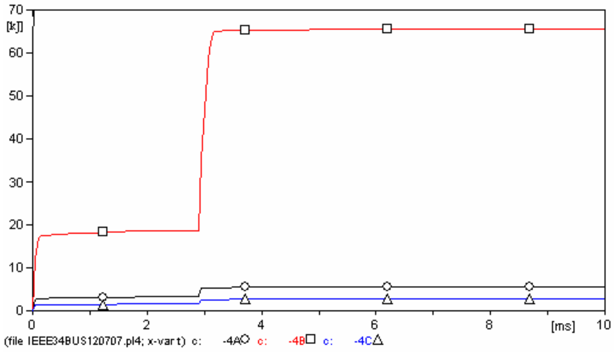

Fig. 17: Case 3-Energy absorbed by Arresters at pole 4 after operation.

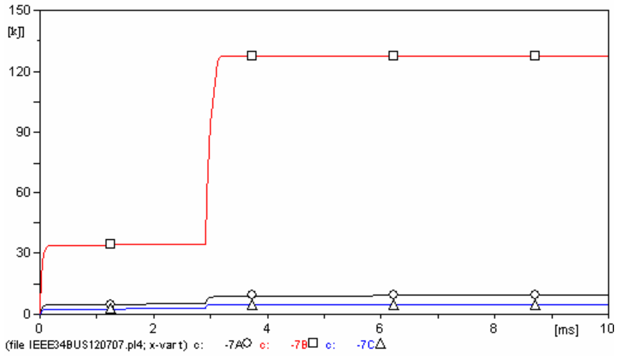

Fig. 18: Case 3- Energy absorbed by Arresters at pole 7 after operation.

III. DISCUSSION OF THE RESULTS

To quantify the need for the provision of shield wire to MOV-protected networks in severe lightning areas in a realistic simulation, an unbalanced IEEE 34-node test feeder was considered for the simulations made in this study, where the line 816-824 was assumed to be most prone to lightning strokes. All the tested cases showed the effects of direct strokes at the strike point, mutual overvoltages to other phases and the propagation effect at the transformers which are very distant to the strike point.

With the use of only arresters on line 816-824 at the designated poles, the overvoltages were reduced by 59%, 41.95% and 48.28% on conductors A, B and C respectively, at the pole number 6 where the lightning flash was terminated. Overvoltage reduction was observed at every other pole including the two transformers. However, energies absorbed by the arresters at pole numbers 4 and 7 (Figs. 12 & 13) located at the extremities of the strokes, were enough to damage the arresters even after successful operation, as they may require replacement for guaranteed protection in future. It will be recalled that the energy rating of the 30kV class MOV arrester is 74.8kJ, 3.4kJ/kV, where Uc= 22kV [7].

With the use of a shield wire on the lines and arresters at the designated poles, the overvoltages were reduced by 84.8%, 54.95% and 79.83% on phases A, B and C respectively, at pole number 6. In addition, energies absorbed by the arresters on pole number 4 were reduced by 49.73%, 72.19% and 73.23%, and those of pole number 7 were also reduced by 77.79%, 48.02% and 78% for phases A, B and C respectively (Fig. 19). These results have shown clearly the effectiveness of adding shield wires to MOV-protected distribution networks in areas where power distribution lines are much more prone to direct strokes. Therefore, the combination of two protection types is very effective in suppressing to ground all overvoltages from the lightning strokes that the kind of network considered in this study is frequently subject to.

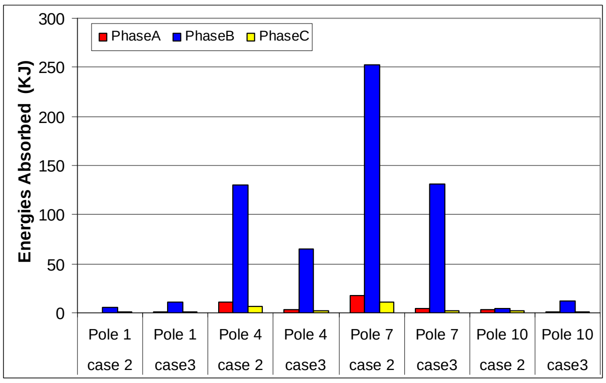

Fig. 19: Energies absorbed by the Arresters installed at Poles 1, 4, 7 & 10. (Case 2-MOV only, Case 3 - MOV with Shield wire)

IV. CONCLUSION

A distribution line located in a high lightning flash area is much more susceptible to lightning strokes than any other lines. For a given voltage level, surge arresters installed on distribution lines are mostly of the same rating and energy capabilities. However, surge protection will be more effective with the combination of shield wire and surge arresters in situations where there is the incessant occurrence of this natural phenomenon.

In this paper, the responsiveness of two protection schemes were simulated and analyzed, using MOVs only and MOVs with a shield wire. The following conclusions are drawn from the results obtained;

1) In distribution networks, multiple lightning strokes which occur in real situations are much more severe than a single lightning stroke, even in a situation where the surge arresters are adequately installed into the network.
2) For the stroke magnitudes simulated in this work, surge arresters were not effective in suppressing the overvoltages due to direct strokes. Arresters at the extremities of the struck point may therefore suffer

physical and electrical damage even after successful operation. However, shield wires can help relieve MOV-protected lines from overvoltage stress if installed in severe areas, such as were tested in this study.

3) The study successfully establishes the need for an augmented protection scheme against lightning overvoltages in distribution networks where lightning incidence is most severe.

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