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Computation of Lightning Overvoltage in 220 kV Substation due to Direct Stroke on Overhead Transmission Line

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Abstract

This paper deals with the computation of overvoltage in a 220 kV line as well as at important locations of the associated substation caused by the lightning, especially, in the event of direct stoke to the line's phase conductor. Comparison of the voltages at various locations of the substation with and without the presence of the lightning protecting system is also carried out. The computations have been carried out using the Electromagnetic Transient Program. Simulation results for the case of without the presence of lightning arrester anywhere in the system showed the obvious very high lightning over voltages at all locations of the system. The results of the case study with the presence of 216 kV lightning arrester only at line terminal (at substation entry) showed that over voltages occurring across all the substation equipment are within the accepted protection margin of 25% with reference to their BILs. However, inadequacy of this protection margin for transformers, prompted use of lightning arresters at its HV terminals also. Computation results of this case study showed the new protection margin 37% for the transformer which is more than the requirement of 30%. It is inferred that lightning arrester on HV side of the transformer is a must for avoiding failure of insulation of transformer due to lightning striking the connected transmission line. The full paper describes the system considered, its modelling in EMTP, study methodology, results of case studies and inferences drawn.

Keywords: BIL, Lightning Arrester, Lightning Overvoltages, Protection Margin, Shielding Failure, Substation

1. Introduction

Lightning is the natural phenomenon which is beyond the control of human being. It causes tremendous high voltage when it strikes the shield wire of a transmission line or directly to its phase conductor. In actual system operating conditions, lightning could strike the overhead shield or ground wire and protect the phase conductors. However, the shielding offered by the shield wire is statistical in nature and it is likely that some lightning strokes may hit phase conductors. This is called as direct stroke and the phenomenon is called shielding failure. Though it happens rarely, it could be catastrophic, if suitable and effective protection is not provided by use of lightning arresters against over voltages caused by the lightning stroke to the phase conductors. The voltage and current rating as well as the protective characteristics of the lightning arrester plays an important role in protecting the line and substation equipment insulation. IEC60071-1[1,2] specify the insulation withstand level of the line and equipment against standard lightning impulse voltage called as the Basic Insulation Level (BIL). Computation of over voltages occurring on the insulation of substation equipment is necessary to ensure the adequacy of the BIL or establish the need for additional over voltage protection.

2. System Description

The system considered here is an air insulated 220 kV substation with equipment such as transformer, CT, CVT, bus duct, cable, lightning arrester, etc., and also having

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a 30 km long outgoing line of ACSR Zebra conductor as shown in Figure 1. The Basic Impulse Insulation levels (BILs) of 220 kV line and associated equipment i.e., standard lightning withstand voltage levels are given in Table 1.

Table 1. Standard rated voltages and BIL

Equipment	Rated Voltage (kV, Peak)	BIL (kV, Peak)
Transmission line insulator at line entry	245	1050
CT	245	1050
PT/CVT	245	1050
Isolator	245	1050
CB	245	1050
LA	216	560 (LA Residual voltage)
Transformer bushing	245	1050

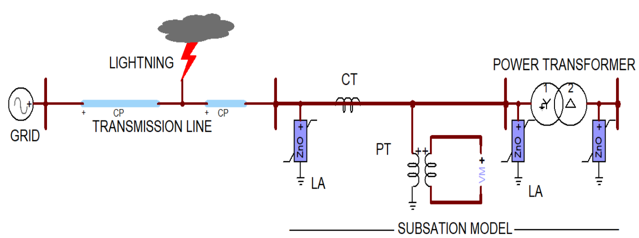

Figure 1. Single line diagram of the system considered.

3. System Modelling

Overhead transmission line is modelled using travelling wave model, with its surge impedance and propagation velocity[3]. The transformers and other substation equipment are represented by bushing/stray capacitance. Conductors in the substation are modelled with J. R. Marti model from[3] with distances and real geometry of the bus bars. The system modelling and simulation has been done using Electromagnetic Transient Program (EMTP).

3.1 Modelling of Tower

Transmission line is of single circuit configuration and its tower dimensions are as shown in Figure 2. Tower is modelled by its surge impedance Z and is calculated using equation[4]

$$Z = 60.\left[ln\left\{\frac{H}{R}\right\} - 1\right],\ \mathbf{R<<H}$$

where, H is the Height of Tower in meters and R is the Radius of the tower base in meters as shown in shown in the Figure 2.

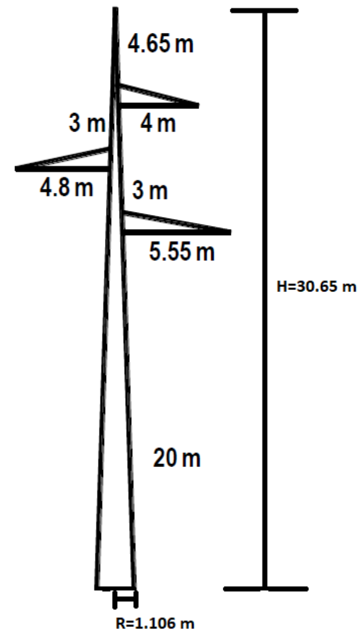

Figure 2. Transmission line geometry.

3.2 Modelling of Lightning

The Lightning stroke is modelled by Surge current source as shown in Figure 3[3].

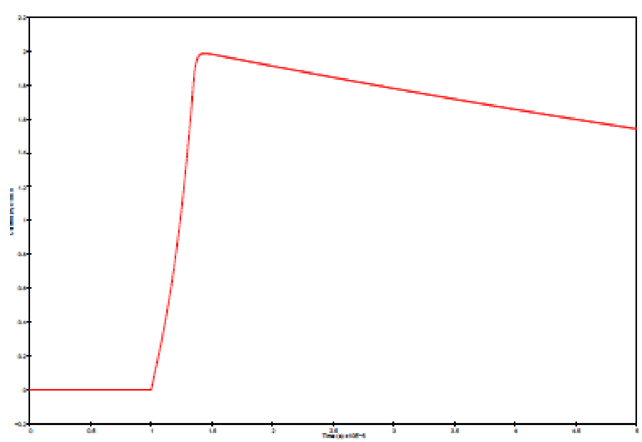

Figure 3. Lightning current source.

I_{max} = Max current (few kA to 200kA)

t_f = front time

S_m = maximum steepness

t_h = time to half peak value: 20µs

3.3 Modelling of Lightning Arrester

The lighting arresters are simulated by their respective V-I characteristics as shown in Figure 4. Real time lightning current magnitude distribution is in such a way, that its occurrence below 10 kA peak is having probability of 85 to 90%. Hence accepting certain amount of risk, arrester impulse current rating has been selected as 10kA peak. The voltage rating of lightning arrester is chosen based upon the effectiveness of the grounding system. For non-effectively grounded system the arrester rating should be 90% of the maximum system operative line – line voltage and for effective grounded system arrester rating should be 80% of the maximum system operative line – line voltage. Considering the worst-case scenario, the arrester rated voltage chosen here is based upon 90% of the maximum operative system voltage.

In this study the 220 kV transmission lines are provided with lightning arresters at both ends. The voltage and impulse current ratings of the chosen arrester are 216 kV and 10 kA peak and the arrester has residual voltage of 510 kV peak at 10 kA. Each segment of the V-I characteristics is represented by ten sets of voltage and current values in the EMTP program.

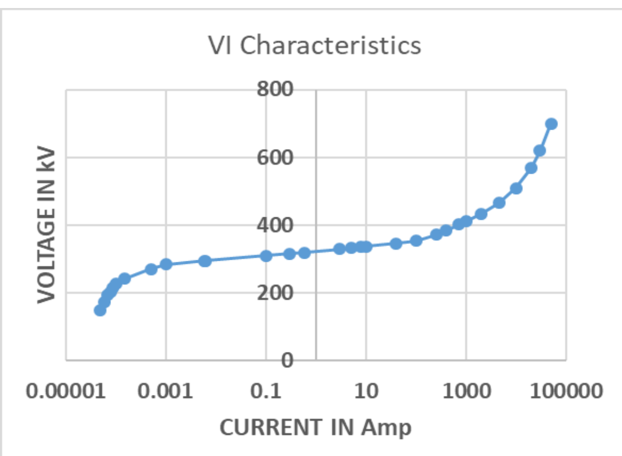

Figure 4. Arrester V-I characteristics.

3.4 Modelling of Transformer and Grid

Transformer is modelled with its stray and bushing capacitance of 5nF. Whereas grid is modelled as the constant voltage source of 220 kV.

Surge impedances, travel time and stray capacitance of the system equipments considered in simulation are provided in Table 2.

Table 2. Modelling parameters of system equipment

Sl. No	Equipment	Surge impedance (Ω)	Travel time (µs)	Stray capacitance (pF)
1	Transmission line	306.83	90.25	-
2	Transmission tower	139.3	7.80	-
3	Bus duct	310.57	2.35	-
4	CT	-	-	50
5	CVT/PT	-	-	30
6	CB	106.4	-	30
7	Isolator	-	-	30
8	Grid	Modelled as constant Voltage Source of 220kV		

4. Methodology

Lightning current of certain magnitude and wave shape is applied to one of the phase conductors (R-Phase in this study) close to the substation entry point (at 100 m) such that the nearest arrester passes its rated current with approximately 8/20 µs wave shape. Using the EMTP simulation, over voltage magnitudes and their wave shapes are computed at line entry points of the substation and at locations of each one of the substation equipment[4,5]. The safety margin achieved for each of the line and substation equipment with reference to their rated BILs are computed and compared with the standard requirement.

5. Simulation and Results

It is necessary to limit the lightning overvoltage magnitudes below the Basic Impulse Level (BIL) of the equipment with a minimum safety margin of 30% for the line & transformer, at least 25% safety margin for other station equipment like CT, CVT, Isolator etc. The BIL of line, station equipment and transformer for 220kV system is 1050 kV. Standard withstand lightning voltage with 30% and 25% protection margin are respectively 735 kV and 787.5 kV.

To investigate the impact of the lightning stroke on substation equipment insulation, one lightning stroke has been injected in the one of the phases of the line near to the substation at 100m. As the over voltage caused by the lightning strike is dependent upon the intensity of the lightning current and not on the distance from the substation. To investigate the adequacy of the arrester protection characteristics and its location, following three different simulations cases are considered. For each case, voltages have been computed at substation entrance and at the transformer terminal for all the three phases.

Case 1: No arrester installed

Case 2: Arrester modelled at substation entrance

Case 3: Arrester modelled at substation entrance and transformer terminal

Case 1: No arrester installed

In this case, a lightning current having magnitude of 31.5 kA with a wave shape of 8/20 μs is injected in the phase A of the transmission line at a distance of 100 m from the substation entrance. The magnitude considered here is the current to produce 10 kA peak magnitude having an approximate wave shape of 8/20 micro seconds. Voltages at the substation entrance and voltage at transformer terminal are shown in blue colour in the Figure 5 and tabulated in Table 3. The voltage computed at substation entrance and transformer terminal is having a wave shape of 2.3/55 μs and 2.1/51 μs respectively. The reason for the high voltage of more than 20 pu at substation entrance and transformer terminal is attributed to not considering the arrester in the simulation. These over voltages are unacceptable and points to the need for arresters at the line entry as well as at transformer terminals.

Table 3. Voltage with no arrester at substation entrance

Sl. No.	Equipment	Voltage (pu)	Voltage (kV)	rise time/ tail time μs
1.	Substation Entrance	25.54	4587.5	2.3/55
2.	Transformer Terminal	19.81	3558.3	2.1/51

Case 2: Arrester modelled at substation entrance

The simulation of CASE 1 is repeated with arrester modelled at substation entrance. It is assumed initially that for short separation between station entry point and the transformer, the arresters at the line entry themselves would provide adequate lightning over voltage protection to the transformer also. In this case a lightning current having magnitude of 31.5 kA with a wave shape of 8/20 μs is injected in the phase A of the transmission line at a distance of 100m from the substation entrance (lightning striking the line within the first span of the line). Due to this, lightning current of 10 kA with a wave shape of 8/20 μs is passing in the arrester, which is its rated current. The computed voltages at the substation entrance and transformer terminals are shown in red colour in the Figure 5 and tabulated in Table 4. The comparison and reduction in voltage at substation entrance as well as transformer terminal after installation of arrester is shown in Figure 6. By modelling the 216 kV arrester at the substation entrance, the over voltages are reduced to 4.38 pu and 4.73 pu at substation entrance and transformer terminal respectively. Since voltage at transformer terminal has been reduced after the installation of arrester at substation entrance but due to reflection of transients this voltage is still more and the protection margin is around 19% which is less than the required protection margin of 30%. Hence, to reduce the voltage further at transformer terminal due to the reflections one more arrester is required to be installed at transformer terminal.

Table 4. Voltage after installation of arrester at substation entrance

Sl. No.	Equipment	Voltage (pu)	Voltage (kV)	rise time/ tail time μs
1.	Substation Entrance	4.38	786.77	1.93/43
2.	Transformer Terminal	4.73	849.64	1.7/40

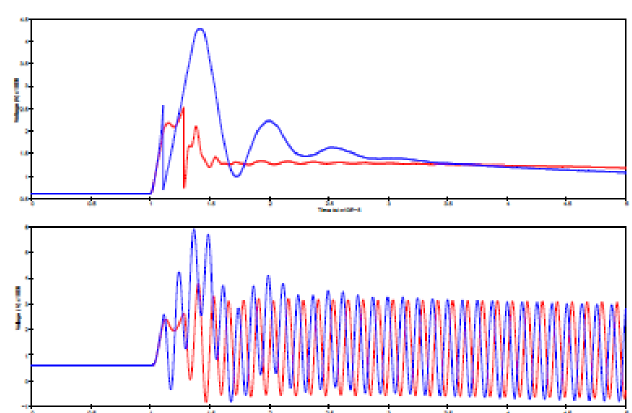

Figure 5. Voltage at substation entrance and transformer terminal (**Blue graph is without arrester and Red graph is with arrester).**

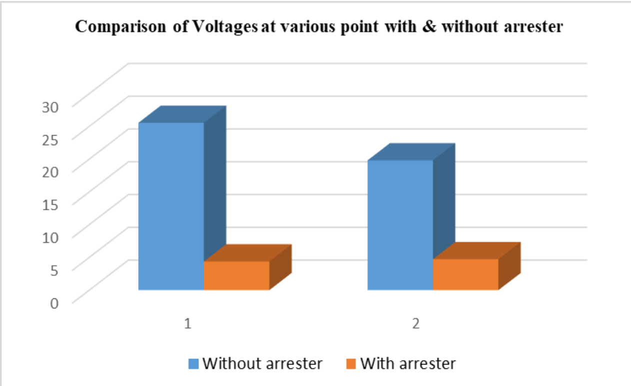

Figure 6. Comparison of voltages.

Case 3: Arrester modelled at substation entrance and transformer terminal

The simulation of CASE 2 is repeated with arrester modelled at transformer terminal along with substation entrance. The rating of this arrester is same as the arrester used at the line entry to the substation. In this case lightning current having magnitude of 31.5 kA with a wave shape of 8/20 µs is injected in the phase A of the transmission line at a distance of 100m from the substation entrance, due to this lightning arrester passes its rated current of 10 kA with a wave shape of 8/20 µs. Voltages at the transformer terminal are shown in the Figure 7 and tabulated in Table 5. The comparison and

Table 5. Voltage after installation of arrester at transformer terminal

Sl. No.	Equipment	Voltage (pu)	Voltage (kV)	rise time/ tail time µs
1.	Transformer Terminal	3.68	661.45	1.63/37.5

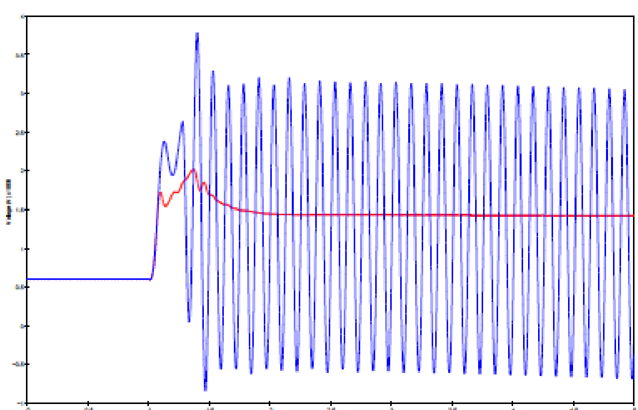

Figure 7. Voltage at transformer terminal after the installation of an additional arrester at the transformer terminal.

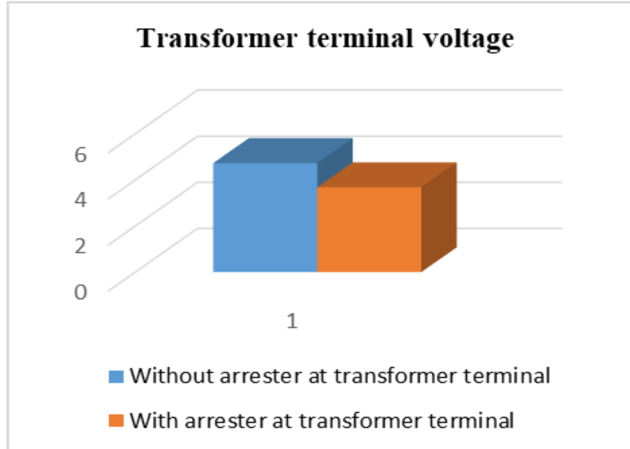

Figure 8. Comparison of transformer terminal voltage.

reduction in voltage at transformer entrance as well as at transformer terminal after installation of arrester is shown in Figure 8. By modelling the 216 kV arrester at the substation entrance and at transformer high voltage terminal, the over voltages at the transformer terminal has been reduced from 4.73 pu to 3.68 pu. With this, the protection margin of 37% could be achieved for the transformer insulation.

6. Conclusion

Overvoltage caused by the lightning specially in the event of direct stoke to a line are computed for 220 kV substation and the connected line. Modelling of the system is carried using the EMTP software. Initially, The system was simulated without arrester to find the magnitude of over voltages. Further, protection performance of the lightning arrester in the 220 kV substation, in particular, lightning overvoltage protection was investigated by modelling the arrester at the substation entrance and both at substation entrance and at the HV terminal of the transformer. Simulation shows that with the help of 216 kV rating arrester installed at line terminal, lightning overvoltage can be clipped to the voltage of 786.77 kV at substation entrance with a protection margin of 25%, and the voltage of 578.40 kV at transformer terminal with a protection margin of 19%. As the protection margin of 19% for transformer is thought to be inadequate, study repeated with arrester also at the transformer terminal showed ample protection margin for the transformer. The protection margin is improved from 19% to 37%. This demonstrates the need for arrester at the transformer terminals in order to safeguard its insulation against lightning caused over voltages. This study also justifies the practice of using arresters at the high voltage terminals of a transformer in 220 kV substations.

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8. References

1. International Electro Technical Commission, IEC 60071-1. Insulation Co-ordination - Part 1: Definition, principles, rules; 2006.
2. International Electro Technical Commission, IEC 60071-4. Insulation co-ordination - Part 4: Computational guide to insulation co-ordination and modelling of electrical networks; 2006.
3. Marti J R. Accurate modelling of frequency-dependent transmission lines in electromagnetic transient simulations. IEEE Transactions on Power Apparatus and Systems. 1982; PAS-101(1). https://doi.org/10.1109/TPAS.1982.317332
4. EPRI. AC transmission line reference book-200kV and above. Third Edition, Electric Power Research Institute; 2005.
5. Vasileva M. Lightning overvoltage in electrical substation 220 kV due to shielding failure of overhead transmission line.