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Original Research Article

Transient Simulations and Analysis of Overvoltage Insulation Coordination of Extra High Voltage Transmission Lines

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ABSTRACT

Insulation coordination of extra high voltage is a designing criterion for transmission lines such that it minimizes interruptions during steady state conditions as well as minimizes damages in case of transient over voltages. In order to prevent Lightning overvoltage strikes and its effects on transmission lines and towers from occurring and to understand the intensity of these effects these four major faults were simulated in Alternative Transient Program (ATP) EMTP software and its effects were observed and presented using the statistical method of insulation coordination to determine the transmission line insulation level, and lightning arresters. Four major case studies simulated include lightning over voltages strikes on: (a) shield wires alone; (b) shield wires with surge arrester; (c) red phase conductor; and (d) red phase conductor with surge arrester. The travelling waves propagate along the transmission lines was 3 x10^8 $\mathtt{mt/sec}$*. A switching withstands voltage for transmission line insulation of Basic Impulse level (BIL) values of 1550 kV was selected; with associated rated lightning withstand voltage of 2300 kV. Lightning arrester rated 420 kV been the minimum rating was selected for the transmission lines. Result showed that maximum continuous over voltages (MCOV) and temporary overvoltages (TOV) determine the criteria for selecting adequate surge arrester voltage rating. It minimizes the arrester discharge voltage for any particular surge, thereby maximizing the protective margins.*

1. INTRODUCTION

Transient phenomena in power systems are caused by switching operations, faults, and other disturbances, such as lightning strokes. The use of high voltage is extremely important in order to meet the rapidly increasing power demand. Increasing demand for electric power and addition of new generation capacity to meet the demand, necessitate enhancement of large transmission capacity between generation and bulk consumption points. This can be achieved either by development of new transmission corridor or by enhancing the power transfer intensity of existing transmission assets (Thukaram and Yelamanchi 2008).

In electric power transmission engineering, extra high voltage (EHV) transmission lines are classified as voltages ranges from 345 kV to 765 kV with solidly earthed line. EHV transmission lines are primarily used to transmit large amount of power usually constructed with bundled conductors over long distances (Hileman 2009), bundled conductors increases the self-geometric means diameter (GMD), and reduce line inductance considerably which increase the power capability of the transmission lines (Leonard 2012). Insulation coordination is the correlation of the insulation of the various equipment of a high voltage power system so as to minimize damage and loss of supply due to over voltages (Kuffel, et al 2000). The insulation level of equipment is defined as the combination of power frequency and impulse voltages that characterize the insulation with regard to the ability to withstand various stresses.

A properly conducted insulation coordination provides (a) the assurance that the insulation provided will withstand all normal operating stresses and a majority of abnormal ones; (b) The efficient discharge of overvoltage's due to the lightning and switching surges as well as other internal causes; (c) The breakdown will occur only due to the external flashover; and (d) The positions at which breakdown takes place will be where breakdown can cause no or comparatively minor damage. The insulation coordination in a power system requires the determination of line insulation level; the selection of the basic insulation level and insulation level of other equipment; and that selection of proper protective devices such as lightning arresters so as to provide to the equipment economically justifiable protection (Gönen, 2009; Mazen, et al., 2010; Syahirah and Halim 2016; Louvan der 2018). In other words, the insulation coordination can be studied under three categories which includes the selection of a suitable insulation which is a function of reference class voltage i.e., 1.05 × operating voltage of the power system; the design of the various equipment's such that the breakdown or flashover strength of all insulation in the station equals or exceeds the selected kV level; and the Selection of lightning arrester that will give the apparatus as good protection as can be justified economically (Wadhwa 2012). Transient phenomenon in power system is a periodic function of time and does not last longer. The duration for which it lasted is very insignificant as compared with the operating time of the system. Yet it's very important because depending upon the severity of these transients, the system can result into black out in a city, shut down of a plant, fires in some buildings. The power system can be considered as made up of linear impedance element of resistance, inductance and capacitance. The circuit is normally energized and carry load until a fault suddenly occurs. The faults, then, corresponds to the closing of a switch or switches in the electrical circuit. The closing of this switch changes the circuit so that a new distribution of currents and voltages is brought about. This redistribution is accompanied in general by a transient period during which the resultant currents and voltages can momentarily be relatively high (Rodriguez et al., 2005; Debapriya 2006). In a power system various equipment like transformers, circuit breakers, bus supports insulators etc, have different breakdown voltages. In order that all the equipment's are properly protected it is desired that the insulation of the various protective devices are properly coordinated (Kothari and Nagrath 2008).

The main task for insulation coordination is therefore the determination of stresses and the assessment of the strength of the system and the equipment installed. Insulation strength is selected on the basis of some quantitative or perceived degree of reliability and the strength cannot be selected unless the stress place on the insulation is known. Also, the methods of reducing the stress can be examined (Zhang et al, 2012; Bruce et al 2016). Thus, the goal of this study is the determination of the electrical stress placed on the extra-high voltage transmission line insulation; selection of the basic impulse level (BIL) and insulation levels of other apparatus and the selection of the minimum insulation strength for the lightning arresters.

2. METHODOLOGY

2.1 Direct Lightning Strike on Transmission Lines Tower

As lightning strikes directly on a phase conductor of a transmission line, it can be regarded as current injection on the line which divides itself into two equal parts at the point of strike. The raised voltage at the contact point propagates in the form of travelling waves in both directions along the transmission lines, away from the point of strike as depicted in Figure 1. When the characteristic impedance of the phase conductor is Z_{phsae} .

The voltage is related to the lightning current I by:

$$V = 0.5IZ_{phase} \quad (1)$$

The voltage wave travelling along the line hit by lightning, for instance, phase a, induces voltage waves on the neighboring phase also. When the coupling factor between phase a and phase b is K_{ab} then the voltage to the ground, induced on phase b is:

$$V_b = K_{ab}\, V_a \quad (2)$$

And the voltage between phase a and b is:

$$V_{ab} = (1- K_{ab})\, V_a \quad (3)$$

The voltage V_{ab} can cause a flashover between the two phases, if the separation distance is not large enough, thus introducing a two-phase short-circuit. When no flashover occurs, V_a , V_b and V_c will travel along the phase conductors a, b, and c and encounter the insulator strings that support the phase conductors in the tower, which is at ground potential. The voltage V_a is the highest, and the insulator string of phase a can be subjected to a flashover. The voltage waves travel in both directions along the line, away from the point of strike, and they travel from tower to tower. In the vicinity of each tower, the phase conductor has a larger capacitance to ground than at other parts of the line, because of the insulator strings and the presence of the metal tower structure that brings the ground potential closer.

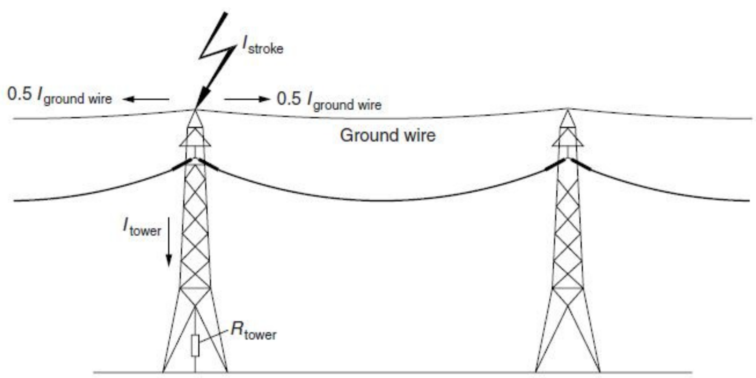


Figure 1: Travelling waves along ground wires on transmission lines

The velocity of surge propagation along transmission line can be expressed as

$$v^2 = \frac{1}{LC}$$

Or:

$$v = \frac{1}{\sqrt{LC}} \quad (4)$$

Where v is the velocity; L is the inductance; and C is the capacitance
Since inductance of a single- phase overhead line conductor, assuming zero ground resistivity, is

$$L = 2 \times 10^{-7} \text{ In} \frac{d}{r} \quad (5)$$

And its capacitance is:

$$C = \frac{2\pi\varepsilon}{In\frac{d}{r}} \quad (6)$$

Where d = distance spacing between the conductors in meters and r = radius of conductor in meters
Substituting these values in Equation (4), the surge velocity of propagation of the waves:

$$v = \frac{1}{\sqrt{(2x10^{-7} In\frac{d}{r} * \frac{2\pi\varepsilon}{Ind/r})}}$$

$$= \frac{1}{\sqrt{4\pi\varepsilon .10^{-7}}} = \frac{1}{\sqrt{4\pi . \frac{1}{36\pi} x\ 10^{-9}\ x10^{-7}}}$$

$$= 3 \text{ x } 10^{8}\ metres/second$$

Hence, its surge velocity is the same as that of light. This means the velocity of propagation of the travelling waves over the overhead transmission lines equals the velocity of light.

2.2. Determination of the Basic Impulse Level and Lightning Arresters

(a) Basic impulse insulation level (BIL)

Basic impulse insulation levels (BIL) defines the maximum crest impulse voltage that insulation will withstand repeatedly and without damage. In this case, a standard wave not longer than 1.2/50 μsec wave. Whereas the Switching impulse levels (SIL) is same as BIL except with a longer switching surge of typical 250 to 2500μsec

(b) Lightning (surge) arrester

Lightning arresters are used to limit overvoltage and as a result, allow reductions in the clearance required for self-restoring gaps e.g. transmission lines tower. Proper selection and application of lightning arresters in a system involve selecting appropriate size of arrester voltage rating based on maximum continuous over voltages (MCOV) as well as the temporary over voltages (TOV). These will be the lowest and best choice because it minimizes the arrester discharge voltage for any particular surge, thereby maximizing the protective margins. In order of protection, capability and cost, the station class arrester has the best protection capability and is the most expensive. The proper approach is to determine the minimum arrester, which can be applied without resulting in damage to the arrester itself. The lightning arresters are physically located at the Transmission lines station. In insulation coordination analysis, the system voltage is the primary criterion for the voltage rating of surge arresters. Extra High Voltage transmission lines have voltages ranges from 345kV to 765kV with solidly earthed line experiences maximum system voltage of 765 kV. Analyzing the statistical insulation coordination techniques to determine the lightning arresters, the highest voltage for Extra High Voltage Transmission line is 765 kV root mean square (rms) for a phase to ground voltage V_{ph} of 442 kV and a peak value of 625 kV. i.e $\sqrt{2}\ x\ (765/\sqrt{3}) = 625$ kV. From system studies, statistical overvoltage (SOV) which is switching overvoltage applied to the transmission lines as a result of an event of one specific type on the system, the peak value of which has a probability of being exceeded of 2% is 1255 kV at peak value. From table 1, the maximum acceptable risk of insulation failure to ground R is 10^{-4}.

Table 1: Choice of insulation's statistical withstand voltage

Statistical withstand voltage (SWV)		Statistical safety factor (SSF)	Insulation failure to ground R
kV	p.u.		
1300	2.08	1.04	1 x $10^{-2} > 10^{-4}$
1425	2.28	1.14	7 x $10^{-4} > 10^{-4}$
1550	2.48	1.24	7 x $10^{-5} < 10^{-4}$

The statistical withstand voltage (SWV) is the peak value of a switching or lightning impulse test voltage at which the insulation exhibits, under specified conditions, a probability of withstand equal to 90%. Thus, a switching withstands voltage for transmission line insulation of Basic Impulse level (BIL) values of 1550 kV is selected. The associated rated lightning withstand voltage is 2300 kV. The lightning arrester rated 420 kV is the lowest or minimum rating selected for the transmission lines, this will provide adequate overall protection of the transmission insulation and have a satisfactory service life.

2.3. Simulation of Transients Overvoltage

Lightning and switching over voltages transients faults causes maximum stress on EHV transmission system; consequently, Lightning strikes and its effects on transmission lines and towers were simulated using Alternative Transient Program (ATP) software (Bayadi, et al. 2013). Four major case studies simulated include Lightning over voltages strikes on: (a) Shield wires alone; (b) Shield wires with Surge arrester; (c) Red Phase conductor; and (d) Red Phase conductor with Surge arrester respectively. ATP software is a powerful tool used program for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature in electrical power systems. With this digital program, complex networks and control systems of arbitrary structure can be simulated. The program can predict variable of interest within electric power networks as functions of time, typically initiated by some disturbances such as the switching of a circuit breaker or a fault, overvoltage protection and power system control.

3. RESULTS AND DISCUSSION

Shield wires installed above phase conductors effectively shield the phase conductors from direct lightning strikes. When lightning strikes the shield wires, travelling voltage and current waves propagate in both directions along the shield wires that it strike. When the wave arrives at the tower, a refracted wave returns toward the point where the lightning strike and two refracted waves occur. One refracted wave moves along the shield wire into the next span. Since the shield wire is electrically connected to the tower, the other refracted wave moves down the tower, its energy being harmlessly diverted to ground. Lightning over voltages strikes on shield wire at tower No 4, and propagate through the shield wire as shown in Figure 2. Due to high magnitude of lightning and the impedance resistance of 300Ω for the tower, the transients are as seen on the phase conductors. During lightning strikes on shield wires, the lightning current divert to ground instantaneously through the tower itself as a path for grounding resistances for transmission towers. Due to the proximity of Red phase conductor from shield wire as shown from the graph in Figure.4, transient overvoltage is higher in Red phase conductor compared to Yellow and Blue phase's conductors. And due to the symmetry in Yellow and Blue phase's conductors with respect to shield wire the peak overvoltage's are approximately same as depicted in Table 2. The calculated phase voltages at tower No 4 for different values of impulse grounding resistance are presented in Table 2.

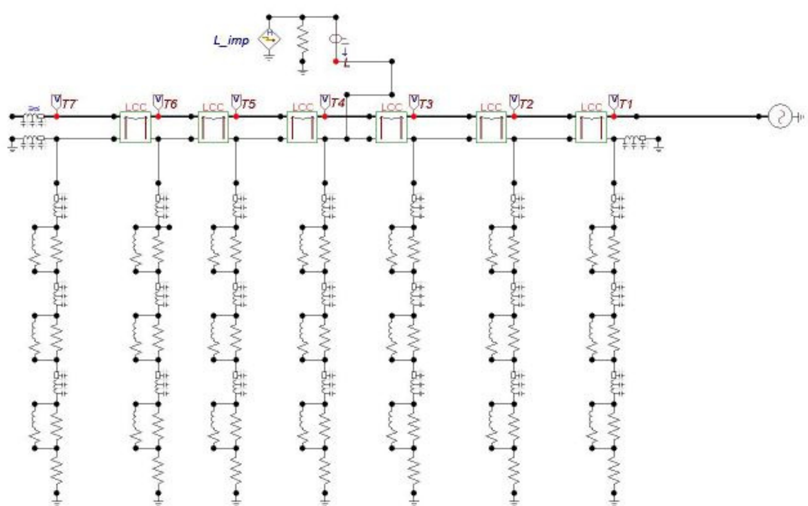


Figure 2: Lightning on shield wire

Table 2: Overvoltage for various grounding resistance at Tower No 4

Impulse grounding resistance(Ω)	Amplitude of overvoltage at tower 4 (in kV)		
	Red Phase	Yellow Phase	Blue Phase
10	1893	1554.65	1556
5	1844	1514	1515

The BIL rating of the given transmission system is 2300 kV and as it can be observed that the overvoltage across tower No 4 Red Phase conductor reaches approximately 1844 kV, with 5Ω resistance grounding the transmission towers protects the system in the worst case scenario of lightning striking the shield. As maximum lightning strike occurs at tower No 4 and then propagates via the shield wire to various towers, as the transient travels from tower to tower it reduces along with a shift in its maximum due to the time required to propagate through 400 meters. As the lightning propagates through the shield wire it affects all the three phases, and the effects can be seen in the Figure 2. Table 3 shown the maximum time plotted against the maximum overvoltage shoot on Red phase conductor at every tower. As the lightning takes time to travel through the transmission line, the variation in the time it takes to propagates can be seen in the graphs in Figures 4 (a and b).

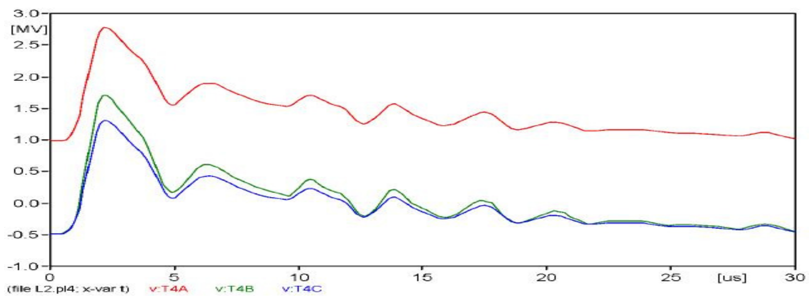
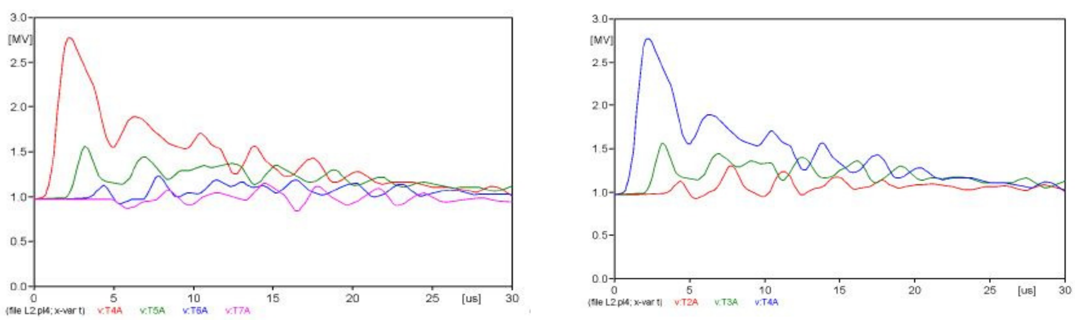


Figure 3: Voltage at tower No 4 with 5 Ω grounding resistances



(a) Tower 4,5,6,7 (b) Tower 2,3,4

Figure 4: Comparison between Red phase conductor voltages along the transmission line

Table 3: Maximum overvoltage with respect to time in microsecond

Maximum amplitude at Phase A with respect to time of maximum		
Tower	Time (µs)	Over voltage (kV)
2	4.395	143.5
3	3.225	580.7
4	2.215	1796.4
5	3.230	580.8
6	4.405	143.3
7	5.875	113.8

A three phase surge arresters is considered and its effect on the phase's conductors were compared to the one without a surge arrester. Figure 6 show the simulated towers of lightning strikes on shield wire with surge arrester.

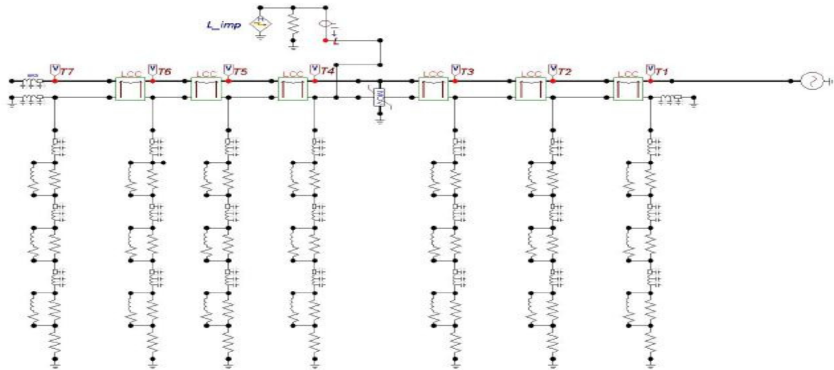


Figure 5: Lightning strikes on shield wire with Surge Arrester

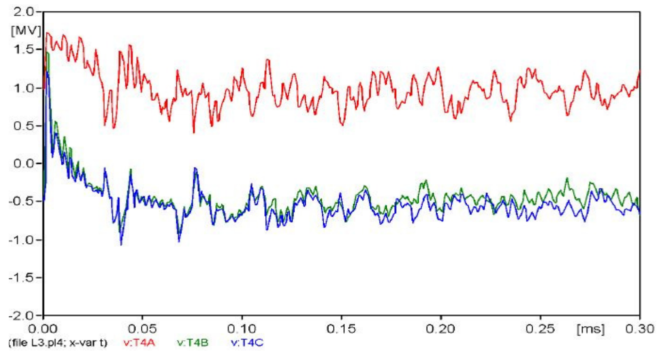
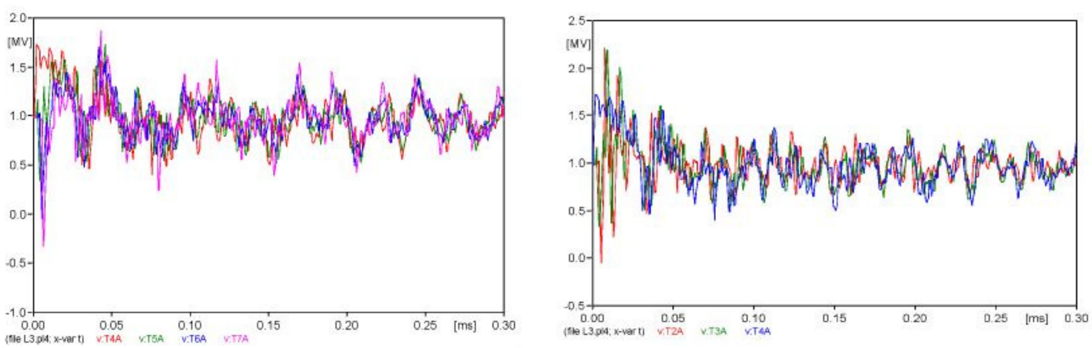


Figure 6: Lightning overvoltage on surge arrester at tower No 4 on Red Phase conductor

With the connection of station surge arresters in the transmission lines, it limits the maximum transients on Red phase conductor and hence the transient overvoltage peak value reduces to approximately 700 kV as shown in figure 7 compared to 1527 kV as shown in Figure 3. Similarly, Figures 7: (a) and (b) shows the comparison of the transients overvoltage wave shapes on the Red phase conductor when Surge arresters were connected to the transmission lines circuit between Towers No 4,5,6,7 and Towers No 2, 3, 4 respectively.



(a) Tower 4,5,6,7 (b) Tower 2,3,4

Figure 7: Comparison between the Red Phase conductor's voltages along the transmission line

Figure 8 showed the simulated lightning strikes on Red phase conductor at tower No 4 along the transmission line. when lightning strikes on Red phase conductor at tower no 4, the transient divides itself into two equal parts at the point of strike and the raised voltages propagates in the form of a travelling waves in both directions of the towers no 4 to 7 and from no 4 to 2 along the transmission lines, away from the point of strike.

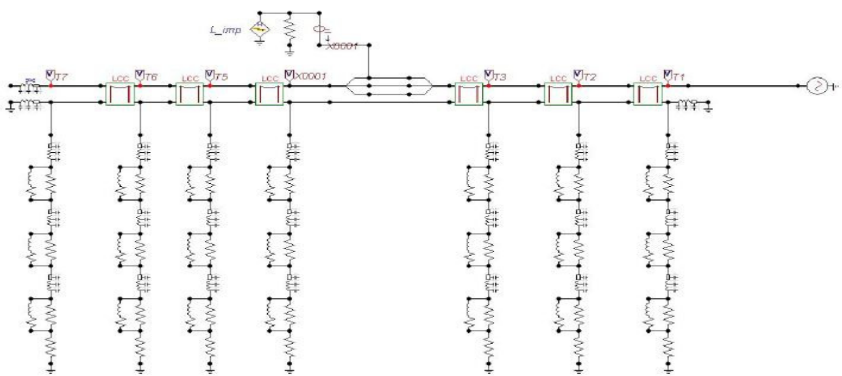


Figure 8: Lightning strikes on Red Phase conductor at tower 4

As shown in Figure 9, the overvoltage is in the order of 26,000 kV when lightning strikes Red phase conductor at tower No 4, this can lead to failure of equipment and cause significant damage to transformers. Hence the needs for surge arresters to be connected in circuit to mitigate these high overvoltage's due to lightning. As shown in Figure 10 the phase cannot be grounded without interrupting the steady state voltage mitigation of phase voltages poses a bigger threat as this fault propagates to transformers. Hence the need for surge arresters to mitigate the overvoltage's at phase conductors.

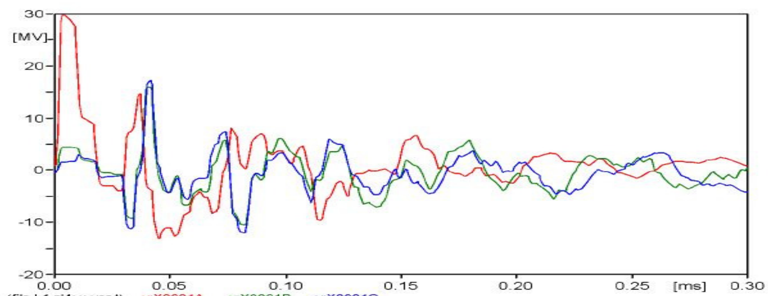
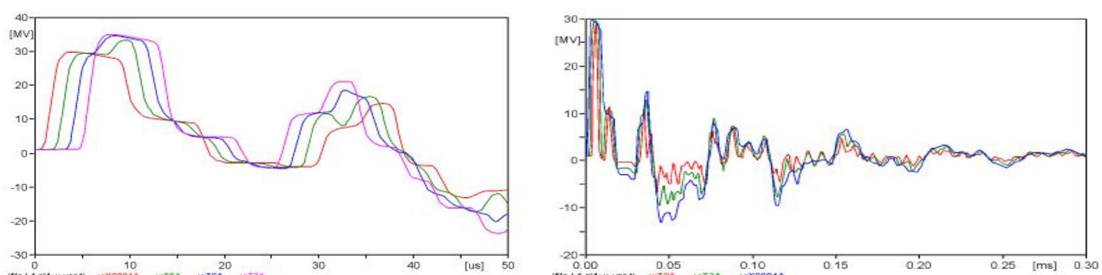


Figure 9: Lightning overvoltage strikes on Red phase at Tower No 4 without surge arrester



(a) Tower 4,5,6,7 (b) Tower 2,3,4

Figure 10: Comparison of Lightning over voltages strikes on Red phase conductor at Tower No 4 along the transmission line without surge arrester

Lightning arresters were applied to transmission line to limit the magnitude of impulse waves and overvoltage and as a result, allow reductions in the clearance required for self-restoring gaps of transmission lines tower. Shielding wires on transmission lines exists to protect phase conductors from a direct lightning strike; however, in case of a shielding failure, then direct lightning strokes hit the phase conductor as shown in figure 11. When this happens, overwhelmingly high voltages rapidly developed at the contact point. In order to mitigate this phase over voltage without affecting the steady state voltage, a station surge arrester was connected to provide protection against surge current without interrupting the steady state voltage.

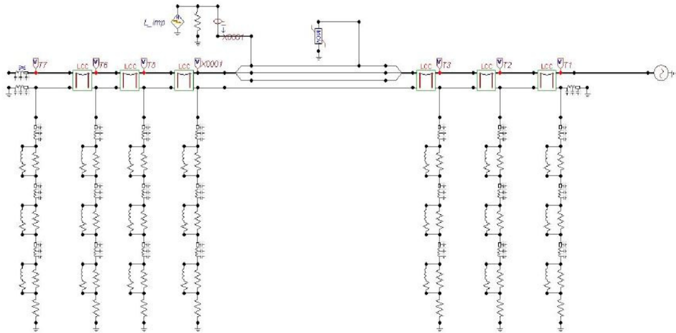


Figure 11: Lightning strikes on Red Phase conductor with Station Surge Arrester

In order to observe the effect of surge arrester compared to its absence at other towers and other phases conductors, surge arrester was considered only on Red phase conductor at Tower No 4. The surge arresters reduces the peak transient's as shown in Figure 12, hence preventing voltage rise which was up to 26,000 kV without surge arrester to about 700 kV overvoltage shoot. As this reduces the cause of overshoot at yellow phase and Blue phase conductors; i.e. voltages at Red phase conductor, this also reduces the maximum of overvoltage on Yellow phase and Blue phase without an exclusive need for surge arrester. Figures 13 (a) and (b) depicts comparison of lightning strikes with surge arrester on Red phase conductor along the transmission lines between Towers 4, 5, 6, 7; and 2, 3, 4. As lightning strikes at the tower no 4., the transient overvoltage divides itself into two equal parts at the point of strike, the raised voltages propagates in the form of a travelling waves in both directions of the towers no 4 to 7 and from tower no 4 to 2 along the transmission lines, away from the point of strike without further attenuation at the line due to absence of any protective device. Usually at EHV transmission lines, station surge arresters are connected on all three phases at regular intervals in order to reduce the transients considerably.

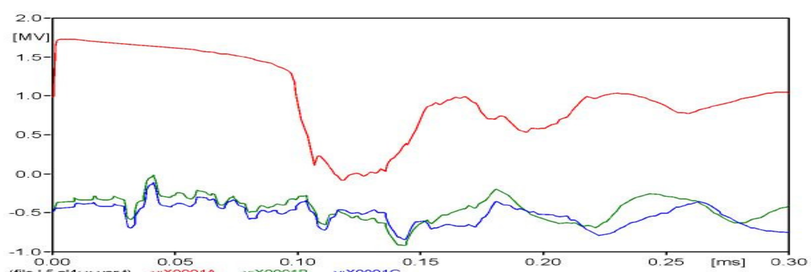
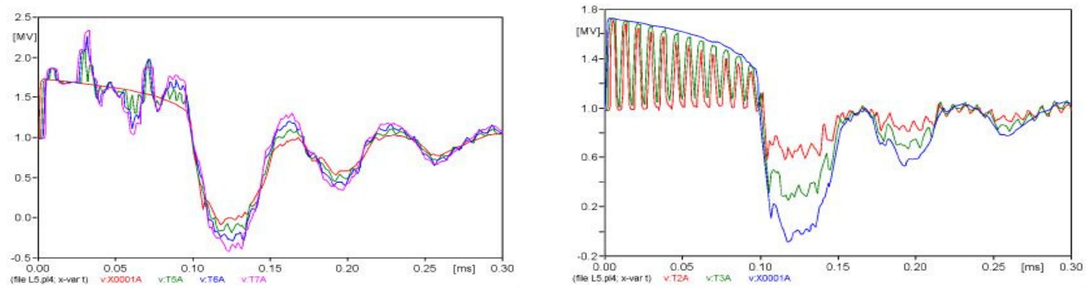


Figure 12: Lightning strikes on Red phase conductor with Station surge arrester on Tower No 4



(a) Tower 4,5,6,7 (b) Tower 2,3,4

Figure 13: Comparison of Lightning strikes with surge arrester on Red phase conductor along the transmission lines between Towers 4, 5, 6, 7; and 2, 3, 4

In determining insulation coordination, power frequency voltage; lightning overvoltage; switching overvoltage and temporary over voltages were examined. The lightning impulse over-voltages have the highest values of voltage rise with transient operating time in microseconds. While Temporary Over voltages transient operating time was found different from switching overvoltage's in term of longer time durations, from a few milliseconds to a few seconds. Two types of overvoltage protection requires in transmission lines such as shield wires and lightning (surge) arresters used to protect power system against severe overvoltage's were presented. It was analyzed that when lightning hits a tower top, some of the current flow through the shield wires, while the remaining current flows through the tower to the earth. The lightning strike propagates in the form of a traveling wave in both directions and raises the potential of the line to the voltage of the downward leader. The surge velocity of propagation of the travelling waves over the overhead transmission lines was determined to be 3 x 10^8 m/s which equals the velocity of light.

Basic impulse insulation levels and the switching impulse levels were determined to be a standard wave not longer than 1.2/50 μsec wave and 250 to $2500\mu sec$ respectively. A switching withstands voltage for transmission line insulation of basic impulse level values of 1550 kV was selected. The associated rated lightning withstand voltage was 2300 kV. Meanwhile, the lightning arrester rated 420 kV is the lowest or minimum rating selected to provide overall protection of the transmission lines. Simulations of transient lightning over voltages strikes using Alternative Transient Program (ATP) software were performed on four major case studies which include (a) Shield wires alone; (b) Shield wires with Surge arrester; (c) Red Phase conductor; and (d) Red Phase conductor with Surge arrester respectively. Figures 3 to 14 shows the voltage waveforms obtained from the simulation at various points along the transmission lines. Table 1 summarized the insulation's statistical withstand voltages, statistical safety factor and insulation failure values of the switching or lightning impulse test voltages. Table 2 presents the amplitude over voltages for the phase conductor for various grounding resistance at tower no 4; while Table 3 depict the maximum overvoltage at various Towers with respect to time in microseconds.

4. CONCLUSION

This paper evaluates insulation coordination in a power system the determination of the transmission line insulation level, the selection of the basic insulation level (BIL), and the selection of station lightning arrester for the protection of 765kV Extra-High Voltage transmission lines were presented. The surge velocity of propagation of the travelling waves over the overhead transmission lines was determined. While designing EHV system the minimum strengths of the system were subjected to maximum possible stress and the difference gives us a sense of reliability of the system. Insulation coordination is especially of major concern for EHV system due to the high steady state voltage; hence an equivalent per unit switching overvoltage in EHV system has higher voltage magnitude on HV experiences during lightning. The insulation level of the system rating of 765 kV transmission line, the lightning and switching impulse withstand voltages as well as the short duration power frequency withstand voltage using statistical method of insulation coordination were presented. Extra high voltage transmission lines protection from overvoltage surges, with thorough review of the power system, including voltage, system stresses, switching surges were also considered.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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