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Effect & mitigation of lightning overvoltage on transformer terminal at substations

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Abstract: *High over-voltage can occur due to lightning strikes in a phase conductor of transmission lines. Induced voltages in neighbor phases and reflection phenomena on the lines may lead to unacceptable high over-voltage between phases. In the simulation, a network model has been developed to study the lightning effect on the substation equipments especially at the transformer terminals. The voltage developed between phases &phase-to-ground has been observed with the traditional arrester configuration and the 6-arrester configuration. It has been observed that the phase-to-ground arrester is not adequate to restrict the lightning over-voltage between the phases to the safe limit and additional arrester is required to compensate this.*
The paper discusses the effect of direct lighting strokes of different magnitudes on the overhead line and transformer terminal connected at the substation and comparison of the voltage developed for different arrester configuration.
Keywords: *Basic Impulse Level (BIL), Electromagnetic Transient Program (EMTP), Lightning Overvoltage (LOV), Maximum Continuous operating voltage (MCOV);*

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I. INTRODUCTION

Transmission is an essential part of the power grid. Transmission lines run all over the geographical location to transmit the power to the load ends. While running through the different locations, these power lines face different kinds of electromagnetic and electrostatic stresses, which may cause interruption or failure to the power transmission for a while or a longer duration, depending upon the nature of the failure. Lightning is one of the phenomena that causes disturbance to power transmission if the lightning strikes the power conductor or the other part of the transmission equipment. Lightning is nothing but the discharge of a large amount of charged particles into the host which is transmission line in this study.When lightning strikes the shield wire at the mid-span of the line, lightning surge moves towards the towers in the opposite direction. Due to this a large transient voltage is developed on the power conductor, which is proportional to the power conductor's surge impedance and depends on the wave shape magnitude of the lightning strike current [1-2]. Protective equipment is provided at the substation end to protect the equipment situated at the substation from these high voltage surges.

In this paper, simulation has been performed for the different magnitudes of the lightning current, and the voltage developed between phases & phase to ground at the substation end, especially at the terminals of the transformer, is evaluated and analyzed with the traditional as well as 6-arrester configuration&4-arrester (Neptune) arrangement.

II. MODELLING

A. Modelling of Lightning as a current source:

As discussed, lightning is the discharge of the large amount of charge particle. It is modelled as a current source with a defined wave shape. [3-4]. Fig.1 shows the variation of the lightning current magnitude with respect to time, which mimics the actual lightning strike. A wave shape of 8/20μs is used in the simulation study to consider a high-stress scenario.

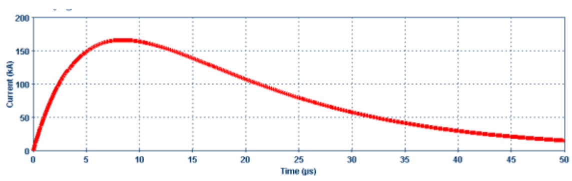

Fig.1: 8/20µs lightning current wave shape

B. Modelling of power transmission line:

The power transmission line is modelled for the simulation study of 110kV single circuit line and transposed throughout its length. The power conductors are modelled as frequency-dependent parameters of three-phase distributed lines [5]. This model represents the distributed line parameters consisting of the surge impedance of the line and surge velocity. Fig 2 shows the EMTP model of the frequency-dependentthree-phasetransmission line.

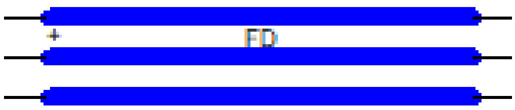

Fig2: Model of frequency-dependent transmission line

C. Modelling of voltage source:

The transmission system is working at the rated voltage during the lightning strike on the power conductor.The transmission system behind the transmission line considered under the simulation study is represented as a three-phase voltage source at power frequency to dismiss the insignificant reflection during the simulation study. Fig 3 shows the model of the voltage source used for simulation in EMTP, and Fig 4 shows a three-phase voltage waveform.

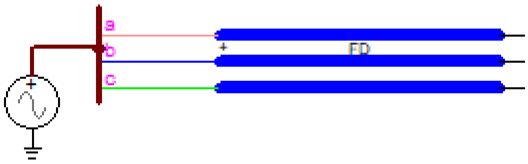

Fig 3: Model of power frequency voltage

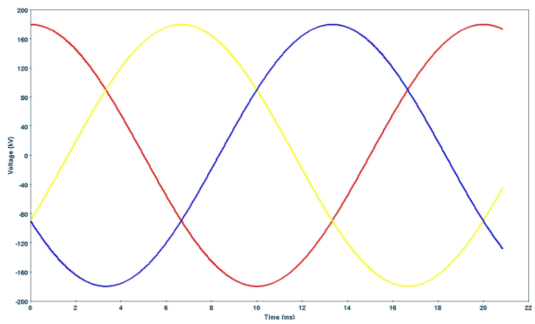

Fig 4: Three-phase voltage waveform

D. Modelling of Arrester:

The gapless metal oxide surge arrester is available in the EMTP software, modelled using the IEEE working group model [6]. The IEEE Surge arrester model is composed of two nonlinear arresters (A0 and A1), two inductors (L0 and L1) in parallel with two resistors (R0 and R1) and a capacitor C0, as shown in Fig. 5. The nonlinear characteristic of A1 is approximately equal to the 8/20µs curve while A0 is 20% to 30% higher. L1 and R1 act as a low-pass filter. For low-frequency transients, A0 and A1 are almost parallel; for high-frequency transients, the transient is distributed in the two nonlinear branches. Linear parameters Lo, L1, Ro, R1 & Co are derived from the physical parameters of the model from the following equations:

$L_1 = 15*(d/n)$ mH
R1 = 65*(d/n) Ω
Lo = 0.2*(d/n) mH
Ro = 100*(d/n) Ω
C = 100*(n/d) pF

Where d is the approximate height of the arrester in meters and n is the number of parallel columns of metal oxide in the arrester.The parameters mentioned above are adjusted to generate the characteristic of a 96 kV arrester.

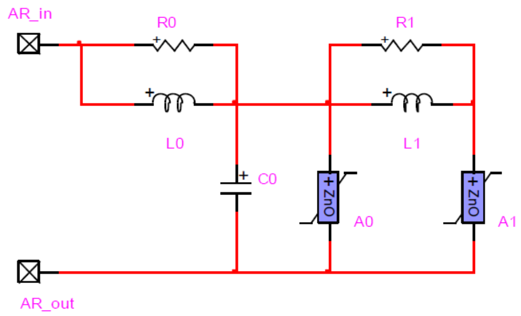

Fig. 5: Surge Arrester Model

E. Modelling of substation equipment:

The general structure of a transmission substation consists of severalcomponent such as Busbar, Interconnecting transformers, CT, PT, Circuit breaker and their interconnection within the substation. The interconnection in the substation is modelled using the distributed parameter of lines in EMTP. The constant parameter line model is used to model the short length of the line conductor, Busbar and interconnecting wires inside the substation. Transformers and other substation equipment, such as current transformers (CTs), potential transformers (PTs), and support insulators, are modelled using stray capacitances or bushing capacitances between phases and ground or between phases, depending on their connection. Figure 6 shows the model of substation in EMTP software. Fig 6 shows the substation model.

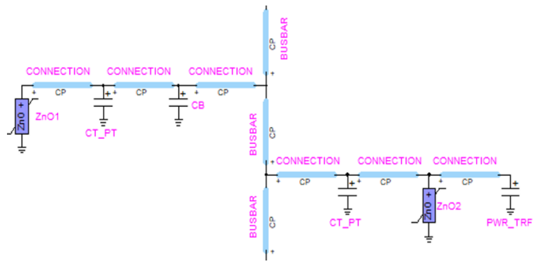

Fig 6: Substation Model in EMTP

III. SIMULATION & RESULTS

A simulation network is built consisting of a transmission line at rated voltage going towards the substation and connected with the various equipment inside it. The possibility of a lightning strike on the power conductor is rare due to the presence of the earth wire on the top of the tower. The earth wire protects the power conductor from direct strike and attracts most of the lightning strike, but still there is some probability that the power conductor gets a direct lightning strike. When this happens, it has severe effects on transmission systems if the protective measure has not been taken during the time of planning. Fig. 7 shows the network model of the 110 kV transmission system developed in the EMTP software for the simulation.

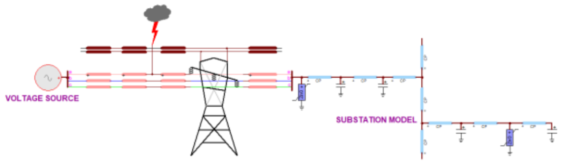

Fig 7:Network model simulated for lightning studies

Simulations were carried out to know the voltages at various terminals in the substation, considering the surge arrester typical configuration of phase to earth and located at the transformer terminals. The lightning current of 8/20µs is simulated in the R phase of the power conductor of the 110 kV transmission line at 200 meters from the substation entry point. The voltage developed at the substation end near the transformer terminal due to the surge is analysed. The simulation had been carried out by varying the magnitude of the lightning strike current from 5 kA to 35 kA to find out the voltage developed at the transformer terminals. The transformer at the substation end is modelled as delta-connected, the Maximum Phase to earth & phase to phase voltage developed for different lightning currents are tabulated in Tables 1 and 2, respectively.

Table 1: Voltage (Ph-Gnd) at transformer terminal

Injected Lightning Current	The voltage at transformer terminal LA (Ph-Gnd) (kV)
5	243.56
10	254.35
15	260.88
20	265.52
25	268.99
30	271.65
35	273.82

Table 2: Voltage (Ph-Ph) at transformer terminal

Injected Lightning Current	The voltage at transformer terminal LA (Ph-Ph) (kV)
5	380.55
10	433.25
15	477.62
20	524.85
25	556.72
30	596.00
35	651.16

Analysing the computed peak phase-to-ground and phase-to-phase voltages at the transformer terminal reveals that the 35 kA lightning current induces a phase-to-phase voltage exceeding the BIL level specified for the 110kV system. This excessive voltage can cause insulation breakdown and transformer failure despite the phase-to-ground voltage remaining within acceptable limits. Hence, the existing phase to ground arrester is not adequate to limit the voltage between phases within the BIL and additional arrester shall be install as a protective measure.

IV. MITIGATION

Lightning phenomena on the transmission systems or transformers can induce substantial over-voltage between their phase terminals. The withstand voltage between phases of these devices may be surpassed, even with the presence of phase-to-earth arresters. From the simulation, it is evident that there are conditions where the phase-to-ground voltage is well within the limit but the phase to phase voltage is not within the limit. To safeguard against these contingencies, surge arresters should be installed between phases wherever the probability of lightning over-voltage is high. The phase-to-phase arresters should operate continuously at a voltage of at least 1.05 times the maximum system voltage to account for potential voltage harmonics. For metal-oxide surge arresters, this translates to protection against temporary over-voltage up to 1.25 times the highest system voltage. For systems withhigher temporary over-voltage greater than 1.25 times, arresters with a higher rated voltage should be used [7-8-9].When transformers employ a delta-connected low-voltage winding, installing surge arresters between phases on the low-voltage side may be crucial to address inductively transferred over-voltage. Additionally, these arresters can protect the high-voltage side of the transformer by neutralising magnetic energy during transformer switching events.IEC 60099-5:2018 part-5 outlines two alternative configurations i.e. 6-arrester arrangement and 4-arrester (Neptune) arrangement as shown in the Fig. 8 andFig. 9 respectively. To effectively reduce phase-to-phase voltage spikes and safeguard equipment against overvoltage-induced damage

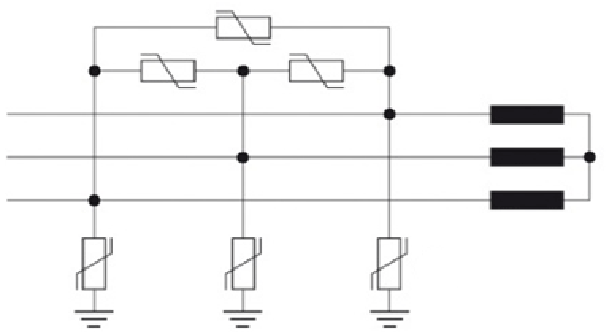

Fig. 8: 6-arrester arrangement

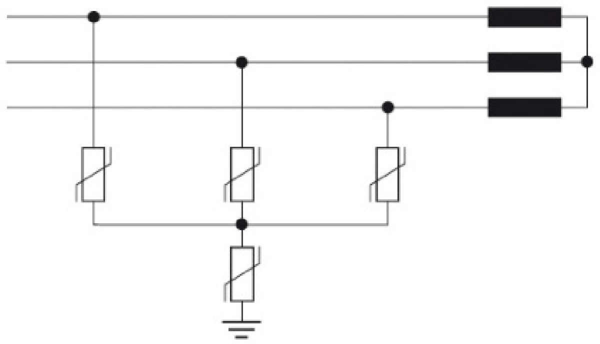

Fig. 9: 4-arrester (Neptune) arrangement

The simulations are carried out with the 6-arrester arrangement &4-arrester (Neptune) arrangementscheme to bring down over-voltage concerns mentioned in Table 2. The maximum phase-to-earth and phase-to-phase voltages achieved with these arrester configurationarrangements are tabulated in Tables 3 and 4.

Table 3: Voltage (Ph - Gnd) at transformer terminal

Injected Lightning Current	**The voltage at transformer terminal LA (Ph-Gnd) (kV)**	
	6-arrester arrangement	**4-arrester (Neptune) arrangement**
10	123.727	135.927
20	164.834	183.740

30	201.465	222.651
35	216.896	239.856

Table 4: Voltage (Ph - Ph) at transformer terminal

Injected Lightning Current	**The voltage at transformer terminal LA (Ph-Gnd) (kV)**	
	6-arrester arrangement	**4-arrester (Neptune) arrangement**
10	219.482	239.432
20	218.350	241.852
30	220.061	242.0671
35	221.563	244.093

A substantial decrease in phase to phase over-voltage is evident from Table 4, indicating the effectiveness of installing arresters between phases along with the existing phase-to-earth arresters and found that 6-arrester arrangement is more effective to reduce the voltage effectively in comparison with 4-arrester (Neptune) arrangement.

V. CONCLUSION

Lightning on transmission systems compromises the reliability of the transmission system by causing unwanted power outages. The simulation study shows the protective measures to safeguard the substation equipment during the direct stroke of lightning on the power conductor in the transmission system. The transient over-voltage developed during the lightning strike on the power conductor of the transmission line are thoroughly analysed for the different magnitude of lightning current and its effect on transformers at substation with the existing protective measures of phase to earth arrester installed at transformer terminals. It is found that the higher magnitude lightning current may develop the voltages between the phases more than the BIL of the system. To restrict the phase to phase voltage with in the safety limit, 6 arrester configuration and4-arrester (Neptune) arrangement have been adopted in the study. The simulation study effectively demonstrates the substantial reduction in phase-to-phase over-voltage induced by lightning surges following the installation of different arrester configurations. It is found that 6-arrester arrangement is more effective to reduce the voltage effectively and better in comparison with 4-arrester (Neptune) arrangement.However, this enhanced reliability comes at the expense of additional costs associated with space limitations, installation efforts, and the need for additional arresters. This idea may be utilised at the substations facing issue of over-voltage between phases in lightning prone areas.

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