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Optimal Surge Arrester Placement for Extra High Voltage Substation

J.V.G.Rama Rao,K.S.Kalyani,K.Ram Charan

Abstract*: *Lighting Phenomena is one of the important considerations during the design of Extra High Voltage and Ultra High Voltage Transmission Lines. Most of the authors have discussed regarding the benefits of using Surge Arresters as a way to improve the performance. In this paper, simulation analysis is done on 400kV/220kV Gwaka Substation, AP, India for optimal, cost effective placement of surge arresters. The most difficult configuration has been identified. A new method of "Voltage-Distance curve" is proposed to evaluate different Surge Arrester installation configurations. Finally the way to determine the optimal surge arrester configuration for each line section is then introduced in this paper.

Keywords*: *Critical Point(CP), Basic insulation level(BIL), Voltage-Distance curve, surge Arrester.

I. INTRODUCTION

For any transmission system, proper insulation design against lightning surges is very important. several authors have discussed regarding use of metal oxide surge arresters(MOSA) as a surge protecting devices. There are several methods to reduce the lightning related outages on high voltage transmission lines. The optimal shielding design was presented in [1], while Mladen S.Banjanin [2] proposed a new method of using external ground wires to improve lightning protection of transmission lines. The risk of lightning outages of transmission lines was introduced by Armstrong and whitehead [3]. Shield wires, in combination low footing resistance, improve the lightning performance of a transmission line, and the application of line arresters provides an additional increment of protection [4].

In India, the number of lightning strokes that hits the ground is between 4 strokes per square kilometer per year [10]. On average 30% of all power outages annually are lightning-related [10]. The keraunic level in a specified locality is roughly proportional to the number of lightning events in that locality/. It is suggested by [10] that

$$N = 0.12T \qquad (1)$$

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When lightning flash terminates within a specified area around the transmission line, the transmission line will flashover. The approximation of the width of the area was given in for a line with two shield wires.

$$W = b + 4h^{1.09} \qquad (2)$$

$$h = h_g - \frac{2}{3}\left(h_g - h_{gw}\right) \qquad (3)$$

The phenomenon of lightning hits on the conductor of a shielded line is usually denoted as shielding failure. Back flashover is the result of a direct lightning stroke to the tower structure and shielded wires. Lightning surges travel in both directions and down the tower into the ground, developing a voltage on the cross arm and stress the insulation. Flashover occurs when the voltage exceeds the threshold of the insulator string. The flashover of insulator then causes a line to ground fault and will be interrupted by the breakers. The back flash usually occurs during a lightning striking to the overhead shield wire where the ground impedance is high. Previous researchers have shown that the back flashover is more prominent in the lightning protection of overhead transmission line rather than shielding failure [11].

There are several methods to reduce the lighting related outages on transmission lines. Installing ground wires are the most common methods for reducing the number of the direct stroke on transmission lines. Mladen S.Banjanin proposed a new method of using external ground wires to improve lightning protection of transmission lines. However, after the transmission lines are built, it is costly and time-consuming to add overhead shield wires or change the configuration of the ground wire. Surge arresters have the advantages that it flexible and can deal with nearly all types of surges.

When no arresters are in service and the shield wire experiences a direct stroke, the lightning surge will travel along the shield wire and down to the ground from nearest pole. If the voltage across the insulator increases and exceeds the withstand level of the line insulator, the insulator flashover occurs, leading to a line to ground fault. If an arrester is installed on the tower, the surge current will directly transfer into the phase conductor. Thus, no flashover would occur across the insulators in this scenario.

II. MODELING OF 400/220KV TRANSMISSION SYSTEM AND SUBSTATION

A. Lightning Surge

The standard waveform of a lightning surge is specified by the IEEE standard 4-2013 [12] . In this paper, the lightning impulse is modeled as a voltage source with external source control, which uses a surge generator to provide the surge waveform. IEEE standard 4-2013 [12] introduced a double exponential wave shape described as:

$$V = V_{pk} * K\, e^{\frac{-t}{\tau_1}} - e^{\frac{-t}{\tau_2}} \qquad (4)$$

For a 1.2*50µs wave, K=1.037, $\tau 1$=68.5µs, $\tau 2$=0.404µs

The crest value is recommended to be the basic lightning impulse insulation levels (BIL) of the equipment [13]. According to IEEE Standard C62.82 [13], the BIL for 220 kV systems is 900 kV while it is 1800kV for 400kV systems.

B. Transmission Line

Transmission lines are modeled with the Frequency Dependent (Phase) Model in EMTP-RV since it is one of the most advanced time domain models. It can distribute the line resistance across the entire transmission line rather than lumped at the end of the line.

The data for the 220kV transmission line and the 400kV transmission line are provided by 400kV/220kV Gwaka Substation.

Table 2.1 Transmission line parameters

Parameters	220kV	400kV
Conductor	Zebra	Moose
Type	ACSR	ACSR
Stranding	54/7	84/19
Average span ft	1000	1000
No of phases, string	3,18	2,12
Insulator size	$5^{3/4}*10$	$11^{1/2}*7$
No of Strings /phase	2	2
No of shield wires	2	2
Material	Alum weld	Alum weld
Diameter	0.385;7 #8	0.385; 7 #8

C. Surge Arrester

The characteristics of the 400kV and 220kV surge arresters used in this paper are given in Table 2.2 and 2..3. The surge arrester type used in this system is SIEMENS 3EL2

Table 2.2 Technical data used for SIEMENS 3EL2 220kV Surge Arrester.

3EL2	1/2 µs	8/20 µs	45/90 µs
I(kA)	10	20	15
U(kV)	458	480	354

Table 2.3 Technical data used for SIEMENS 3EL2 400kV Surge Arrester

3EL2	1/2 µs	8/20 µs	45/90µs
I(kA)	5	20	15
U(kV)	930	1088	821

D. Transmission Line Tower

Fast front transient tower models include the effect of tower geometry and tower grounding resistance. The tower body and tower arm can be represented using the transmission line Bergeron model in EMTP-RV since only the surge impedance and the surge travel velocity of the tower are needed to be concerned. The insulators are modeled with their flashover characteristics.

E. Insulators

The insulators are represented by switches in parallel with capacitors connected between the respective phases and the tower. The switch, which is voltage-dependent, is open when the insulator is under normal operation condition and close when the insulator flashover occurs. The capacitors can represent the coupling effect of conductors to the tower structure. The back flashover mechanism of the insulators can be modeled by volt-time method. The volt-time characteristic of insulators is represented as a function of insulator length. The equation (5) can be used to calculate the insulator flashover voltage.

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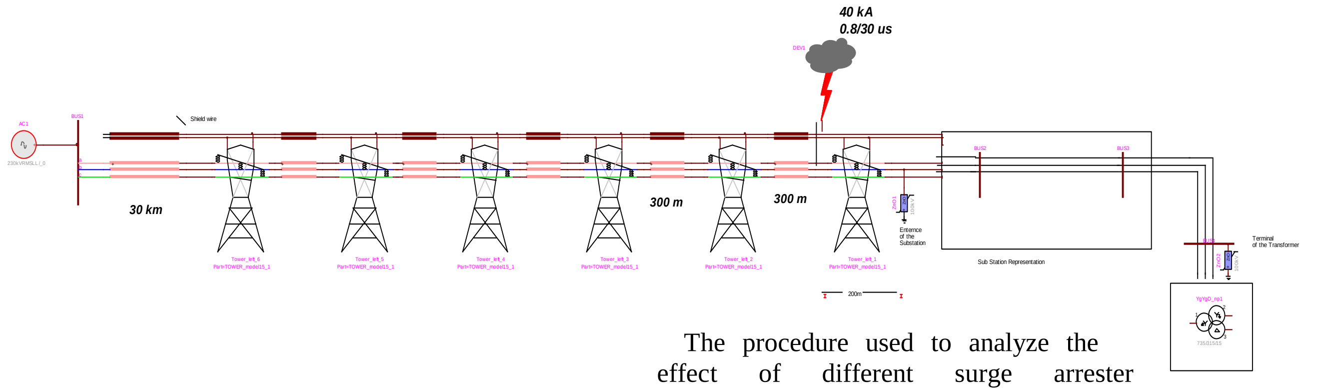
Fig. 2.1 EMTP-RV Simulation Model of 400kV/220kV Transmission line & Substation Model



If the voltage across the insulator exceeds V_{v-t}, back flashover occurs.

$$V_{v-t} = K_1 + \frac{K_2}{t^{0.75}} \qquad (5)$$

Where K_1: 400* L & K_2: 710*L

In Above Fig,2.1,only one shield wire and phase B conductor are depicted. By varying the lightning struck location, the critical point which has the maximum overvoltage on the terminal of the transformer can be determined. The lightning stroke is terminating on the phase B. Travelling waves are generated on both side of the lightning struck location. In this chapter, surge arresters are not installed on the transmission line towers. They are installed at the entrance of the substation, or the terminal of the transformer, or both. Four different surge arrester configurations are developed and investigated for studying the surge arrester placement on substations.

These four configurations are:

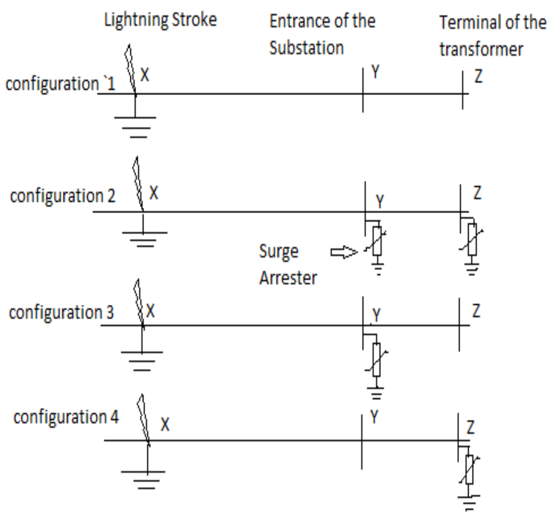


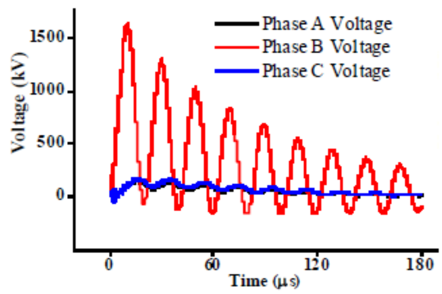
Fig. 2.2 A one-line diagram with four different configurations

The procedure used to analyze the effect of different surge arrester configurations on the substation as shown in Fig.2.2 are listed below:

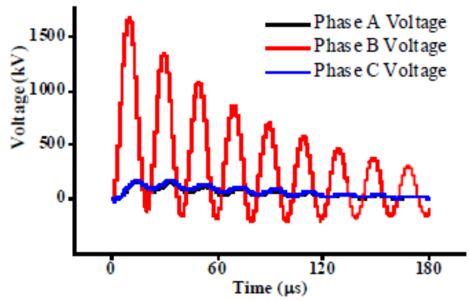
1. Designing the line section which comprises ten spans of the 220kV transmission line and the connected substation in EMTP using the field data. No surge arrester is installed in this configuration at step (1). It is assumed that the lightning hits on Phase B of the transmission line.
2. Gradually changing the distance from the lightning stroke location to the entrance of the substation. For each lightning stroke, the crest voltages at the entrance of the substation and the transformer terminal are recorded.
3. The improvement of the system lightning performance for the rest of the three configurations, which use surge arresters, are analyzed by repeating step (2). In addition, the performance of the surge arresters is recorded. The Step (2) describes how the voltage-distance curves are drawn. The voltage- distance curve can identify the critical point which is used to determine the maximum recommended length of the line before an arrester needs to be applied. Moreover, the voltage-distance curves can help determine the optimal configuration which can satisfy the specific lightning performance.

III. SIMULATION RESULTS

For a specific stroke location, for instance, the distance from lightning stroke to the entrance of the substation is 200m. Simulation results are given regarding plots of waveforms for the important variables such as arrester voltage, current, and energy duties. The voltages over time at Point Y and Point Z for configuration C1 are shown in Fig. 3.1, Since there is no surge arrester in this system, the maximum voltage is about 1600kV which is much higher than the BIL value (900kV). The equipment in the substation including circuit breakers, instrument transformers, and Power transformer are about to effected. It is unnecessary to design a system whose insulation can withstand all types of over voltages for all duration of time. For example, a lightning impulse voltage appears on the system for a period of microsecond rage and this is cleared from the system by lightning arrester as rapidly as possible.

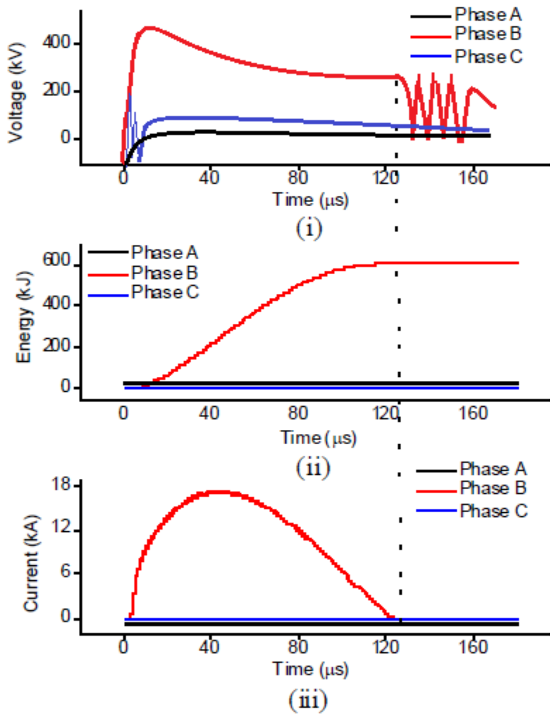


(a)Entrance of the substation

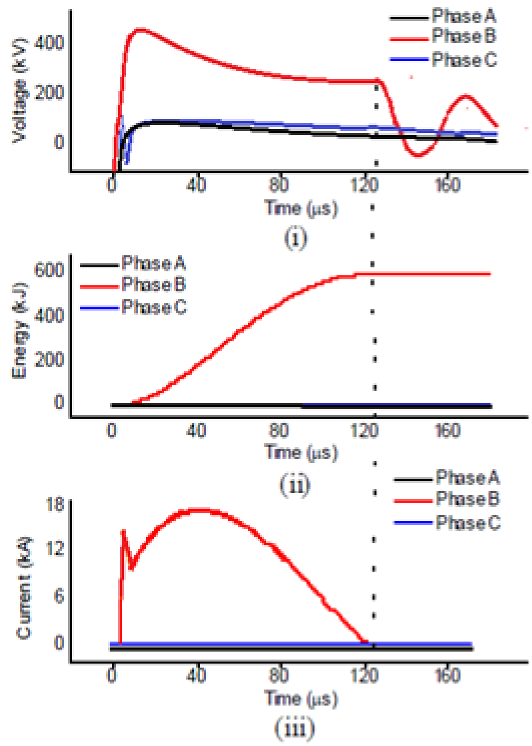


(b)Terminal of the Transformer

Fig: 3.1.The voltage at point Y and Z for C1



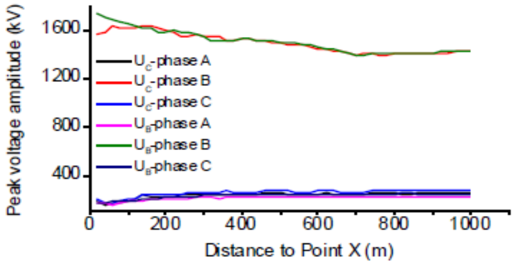
(a)Entrance of the substation



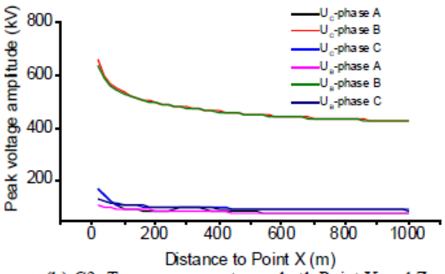
(b)Terminal of the Transformer

Fig. 3.2. Voltage and the Surge Arrester Energy as well as the current at point Y and Z for C2

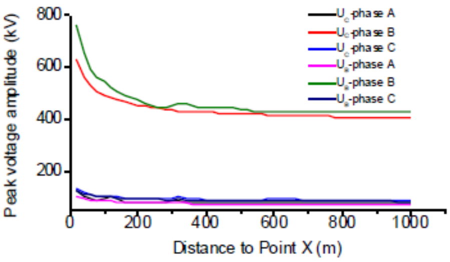
Fig. 3.2 (a). (i) and Fig. 3.2 (b).(i) illustrate the voltages at Points Y and Point Z for C2 respectively. The energies absorbed by the surge arresters at Point Y and Point Z are shown in Fig. 3.2 (a).(ii) and Fig. 3.2 (b).(ii) respectively. When the currents in the surge arresters drop down to zero (see the dash line in Fig. 3.2), the arrester returns in normal operation condition i.e., the surge arrester's impedance returns to infinity. After 120 µs, the voltage becomes oscillating, which is caused by the transformer inductance and capacitance. Since phase A and phase C do not have surge arrester functioned, the energy and the current of the surge arresters installed on these two phases are all zero. Therefore, the energy and current curves of phase A and phase C are overlapped in Fig. 3.2. The analysis described above also applies to C3 and C4. It is worth noting that the energies absorbed in C3 and C4 are close to C2, but they are a bit lower than the sum of the energy absorbed by the two surge arresters in C2. Meanwhile, the average voltage of C3 and C4 are higher than the average model of C2. The effect of the surge arrester configurations concerning the point which injected the lightning stroke on a 220 kV transmission line and the substation is studied using the voltage-distance curve in Fig.3.3. From Fig. 3.3 the peak voltage amplitude curves of all four configurations decreases as the distance between the lightning stroke location and the substation increases. However, for C1, the crest voltage at the entrance of the substation reaches the peak when the lightning stroke is 160m away from the substation. Therefore, the critical point is 160m. Also, for C4, the curve of the crest voltage is oscillating and thus, it has several maxima.



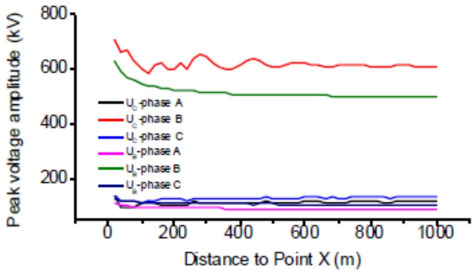
(a) C1-No installed surge arrester



(b) C2- Two surge arrester on both Point Y and Z



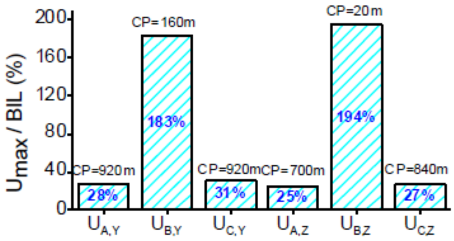
(c) C3- One surge arrester on Point Y



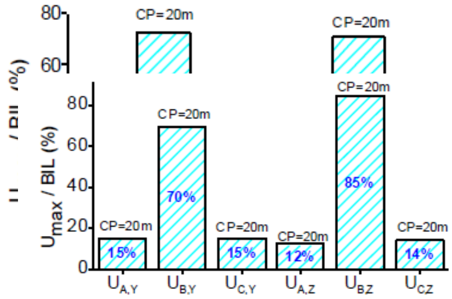
(d) C4- One surge arrester on Point Z

Fig.3.3 (a-d). The Voltage-Distance Curve for All Three Phase of the point Y & Z.

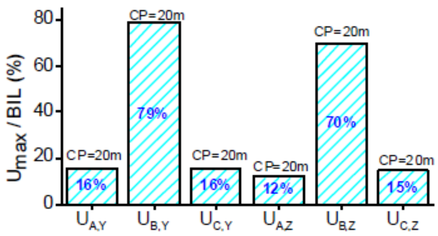
From Fig 3.3.The Phase B Voltage at the entrance of the substation and terminal of the transformer exceeds the BIL value and the system is about to failure. Fig. 3.3 (b) shows that the crest values of the phase B voltage on Point Y and Point Z are almost overlapped. The voltages drop down sharply from lightning strokes located at 0m to 400m and then stabilize for the locations that are over 800m away from the entrance of the substation. From Fig. 3.3 (b), the maximum voltages at Point Y and Point Z are 73% and 71% of the BIL value respectively. C2 has the best lightning protection performance as the average of the maximum voltage at Point Y and Point Z are the lowest among the four configurations. Since a transformer is very vulnerable and expensive equipment in the power networks. Therefore, it is better to leave some margin for the peak voltage amplitude at the transformer terminal. Regarding the protection of the transformer, C4 has a better lightning protection performance than C3. In addition, the maximum voltage for the two points is 85% in C3 and 79% in C4, which shows another advantage of C4 over C3. Fig. 3.4, it is clear that phase A and phase C voltages can only reach up to 31% of the BIL value. The probability for lightning stroke on a transmission line within 100m to the entrance of the substation is very low. Therefore, C3 may provide a better protection for the equipment in the substation since the voltage at the entrance of the substation is always high in C4. C3 also performs better than C4 with respect to transformer lightning protection.



(a) C1



(c) C3



(d) C4

Fig. 3.4(a-d). The Ratio between the Maximum Voltage and BIL Value under Different Configurations.

Lightning strokes are applied at different distances from the entrance point. The corresponding lightning stroke location of the maximum voltage at the entrance of the substation or the terminal of the transformer id defined as critical point.

IV. CONCLUSIONS

The primary objective of this section is to examine whether only installing arrester at the terminal of the transformer can efficiently protect the 400/220kV substation. By analyzing the performance of four different configurations regarding the location of surge arresters, appropriate parts of a 220kV transmission line, as well as the

400/220kV substation are modeled using EMTP-RV. The model built using the real line data is utilized to simulate the effect of lightning stroke hitting at a different locations on the transmission line. The voltage-distance curve is proposed to evaluate the effectiveness of the lightning protection of the four different surge arrester configurations when a lighting stroke hits on the transmission line feeding to the substation. A good visual depiction of the simulation results is offered by implementing the voltage distance curve. Though installing the surge arresters at both the entrance of the substation and the terminal of the transformer has the best performance among the four configurations. Moreover, the other two configurations which have surge arrester installed either at the entrance of the sub-station or the terminal of the transformer are sufficient for lighting protection. In the configuration of installing the surge arrester at the entrance of the substation, it is possible that the transformer may suffer with the voltage up to 85% of the BIL. However, this happens only when the lighting stroke hits on a small area that is very close to the substation. It is rare that the lighting would hit on that area.

The voltage at the entrance of the substation when the surge arrester is installed at the terminal of the transformer is always high, which may require the equipment at the entrance of the substation to have a better lightning voltage withstanding capability. Regarding the economic impact, the failure of the transformer can result in high cost due to repair or replacement costs and outage losses. To guarantee that the transformer is well-protected, the configuration which only has surge arrester installed at the terminal of the transformer can be implemented. Therefore, installing surge arrester at the terminal of the transformer in the Gwaka 400kV/220kV substation proved to be adequate and efficient concerning both the lightning performance and the economic cost. In addition, the location of the lightning stroke does not have a significant effect based on the reflection and refraction characteristic of the travelling wave. However, the location of the lightning can still affect the maximum over voltage on the substation due to the changing distance of travelling wave to the substation.

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