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Surge Arrester Placement for Substation Lightning Protection with Practical Utility Cases

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SUMMARY

A significant number of faults are caused by lightning every year. Surge arrester is an effective way to improve the lightning performance of power systems. Most utilities install surge arresters at both the entrance of the substation and the terminal of the transformer. Due to the high installation cost of surge arresters, however, some utilities like Salt River Project (SRP) only install the surge arrester at the transformer side. An evaluation of lightning protection design for a 500-230 kV substation with surge arresters is presented in this paper. This evaluation utilizes a field data based model. This model is developed by a professional simulation tool which is known as PSCAD/EMTDC. Four different surge arrester configurations for substation lightning protection are investigated. They include: no surge arrester in the substation, surge arrester installed at the entrance of the substation, surge arrester installed at the terminal of the transformer, and surge arresters installed at both the substation line entrance and the terminal of the transformer. The voltage at the substation entrance and the voltage of transformer terminal are measured, along with the arrester energy duty and current. The voltage-distance curve is proposed to analyse the lightning performance of the four different configurations. Simulation results show that installing surge arresters just at the transformer location is adequate for the substation lightning protection. Advantages and disadvantages of installing surge arresters at the entrance or at the transformer are discussed. Case studies demonstrate the advantage of the voltage-distance curve in terms of visual representation for evaluating the performance of different surge arrester configurations.

KEYWORDS

Lightning protection, Surge arrester, Surge arrester location, Transmission lines, Substation.

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I. INTRODUCTION

Most of the surge arrester placement studies focus on the transmission line [1-5] while very few papers discuss the effect of the placement of surge arresters in a substation. Past research effort has investigated a method which has significant effect on the improvement of shielding devices which are required to adequately protect the substation equipment [6]. In addition, the backflashover study of the substation study is performed in [2], [7]. The direct stroke on the transmission line feeding into the substation hasn't been fully discussed. Thus, this paper focuses on the direct lightning stroke which can cause very severe damage to the equipment in the substation. The effectiveness of surge arresters' function in terms of limiting the arising overvoltage is identified in [8]. The correlation between overvoltage and the rise time of the lightning stroke current was investigated in [9] and the effect of tower footing resistance variation is studied in [2]. In this paper, only the placement of the surge arresters on the substation is of concern. In literature, most of the studies use the EMTP-type programs to evaluate the lightning performance of surge arrester [4], [10]. Since EMTDC program can provide better transmission models, the PSCAD/EMTDC program is used in this paper.

The reason for the overvoltage caused by lightning in a substation is either the station shielding failure or the lightning stroke to a transmission line feeding to the substation [11]. In a well-designed substation, the majority of strokes are on the lines, creating surges that travel along the line and enter into the substation. The lightning surge that originates in the transmission line can be divided into three categories: a lightning flash terminating on a phase conductor, on an overhead shield wire, or on nearby ground which induces a surge into the conductors [11]. The lightning that strikes on a phase conductor is the focus of this paper since the overvoltage it causes to the substation is expected to be the most severe. The lightning striking on the line sets up traveling waves moving along the line. When the traveling wave reaches the entrance of the station, it will be modified by the terminating impedance of the substation. The crest voltage will double when the traveling wave encounters an open circuit breaker and then reflects back to the transmission line, which corresponds to the worst case. When the lightning stroke that hits a transmission line causes a phase to ground fault, it may provide a path for current to flow into the ground and the impedence at that point will change significantly. In this case, the traveling wave will reflect back and forth between the lightning striking point and the entrance of the substation. Lattice diagram, shown in Fig. 1 (a), is used to illustrate the situation. Note that, in this figure, X denotes the lightning stroke point; Y denotes the line entrance of the substation; and the terminal of the transformer is marked as Z.

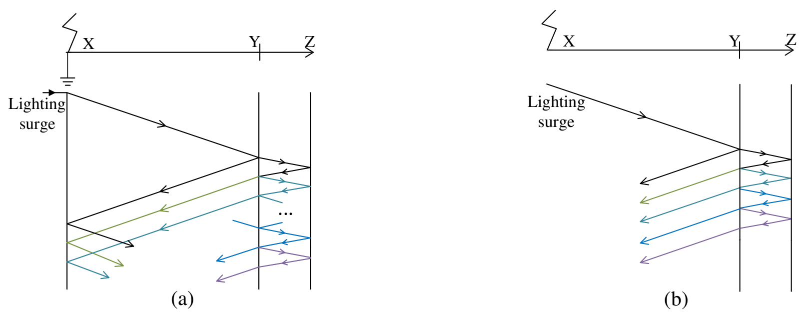


Fig. 1. Lattice diagram of traveling wave

The voltage of a specific point at a transmission line is the sum of the instantaneous values over all individual traveling waves at that point. Thus, it is very likely that the highest overvoltage at the substation entrance will occur when a lightning strikes on a critical point. A critical point is defined as a specific location where if lightning hits, the maximum peak voltage amplitude would occur at the terminal of the transformer. The critical point is one of the major concerns of this paper and is discussed in Section III. Another situation considered in this paper is that no impedance change occurs along the transmission line when the lightning does not cause any ground fault. With the assumption that there is no attenuation of the lightning surge along the transmission line, the distance of lightning stroke to the substation will be independent of the voltage at the entrance, which is illustrated in Fig. 1 (b).

According to IEEE Standard C62.22-2009 [11], surge arresters can be installed at the line entrance of the substation to protect apparatus in the substation such as the circuit breakers, disconnect switches, and instrument transformers. However, due to the high cost of surge arresters, this standard is not enforced by all utilities. The following parts of this paper will evaluate four different models: 1) no surge arrester in the substation; 2) surge arrester installed at the entrance of the substation; 3) surge arresters installed at the terminals of the transformer; 4) surge arresters installed at both the substation line entrance and the terminals of the transformer. Then, the protection scheme that provides the optimal protection with the least cost will be determined.

II. MODELLING

A. Lightning surge

The standard waveform of a lightning surge is specified by the IEEE standard 4-2013 [12] and is described as a 1.2/50 µs voltage impulse, which means the voltage wave reaches a crest in 1.2 µs and diminishes to half the crest value in 50 µs. In this work, the lightning impulse is modelled as a voltage source with external source control using a surge generator to provide the surge waveform. The crest value is recommended to be the basic impulse insulation level (BIL) of the equipment [13]. According to IEEE Std C62.82 [14], the BIL for 230 kV systems is 900 kV while it is 1800kV for 500kV systems.

B. Transmission lines

Transmission lines are modelled with the Frequency Dependent (Phase) Model in PSCAD, 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 [15].

The data for the 230kV transmission line and the data for the 500kV transmission line are provided by Arizona Public Service Electric (APS) and Salt-river project (SRP) respectively. Table 1 shows the parameters of those two transmission lines.

Table 1 Data for 230kV transmission line and 500kV transmission line

Parameters	230kV	500kV
Conductor		
Type	Cardinal, 954 KCM, ACSS	Chukar, 1780 KCM, ACSR
Stranding	54/7	84/19
Average Span, ft.	1000	1000
No./phase; spacing, in.	3, 18	2, 12
Suspension Strings		
Configuration	I	V
Insulator size, in.	$5^3/_4 \times 10$	$11^1/_2 \times 7$
No. strings/ phase	2	2
Lightning Protection		
No. shield wires	2	2
Material	Alumoweld	Alumoweld
Diameter, in.	0.385; 7 #8	0.385; 7 #8

Fig. 2 shows the geometrical features including the location of ground wires and phase conductors. Dotted lines represent the suspension insulators. The 230kV transmission line comprises a three phase double circuit (see Fig. 2 (a)) while the 500kV transmission line is a three phase single circuit (see Fig. 2 (b)).

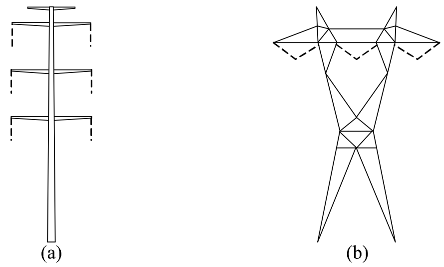


Fig. 2. Tower design and conductor arrangement

C. Transformer

The auto transformer used in this simulation is connected in star-star and has a rating of 533kVA as per the data provided by SRP. A high frequency transformer model, as shown in Fig. 3, must be used in the study of fast front transient. There are several detailed models which may include each winding turn and turn-to-turn inductances and capacitances. However, the model corresponding to each specific turn is not efficient for most applications due to computational complexity. A much simpler model can be obtained by using lumped capacitors and inductors.

In Fig. 3, C_{hg} denotes the distributed capacitance of the high-voltage windings; C_{lg} denotes the distributed capacitance of the low-voltage winding; and C_{hl} denotes the distributed capacitance between the high-voltage winding and low-voltage winding [16].

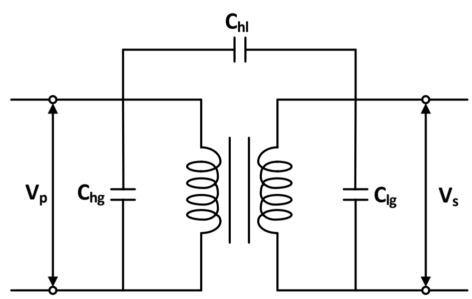


Fig. 3. High frequency model for transformer

D. Surge Arrester

The characteristics of the 500kV and 230kV surge arresters used in this paper are given in Table 2 and Table 3 respectively. The surge arrester type used in this system is SIEMENS 3EL2.

Table 2 Technical data for SIEMENS 3EL2 230kV surge arrester

3EL2	1/2 μs	8/20 μs				45/90 μs		
I(kA)	10	5	10	20	40	0.5	1	2
U(kA)	458	406	432	480	544	346	354	372

Table 3 Technical data for SIEMENS 3EL2 500kV surge arrester

3EL2	8/20 μs				45/90 μs		
I(kA)	5	10	20	40	0.5	1	2
U(kA)	930	989	1088	1187	801	821	860

U denotes the maximum discharge voltage. I denotes the peak current amplitude.

Four different surge arrester configurations are developed and investigated. These four configurations are:

- C1: No installed surge arrester on the substation
- C2: Two surge arresters are installed at the entrance of the substation and at the terminal of the transformer respectively.
- C3: One surge arrester is mounted at the entrance of the substation;
- C4: One surge arrester is installed on the terminal of the transformer.

The procedure used to analyse the effect of different surge arrester configurations on the substation is listed below:

(1) Designing the line section which comprises 10 spans of the 230kV transmission and the connected substation in PSCAD 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 at 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 also needs to be recorded.

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. In addition, the voltage-distance curve can help determine the best configuration that meets a specific lightning performance requirement.

III. SIMULATION RESULTS

It is explained in Section I that the worst case would occur when lightning hits the transmission line and causes line to ground fault, which is the focus of the simulations performed with PSCAD in this section of case studies.

Fig. 4 illustrates a simplified model for the transmission line and the substation. For simplicity, only phase B is depicted in Fig. 4.

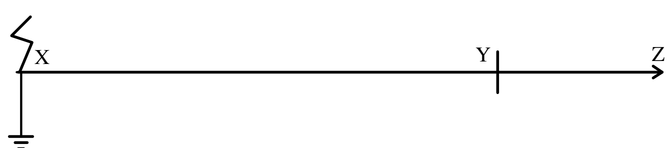


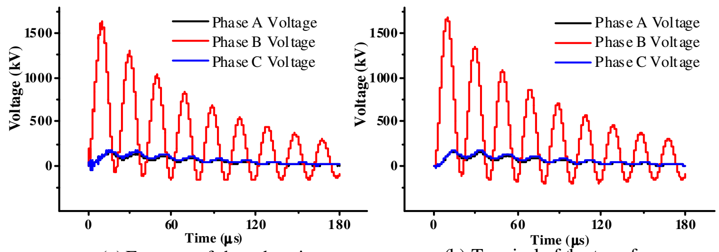
Fig. 4. Simplified model for the transmission lines and the substation

The point of the lightning stroke on the transmission line is denoted as Point X. Point Y is the 230kV line entrance of the substation. Point Z represents the 230kV terminal of the transformer, which connected to the substation.

For a specific stroke location, for instance, the distance from lightning stroke to the entrance of the substation is 200m. The simulation results are given in terms of plots of waveforms for the important variables such as arrester voltage, current, and energy duties. With configuration C1, the voltages at Point Y and Z over time is shown in Fig. 5.

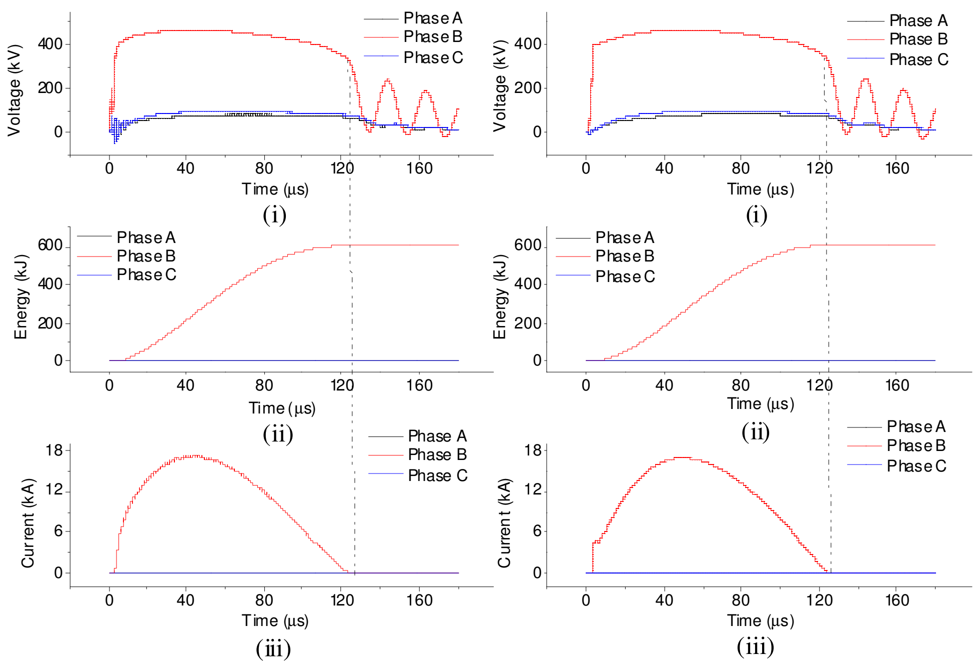
The oscillation in Fig. 5 may result from the transformer capacitors and inductors. Since there is no surge arrester in this system, the maximum voltage is over 1600kV that is much higher than the BIL value

(900kV). The equipment in the substation including circuit breakers, instrument transformers, and the transformer, may be in danger.



(a) Entrance of the substation (b) Terminal of the transformer

Fig. 5. Voltage at Point Y and Z for C1



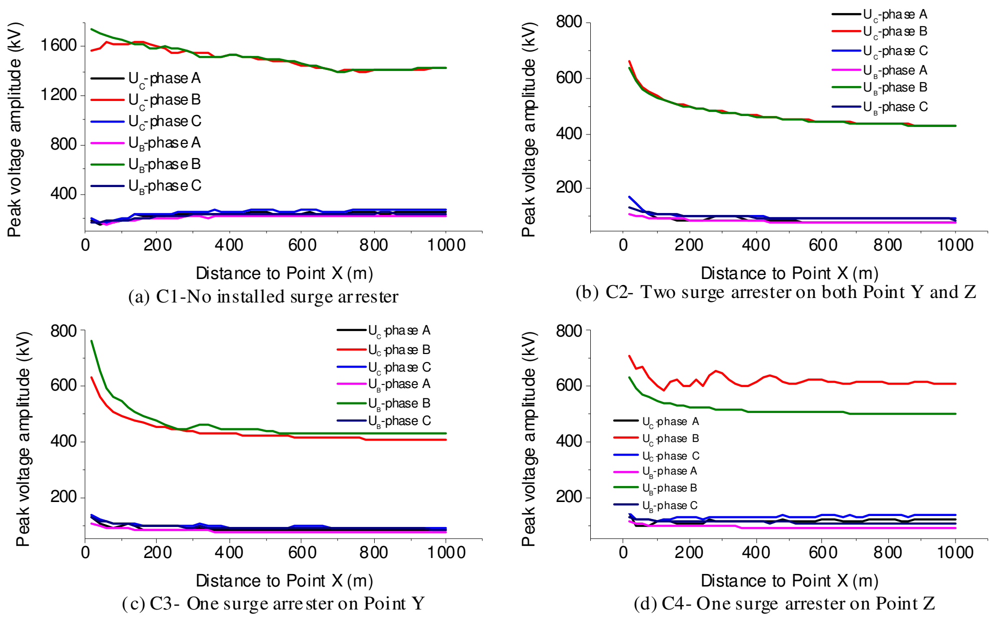
(a) Entrance of the substation (b) Terminal of the transformer

Fig. 6. Voltage and the surge arrester energy as well as the current at Point Y and Z for C2

Fig. 6 (a).(i) and Fig. 6 (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. 6 (a).(ii) and Fig. 6 (b).(ii) respectively. The currents flowing through the surge arrester are present in Fig. 6 (a).(iii) and Fig. 6 (b).(iii). In Fig. 6 (a).(i) and Fig. 6 (b).(i), the flat part of the voltage curves is caused by the surge arresters when the currents in the surge arresters drop down to zero (see the dash line in Fig.6). In other words, the surge arrester's impedance returns to infinity. 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 6. 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 with respect to the point which injected the lightning stroke on a 230 kV transmission line and the substation is studied using the voltage-distance curve in Fig. 7.

Fig. 7 illustrates that the trend of 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. In addition, for C4, the curve of the crest voltage is oscillating and thus 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

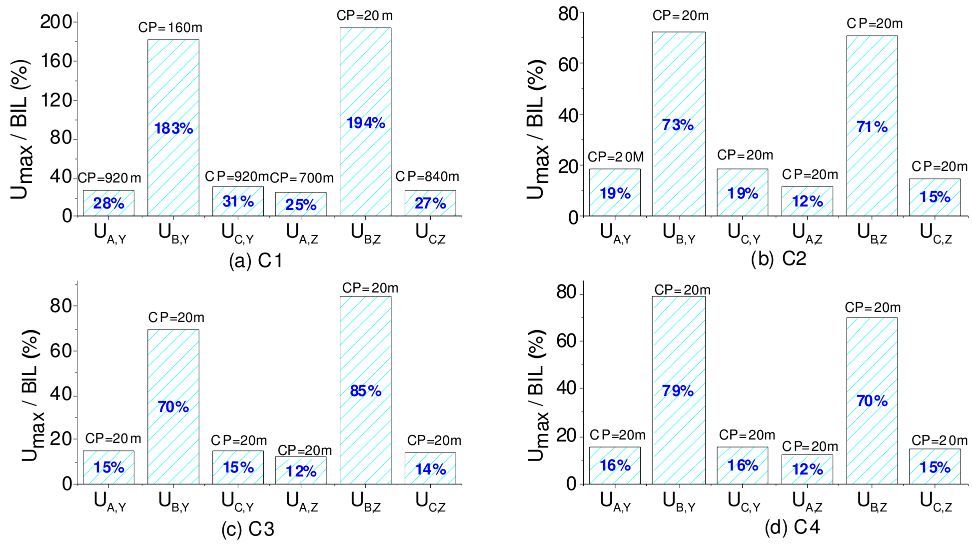
Fig. 7. The voltage-distance curve for all three phase of the Point Y and Z

Fig. 7 (a) shows the simulation results with C1. This is one of the cases which have a critical point. Fig. 8 (a) shows the difference of the maximum voltage of each phase on Point Y and Point Z with BIL value. The phase B voltage at the entrance of the substation and the terminal of the transformer exceed the BIL value and the system are in danger.

Fig. 7 (b) shows 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 on 0 m to 400m and then stabilize for the locations that are over 800m away from the entrance of the substation. From Fig. 8 (b), the maximum voltage at Point Y and 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 Z are the lowest among the 4 configurations.

Except for the voltage of C1, the maximum voltage at Point Z of C3 is the highest. The voltage at the terminal of the transformer (Point Z) is 85% of the BIL value. Since a transformer is a very vulnerable and expensive equipment in the power networks, a failure of a transformer can result in high cost due to repair or replacement and outage losses. Therefore, it is better to leave some margin for the peak voltage amplitude at the transformer terminal. Therefore, in terms of 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 while it is 79% in C4, which shows another advantage of C4 over C3.

Due to the mutual coupling effect, phase A and C have the peak voltage amplitude around 100kV. The voltages on phase A and phase C are far less than the voltage on phase B. In Fig. 8, it is clear that phase A and phase C voltages can only reach up to 31% of the BIL value. Therefore, the voltages of phase A and phase C are not shown in Fig. 9.



CP - critical point

Fig. 8. Ratio between the maximum voltage and the BIL value with the distance of the critical point

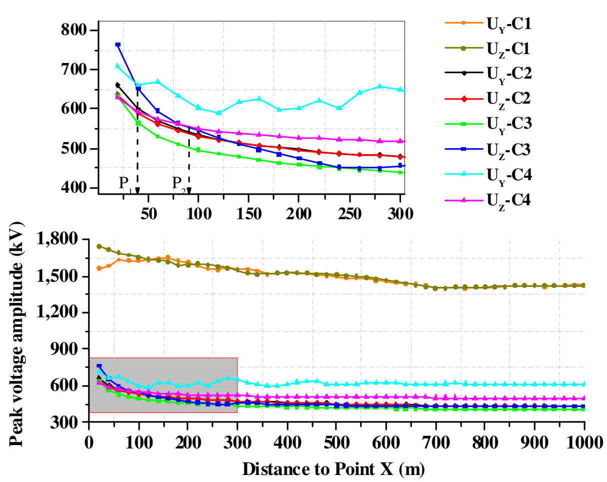
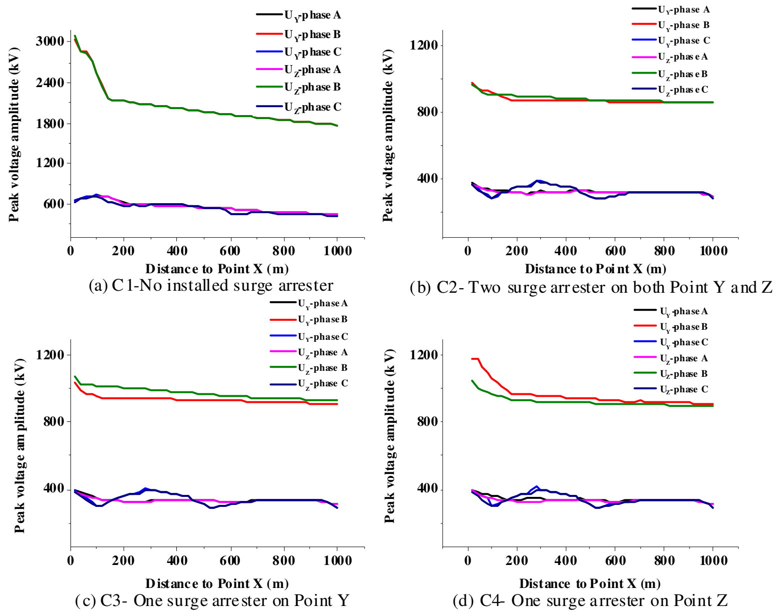


Fig. 9. Voltage-distance curve for Phase B at Point Y and Z

For C4, the peak voltage amplitude at Point Y is higher than the peak voltage amplitude at Point Z. However, the situation is the opposite for C3. Point P_1 is the intersection of the two curves U_Y-C4 and U_Z-C3. The difference between the peak voltage amplitude at Point Z in C3 and the Point Y in C4 is large at the beginning and gradually reduces to zero at the intersection Point P_1. Then the peak voltage amplitude at Point Y in C4 surpasses the voltage at Point Z in C3. After Point P_2, the curve of U_Z-C3 becomes even lower than the U_Z-C4. 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.

The simulation for the 500kV substation is also performed. The procedures of obtaining the voltage-distance curve is the same as the 230kV substation. Moreover, Fig. 10 is similar to Fig. 7, which shows that the characteristic of lightning performance for different surge arrester configurations under different voltage levels is almost the same.



(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. 10. The voltage-distance curve for all three phases of the Point Y and Z of 500kV substation

IV. CONCLUSIONS

The primary objective of this study is to examine whether only installing arrester at the terminal of the transformer can effectively protect the 500-230kV substation.

By analysing the performance of four different configurations in terms of the location of surge arresters, appropriate parts of a 230kV transmission line as well as the 500-230kV substation are modelled using PSCAD. The model uses the real line data and is used to simulate the effect of lightning stroke hitting at different location on the transmission line.

The voltage-distance curve is proposed to evaluate the effectiveness of the lighting 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, the high installation cost of the surge arrester makes it less competitive. Moreover, the other two configurations which have surge arrester installed either on the entrance of the substation or on 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 the voltage up to 85% of the BIL value. 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 for installing the surge arrester 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 withstand capability. In terms of the economic impact, the failure of the transformer can result in high cost due to repair or replacement costs and outage losses. To ensure 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 Rudd 500-230kV substation by SRP is proved to be both adequate and efficient with respect to both the lightning performance and the economic cost.

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