Insulation Coordination Study of 275kV AIS Substation in Malaysia

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Abstract- **Over voltages are phenomena which occur in power system networks, either externally or internally. The selection of certain level of over voltages which are based on equipment strength for operation is known as insulation coordination. A study has been carried out to investigate over voltages due to lightning, which is affecting an air insulated substation (AIS). The objective of this study is to determine whether the withstand capability or the Basic Insulation Level (BIL) is the cause of fault occurring in a substation.**

Index Terms- **Over voltages, PSCAD software, Bergeron model, Frequency dependent model**

I.INTRODUCTION

Malaysia has a very high number of thunderstorms per year, at 220 days per year and recorded flash density of 20 flashes per km per year. This typically causing Malaysia to experience over voltages due to lightning strikes. Lightning over voltages are caused by a back flashover when it strikes towers [1].

Whilst shielding failure occurs when lightning strikes of less or equal to 20 kA bypass overhead shield wires, back flashovers occur when lightning strikes the tower or the shield wire. The resultant tower top voltage becomes large enough to cause flashover of the line insulation from the tower to the phase conductor. Induced over voltages in the phase conductor due to strokes to ground in a close proximity may also happen but they are generally less than 200kV [1] and is significant for lower voltage systems. The minimum transmission voltage in Malaysia is 132kV and the BIL is 650kV.

In the simulation in this work, only back flashovers are evaluated, excluding induced over voltages or shielding failures. The reason is lightning current in Malaysia is typically more than 20kA. Transient over voltages may also be caused by switching operations but for voltages lower than 300kV, problems correlated with operating switches do not occur [2]. Many power utilities have carried out similar insulation coordination studies on their installations [3, 4, 5]. This paper presents a study on the effects of insulation coordination in 275kV AIS at North Substation in Kuala Lumpur city, Malaysia.

The objectives of this study are:
i) To perform an over voltage assessment of air insulated substation (AIS) due to lightning surge.
ii) To calculate basic insulation level for AIS substation equipment.

II. MODELLING

The overall substation models are derived from the substation layout drawings, which is based on the models in [6]. The interested area is the transmission line models because they are the main component in the simulation model. The components which are related to transmission line are towers, conductors and AIS substations. Three models are available in PSCAD but only the Bergeron and the frequency dependent (phase) models will be implemented because the frequency dependent (mode) model is not suitable for modelling of multiphase and untransposed transmission lines. The incoming 275kV double circuits are placed on a quadruple circuit tower and132V double circuit towers. However, in this study only the 132kV quadruple circuit towers will be used.

The overhead lines are represented by multi-phase model because the distributed nature of the line parameters due to the range of frequencies involved. Phase conductors and shield wires are modelled in detailed between the towers. Only back flash is considered since the shielding angle is zero and the current magnitude is greater than 20kA [1]. For back flash, the initial line voltage and polarity are of importance. Thus, a custom model for the effect of power frequency is included in the model. The variation of the tower footing resistance with the soil ionization is also considered.

A. Tower Modelling

The towers are modelled as a single conductor distributed parameter line (Bergeron model travelling wave) segments of transmission lines in PSCAD. The tower model is constructed geometrically similar to that of the physical tower. The tower is terminated by a resistance which represents the tower footing impedance. For the insulator strings, it is modelled as a capacitance in parallel with a circuit breaker across a gap. If there is a back flash, it is simulated by closing the circuit breaker (green changes to red colour). Part of the tower model that has been developed is shown in Fig. 1.

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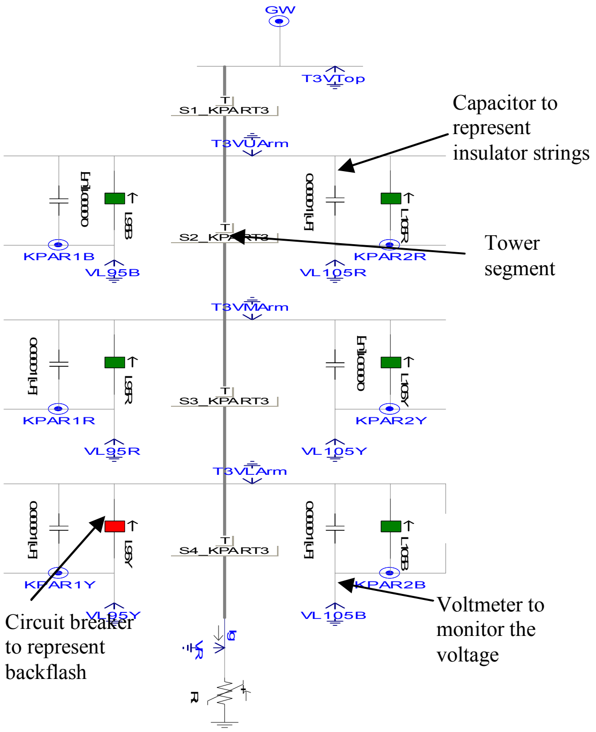

Figure 1. PSCAD Tower Model

The overhead line is modelled in detailed in PSCAD to simulate the flashover occurrence which depends on power frequency. Fig. 1 shows the line configurations drawn in PSCAD simulation model for the circuit entering a substation. When using the frequency dependent (phase) model, conductor geometries such as conductor dimensions, spacing, bundling, heights and so on are necessary since they determine the frequency dependent surge impedance and propagation characteristics. When using the Bergeron model, since the line parameters are constant at the chosen frequency, a user can enter the R, L and C values manually. The overhead lines are modelled with the Bergeron Model and the Frequency Dependent (Phase) Model to compare the difference in the surge voltage between these two models. Three spans of 300m each are modelled and the third span is taken as an infinite line to represent no reflection from the distant end.

1. Power Frequency Effect

In addition to the voltage caused by the lightning strike, the system voltage at power frequency is added or subtracted to the actual voltage across the insulator, depending on the quadrant of the system voltage sine wave when strike on the ground wire occurs. To account for this effect, a custom module '*power frequency effect*' is added to the leader progression model, which calculates the effective voltage to determine if a back flash occurs across the insulator string.

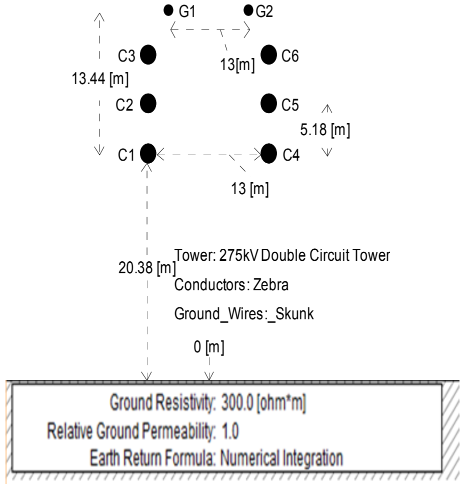

Fig.2. 275kV double-circuit tower in Kapar city, Malaysia

2. Line Insulator Flashover

There is a wide variety of lightning stroke characteristics and the modification effects of the power system components on the impinging current surges stress. The insulation is structured with a variety of impulse voltage shapes. A traditional model for insulator flashover uses the measured volt-time curve, which have been determined empirically for a specific gap or insulator string by using the standard 1.2/50 µs wave shape. However, since the insulator string is subjected to non-standard impulse wave shapes, the empirical volt-time curves bear little resemblance of the physical breakdown. A better model is the leader progression model, which is described in the next part.

3. Leader Progression Model

In leader progression model, the discharge development consists of corona inception, streamer propagation and leader propagation. When the applied voltage exceeds the corona inception voltage, streamers propagate and cross the gap after a certain time if the voltage remains high enough. The streamer propagation is accompanied by current impulses of appreciable magnitude. When the streamers have crossed the gap, the leaders are developed to a significant extent. The leader velocity increases exponentially. When a leader bridges the insulator gap, breakdown occurs.

Back flash occurs when the voltage is higher than the line critical flashover (CFO) voltage across the insulator string. It is used as a condition to determine whether the current leaders have formed or not. The calculation procedure consists of determining the velocity at a time instant, the extension of the leader for a time instant and the total leader length. This value is subtracted from the gap spacing to calculate a new value of x. This process is continued until the leader bridges the gap. When this happens, the breaker closes to indicate that a back flash has occurred.

4. *Tower Footing Resistance*

High magnitude of lightning current, which flows through the ground resistance, reduces the resistance significantly below the low-current values. When the gradient exceeds a critical gradient E_0, breakdown of the soil occurs. When the current increases, streamers are generated, evaporating the soil moisture and producing arcs. Within the streamer and arcing zones, the resistivity decreases from its original value. When the limit approaches zero, it becomes a perfect conductor. In the TFR model, the user inputs are E_0 and R_0 (the DC resistance). The model then calculates the effective resistance of the ground rod, using the IEEEstd 80 2000 formula. Fig. 3 shows the decrement of resistance from 50 Ω at low frequency to $R_i < 15\ \Omega$ during the strike. This has been proven by calculation of $E_0 = 400$kV/m, $R_0 = 50\Omega$, $\rho = 300\Omega$m, $I_R = 100$kA at peak, yielding $R_i = 13.3\ \Omega$.

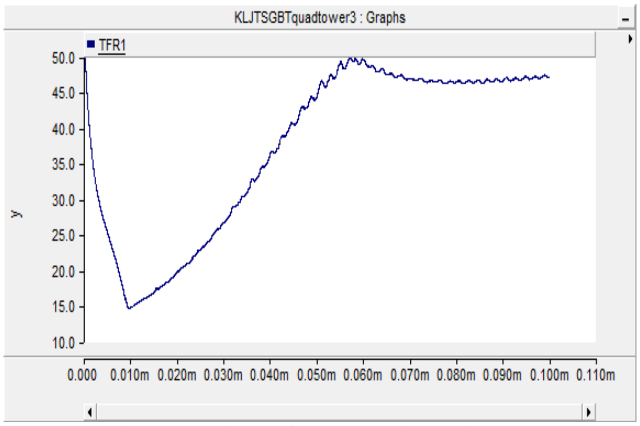

Figure 3. Variance of Tower Footing Resistance

5. *Concave wave shape*

The triangular wave shape is very simplistic. For a more realistic representation, the CIGRE concave wave shape provides more realistic results. Fig. 4 shows the concave wave shape characteristics. If I is the crest current, S_m is the maximum front steepness and t_f is the equivalent front duration. For the front current, the wave shape can be expressed by:

$$I = At + Bt_n \tag{1}$$

B. Substation Modelling

The overall substation models are derived from the actual substation layout. A site visit was made to obtain the arrangement of the circuit bays and for the measurements of length and diameter of the AIS equipment.

1. *AIS Substations*

Most of the substation elements can be modelled by surge capacitances. The simplest substation model is by representing only the power transformer surge capacitance and neglecting the bus works and conductor elements. Other elements such as capacitive voltage transformer and current transformer are considered. For the best precision, the entire substation elements are modelled. These elements are also modelled by surge capacitances. The IEEE modelling and Analysis of System Transient Working Group (WG) have recommended such as guidelines to determine the value of these input parameters. However, these input parameters are always determined by voltage level in the substation.

In the PSCAD simulation model, the Bergeron model with reflection option enabled is used to represent the air insulated bus works and the overhead lines. The Bergeron model represents the L and C elements of a PI section in a distributed manner and is accurate only at a specified frequency. Transmission lines are recommended to be modelled at 500kHz for lightning studies to account for the skin effect [14]. The simulation is repeated with the overhead lines using frequency dependent (phase) model to compare any difference in the results.

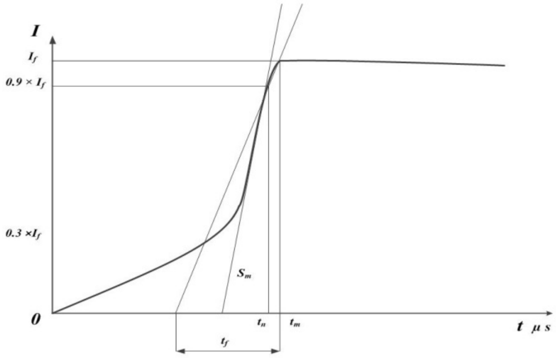

Figure 4. CIGRE concave shape

2. *Bergeron model parameters*

In the following Bergeron input parameter model, the values of R, travel time, surge impedance can be entered manually. For short distances, the line is considered as reflection to enable reflections for a more accurate simulation of over voltages due to reflections at impedances change or discontinuities. The travel time interpolation is set to be ‘on’ because of the short lengths.

3. *Spacers*

According to [2], the influence of spacers supporting the conductors can usually be neglected. However, in this case, additional capacitances of 20pF for the spacers are accounted.

4. *Circuit breakers and disconnectors*

Circuit breakers in a closed position are modelled using PSCAD as a path of low resistance. In an open position, a capacitance of 10pF is placed across the contacts of the circuit breaker and disconnector, as shown in Fig. 5.

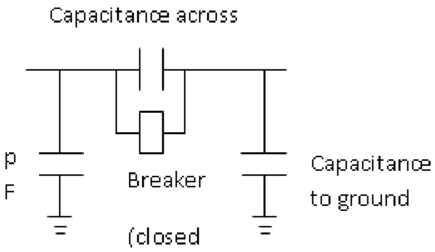

Figure 5. Circuit Breaker and Disconnector Representations

5. Surge Arresters

The Metal Oxide Surge Arrestor is modelled as a non-linear resistor in series with a variable voltage source in the PSCAD library. Interpolation technique is used for switching between linear parts of the *I-V* characteristic for the best accuracy. The user may enter the *I-V* characteristic directly and read the *I-V* data from an external file. In this simulation, the *I-V* data is entered directly. The data to be entered is the maximum discharge in p.u. for the 8/20 µs current wave.

III.SIMPLIFIED METHOD CALCULATION

A simplified method is suitable for obtaining an approximation of BILs for a simple station. It can also be used to obtain initial estimations for a more complex station and the data can be used for comparison with a computer simulation (PSCAD simulation).

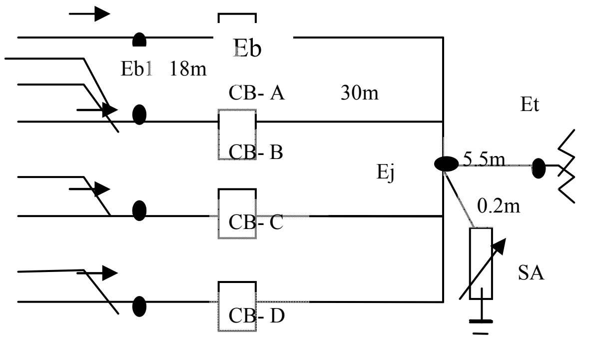

Figure 6. Single-line diagram of a 275kV station, four-line station

The IEEE standard recommends that a more conservative value of the surge amplitude, *E* is 1.2CFO. The CFO for 275kV is 1587 kV.

The incoming surge, E = (1.2)(1587) =1904kV

Number of incoming line = 4

$$d_m = \frac{1}{n(MTBF)(BFR)} = \frac{1}{4(100)(2/100)} = 0.125km$$

Thus, the distance of one increased span lengthis0.3 km.

$$S = \frac{Ks}{d} = \frac{1000}{0.3} = 3333.33kV/uS$$

$$VPF = 275\frac{\sqrt{2}}{\sqrt{3}}(0.83) = 186.4kV$$

$$R_A = \frac{E_{A2} - E_{A1}}{I_{A2} - I_{A1}} = \frac{732kV - 689kV}{10kA - 5kA} = 8.6\Omega$$

$$E_0 = Ed - I_A R_A = 689 - (5)(8.6) = 646 \text{ kV}$$

The line surge impedance is calculated by

$$Z = 60In\frac{2h}{r}$$

If h = 30.74 m and r =0.01431 m, Z = 502 Ω.

The arrester current is calculated by

$$I_A = 1.6\frac{\frac{2E}{n} - Eo - V_{PF}}{\frac{Z}{n} + R_A} = 1.6\left(\frac{2x\frac{1904}{4} - 646 - 186.4}{\frac{502}{4} + 8.6}\right) = 0.892kA$$

The arrester voltage is calculated using

$$Ed = Eo + I_A R_A = 646 + (0.892)(8.6) = 653.67kV$$

$$E_A = Ed + V_{PF} = 653.67 + 186.4 = 840kV$$

When the distance from the junction to surge arrester is 0.2 m and the distance from junction to transformer is 5.5 m,*T*= *d*/*v,* where *d* is the distance and *v* is the velocity of light.

$$K_1 = \frac{S(T_T + T_A)}{E_A} = \frac{3333.33(0.0183 + 0.00067)}{840} = 0.0753$$

The constant A and B for 4 line is 0.68 and 0.25.

$$\frac{E_T}{E_A} = 1 + \frac{A}{1 + \frac{B}{K1}} = 1 + \frac{0.68}{1 + \frac{0.25}{0.0753}} = 1.1574$$

Surge voltage at the transformer, T_x:

$$E_T = 1.1574(E_A) = 1.1574(840kV) = 972.22kV$$

Voltage to ground at T_x:

$$E_t = E_T - V_{PF} = 972.22kV - 186.4kV = 785.82kV$$

Arrester voltage at bus-junction for the transformer,

$$K_2 = \frac{ST_A}{E_A} = \frac{3333.33(0.00067)}{840} = 0.00266$$

$$\frac{E_J}{E_A} = 1 + \frac{A}{1 + \frac{B}{K_2}} = 1 + \frac{0.68}{1 + \frac{0.25}{0.00266}} = 1.0072$$

$$E_J = 1.0072(840kV) = 846kV$$

$$E_j = E_J - V_{PF} = 846kV - 186.4kV = 659.6kV$$

For others equipment which are not on transformer bus,
Incoming surge with n =1

$$d_m = \frac{1}{n(MTBF)(BFR)} = \frac{1}{1(100)(2/100)} = 0.5km$$

Thus, the distance of increased two span length is 0.6 km.

$$S = \frac{Ks}{d} = \frac{1000}{0.6} = 1666.67kV/\mu S$$

$$K_2 = \frac{ST_A}{E_A} = \frac{1666.67(0.00067)}{840} = 0.00133$$

$$\frac{E_J}{E_A} = 1 + \frac{A}{1+\frac{B}{K_2}} = 1 + \frac{0.68}{1+\frac{0.25}{0.00133}} = 1.0036$$

$$E_J = 1.0036(840kV) = 843.02kV$$

$$E_j = E_J - V_{PF} = 843.02kV - 186.4kV = 656.62kV$$

The voltage at circuit breaker,

$$E_B = E_J + 2ST_B = 843.02kV + 2(1666.67)(0.1) = 1176.35kV$$

$$E_b = E_B - V_{PF} = 1176.35kV - 186.4kV = 989.95kV$$

The voltage at station entrance,

$$E_{B1} = E_J + 2S(T_C + T_B) = 843.02kV + 2(1666.67)(0.06+0.1) = 1376.35kV$$

$$E_{b1} = E_{B1} - V_{PF} = 1376.35kV - 186.4kV = 1189.95kV$$

IV.RESULTS AND DISCUSSIONS

Simulations have been performed for different overhead line models, lightning impulse wave shapes and frequencies (for Bergeron models). A time step of 0.005 µs is used for the minimum length of 1.5m in the AIS segments. The total simulation time is 100 µs. In this simulation, the Bergeron model is used for the overhead lines and the AIS. The simulation parameters chosen are

i) Frequency 500 kHz as recommended in [6].
ii) The impulse wave shape is concave with amplitude of 100kA, time to half of 75µs, and front time of 4.5 µs as calculated using the log normal distribution.
iii) The strike to the conductor at tower 1 of 275kV double-circuit tower is causing back flash since *I*> 20kA (back flash domain as per [4]).
iv) The tower footing resistance is 10 Ω at low frequency.
v) The power frequency effect is 270° phase shift.

TABLE I. CASE STUDY RESULT

Voltage for 100 years	Simplified calculation (kV)	PSCAD Simulation (kV)
Eb(V95)	989.95kV	979.1kV
Eb1(Vkp1)	1189.95kV	1166kV
Ej(Vsat3)	659.6kV	597.3kV
Et(Vt3)	785.82kV	600.7kV

Table I summarises the study with various injected lightning current. The injected lightning current from 50 kA shows that all results agree to the simplified method calculation. The BIL of 275kV transformer is 1050 kV, hence all case studies above results in the transformer overvoltage below the transformer BIL. The surge arrester installed near to the transformer protects the transformer from failure during lightning strike**.**

Fig. 7 to Fig. 10 shows the voltage waveform obtained from the simulation at various substation equipments.

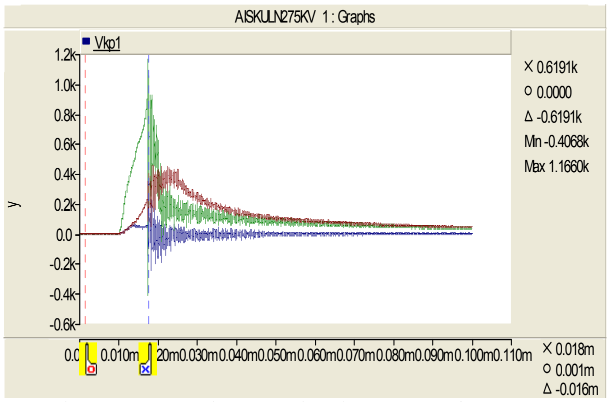

Figure 7. Surge voltage at Substation Entrance for KPAR1

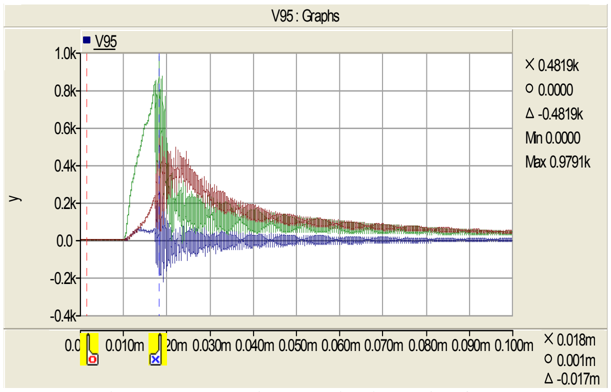

Figure 8. Surge voltage at Circuit Breaker for KPAR1

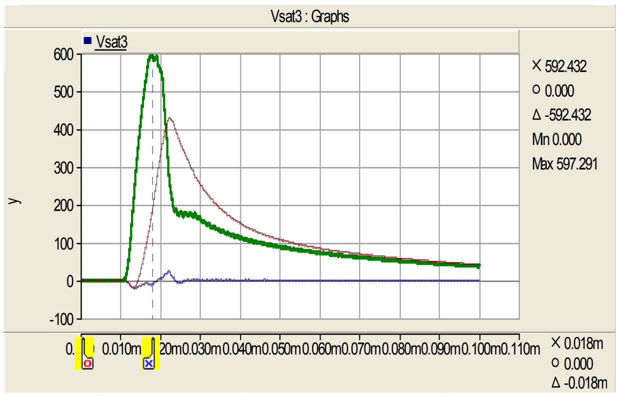

Figure 9. Surge voltage at Surge Arrester for T_xNo.3

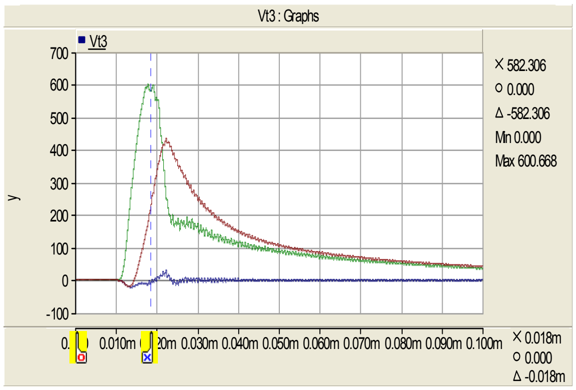

Figure 10. Surge voltage at T_x No.3

Table II summarise the simulation studies with various current magnitude on the actual transmission substation 275 kV in KL.

TABLE II. SELECTION OF BIL FOR FOUR OVERHEAD LINE STATION

Equipments	**Voltage**	**Crest, kV**	**Req'dBIL, kV**	**Selected BIL, kV**
Transfomer	E_t	821.5	950	1050
Breaker	E_b	860.82	950	1050
Disc. Switch	E_b	860.82	950	1050
Bus Support Insulator	E_{b1}	1034.7	1050	1050

V. CONCLUSION

From the simplified method and PSCAD simulations, the following conclusions can be drawn:

a) Multiple lines in a station provide the benefit of reducing the surge crest voltage and front steepness. However, these lines collect more surges, and therefore an incoming surge with a larger steepness is required. The two combating features tend to compensate each other. As shown in the simulation result, the voltages at transformer tend to increase slightly for multi-line stations but the voltages at other locations tend to decrease.

b) In general, the voltage ahead of the arrester, i.e. at the transformer, is greater than the voltage behind the arrester. The arrester provides better protection behind it than ahead of it, except for the maximum attainable voltage.

c) The simplified method can be used to estimate the initial voltages in more complex stations.

d) The voltages calculated by the simplified method and those obtained using PSCAD simulation show that all calculated voltages are greater than those from PSCAD by 1 to 30%. The calculated transformer voltage is 25 to 30% greater than those obtained using PSCAD.

e) The highest crest voltage is 1034.7 kV at the entrance of the substation. Thus, the highest BIL for substation is 1050kV. For 275kV north substation in Kuala Lumpur city, the BIL selected for transformer is 1050kV.

f) From the simulation results, the over voltages show that all results are below the BIL value of substation equipment (1050kV). The placement of surge arrester at the entrance of the substation could be dealt with. The voltage level within safety range can be maintained even though a high current is injected. When both arresters are placed at the entrance of the substation and nearby, the service of the transformer is crucially needed in order to optimize the substation performance in term of reliability and cost effective.

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