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Earthing Resistance Impact on Fast Front Back-Flashover of a 25 kV Traction Feeder Station

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Abstract: Lightning stroke on a tower structure is one of the major reasons which results in high induced voltages at tower arms due to the excessive lightning current flowing through the tower to earth. If this induced Lightning stroke on a tower structure is one of the major reasons which results in high induced voltages at tower arms due to the excessive lightning current flowing through the tower to earth. The worst case is to have this induced voltage on the first tower close to a substation. If it is higher than the withstand level of insulator string, the insulation of substation' equipment will be exposed to transient overvoltage (fast front back-flashover (FFBF)). The peak of this transient overvoltage is affected by the value of system earthing resistance. This paper studies the effect of surge arrestor (SA) earthing resistance and the footing resistance of 1st tower adjacent to a 25 kV traction feeder station on FFBF. Three case studies using PSCAD/EMTDC software are presented to simulate the back-flashover with variable earthing resistances at the 1st tower footing and SA. The paper also addresses the critical earthing resistance for designing an economic protection system for solving the problem of transient overvoltage produced due to fast front back-flashover. This study proves that the proper design of a grounding system for the first tower and SA not only enhances the safety of the system but it also minimizes the construction cost of the grounding system

Keywords: Back-flashover; Insulation Coordination; Fast Front Transient Study; 25 kV Traction Feeder; Footing Resistance; Lightning Impulse Withstand Voltage; PSCAD/EMTDC.

I. INTRODUCTION

Fast Front Back-Flashover (FFBF) is an effective phenomenon across the insulator. It occurs when a fast front time lightning stroke hits an OHTL sky wire or overhead tower. The high-current flowing through the tower surge impedance and footing resistance produces a transient overvoltage on this tower [1]. If the voltage across the tower insulator exceeds the insulator voltage withstand capability, a back-flashover will occur causing a significant overvoltage on the power line. If the resulting overvoltage at the equipment exceeds the BIL of installed equipment, it is likely that insulation damage will happen [2]. In the past decades, railway electrification has constantly increased because it offers substantially better energy efficiency and lower emissions. Also, Electric locomotives are usually quieter and more powerful. By 2012, electrified tracks account for nearly one-third of total tracks globally [3]. The most severe condition in the traction electrification network is the overvoltages produced by lightning strokes on their electrical lines. The insulation strength of any equipment must be selected to avoid damage in case of overvoltages related to lightning strikes. The occurred overvoltage includes Fast Front Overvoltage (FFO), switching actions (Slow Front Overvoltage (SFO)) or the phenomena related to fundamental frequency overvoltages (Temporary Overvoltage (TOV)). A suitable surge arrestor should be designed and located properly to avoid exceeding the Basic Insulation Level (BIL) of equipment [4].

The effect of earthing resistance on fast front back flashover study has been conducted by some researchers. The striking current and the tower footing resistance values required to make back flashover on the tower insulators are determined in [4-5]. According to these references, if the magnitude of lightning stroke is more than 50kA, the back flashover on the tower insulators will occur whatever the value of the tower footing resistance. Reference [6] stated that the induced voltage is inversely proportional to the striking distance. It is noticed that the induced voltage magnitude decreases with increasing striking distance. Its highest value is at the point nearest to the lightning strike point. The back flashover across phase insulator string increases with the fast front time of lightning stroke current. The use of counterpoise wires decreases the transient overvoltage at tower insulator and at tower footing. The influences of the length of counterpoise earth wire are studied in [7]. The propagation of lightning surge is analysed with the variation of tower footing resistance in [8]. The proper design for the tower footing resistance was found to be maintained between (5-6) Ω to avoid the electrical stresses on both the power line insulation and surrounding structures [8]. In [9], installing guard wires on the transmission lines was found to be insufficient to protect system against lightning stroke. Therefore, towers footing resistances should be decreased. Otherwise, the under study substation is not safe against lightning stroke. Reference

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[10] described the factors affecting the back flashover across insulator in a transmission system. Parameters of this study focused on magnitude of lightning stroke current and front/ tail times of lightning stroke impulse.

The achievement of low values of earth resistance is an essential requirement, since a good grounding system reduces considerably the corresponding insulation breakdowns, however, very low grounding resistance values may result to increasing probabilities for surge arresters' damage due to energy absorption capability [11]

Most of existing techniques are interested in controlling the back flashover by variation the tower grounding system. Some researchers studied the impact of peak and front time of lightning current, and striking distance on the induced overvoltage.

The proposed study is applied on a 25 kV traction feeder for the following reasons:

- Due to its low nominal voltage, the corresponding basic insulation level (BIL) for its components is also relatively low and hence, the study of overvoltage due to lightning extremely become importance.
- The lower the system voltage, the higher the probability of a back flashover occurs [4].
- FFO is very critical, when the system voltage is below 245 kV [12].

In this paper, only the earthing resistance impact of both SA and the first tower adjacent to the substation on FFBF is studied. The first tower is selected as it represents the worst case for the substation insulation when the lightning stroke strikes it. The magnitude of lightning stroke current is increased to 190 kA compared to 50 kA used in previous studies. The tower footing resistance is selected to be 15 Ω instead of 5-6 Ω.

This study proves that the proper design of a grounding system for the first tower and SA is not only enhance the safety of the system but also reduce the construction cost of the grounding system to minimum.

The benefits and key contributions of the proposed study can be summarized as follows:

1. S.A earthing resistance is one of the most important factor affect the result of the induced voltage due to fast front back-flashover
2. Enhancement of earthing resistance for 1st adjacent tower to the substation shall reduce the induced overvoltage on the power line due to a back-flashover with no need to enhance the other footing resistance of other towers.
3. As most practical cases, the 1st tower shall be at a short distance to the substation and the substation earthing system is permanently low, so it is highly recommended to connect between the earthing system of the 1st tower and substation earthing system. This shall be the most techno-economic solution to reduce the induced overvoltage due to back-flashover and protect the substation apparatuses.

The organization of this paper is presented as follows:

- The power system modelling is introduced in Section II,
- The modelling back flashover is described in Section III,
- Case studies and the simulations results are illustrated in Section IV, and
- The conclusions are presented in Section V.

II. POWER SYSTEM MODELLING

The accuracy of the transient overvoltages calculation depends largely on the accuracy of the modelling method of each component in the power system. During fast front back-flashover and due to the high current and frequency values, the power system components must be modelled with their capacitances to ground, surge impedance and velocity of propagation values [13]. This section encompasses the modelling of each power system component during the FFO.

A. Modelling of Phase Conductors and Tower

The transmission line has been considered in performing fast transient studies. The line consists of two conductors, one contact conductor and one return conductor. The traction system sections and spans are modelled using the frequency dependent model in PSCAD [14].

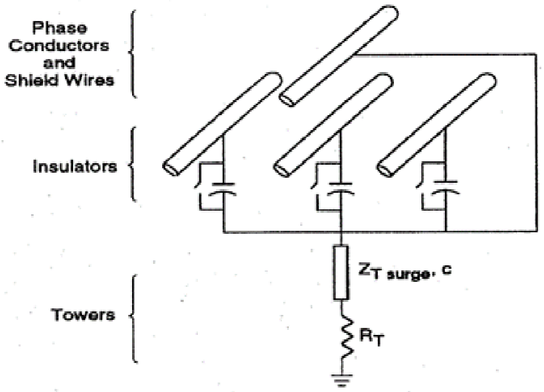

Fig.1 Overhead Transmission Line and Tower with its Insulators

Figure 1 shows the model of the used tower and transmission line [15].The surge impedance of the tower depends on the structure details, and it is calculated according to the procedure outlined in [16-17]. Formulas to calculate this parameter is shown in [18-20]. Typical values ranges from (100 – 300) Ω. The velocity of propagation can be assumed to be equal to the speed of light [15]. In this paper, the surge impedance of the tower is assumed to be 150 Ω.

B. Modelling of Tower Footing Resistance

The tower footing resistance is not a constant for fast front surges and varies with the surge current magnitude. This is due to the soil ionization and breakdown characteristics of the soil surrounding the tower earth electrodes. At a certain surge current magnitude, the voltage gradient exceeds a critical value. This causes soil breakdown thereby forming conductive paths for current flow. Therefore, the tower footing resistance for fast front surges is less than that measured at low current and low frequency. The current dependence of the tower footing resistance is represented by the following formula, equation (1) [21]:

$$R_i = \frac{R_O}{\sqrt{1+\left({}^{I_R}\!/_{I_g} \right)}} \tag{1}$$

Where;

R_0 = the measured tower footing resistance at low current and low frequency (Ω)
R_i = tower footing impulse resistance (Ω)
I_g = limiting current to initiate sufficient soil ionization (kA)
I_R = lightning current through the footing resistance (kA)

The limiting current is a function of soil ionization and is given by equation (2) [21]:

$$I_g = \frac{1}{2\pi}\frac{E_O \rho}{R_O^2} \tag{2}$$

Where;

ρ = soil resistivity (Ω.m) and can be considered about 800 Ω.m
E0 = soil ionization gradient and can be considered about 400 kV/m

The first ~~tower~~ footing resistance shall be modelled by impulse resistance instead of the measured low frequency footing resistance.

C. Modelling of Line Insulators

The composite insulators between the tower and the phase lines conductors are represented as capacitors in the model. Capacitance of a composite insulator unit is typically around 10 pF. Hence, each line insulator is represented with an 80-pF capacitor in the PSCAD model [14].

D. Modelling of Surge Arrester

The SAs can be represented by two methods; simplified IEEE prepared by Pinceti Model and IEEE frequency-dependent model as shown in figures 2.a and 2.b, respectively [22-23]. The frequency dependent model for the SAs in the system is used in this paper. As shown in figure 2.b, the two nonlinear resistors A0 and A1 are separated by an RL filter. For the slow front surges (SFS) (e.g. switching surges), the impedance of the RL filter becomes very low and hence the two nonlinear resistances act in parallel. For the FFS (e.g. lightning surges), the impedance of the RL filter becomes significant and as result, more current flows in the nonlinear resistor A0 than in A1 [14].The inductor L0 in the models represents the inductance associated with magnetic fields in the immediate vicinity of the arrester. The resister R0 is used to stabilize the numerical integration when the model is implemented on a digital computer program. Capacitor C represents the terminal-to-terminal capacitance of the arrester. The inductance L1 and resister R_1 of the models represent the filter between the two non-linear resisters [24]. The most important characteristics of these models are that their parameters are calculated from electrical data. The details of surge arrester frequency dependent model parameters have been presented by equation (3):

- $L_1 = 15\ d/n$ (μH)
- $R_1 = 65\ d/n$ (Ω)
- $L_0 = 0.2\ d/n$ (μH) (3)
- $R_0 = 100\ d/n$ (Ω)
- $C = 100\ n/d$ (pF)

Where d: is the estimated height of the arrester in m (assumed to be 0.5 m).
n: is the number of parallel columns of metal oxide in the arrester (assumed to be 1).

The nonlinear resistors A0 and A1 can be modelled as a piecewise V-I curve with characteristics defined point by point. The V-I characteristics of A0 and A1 are chosen to be the same as mentioned in [25].

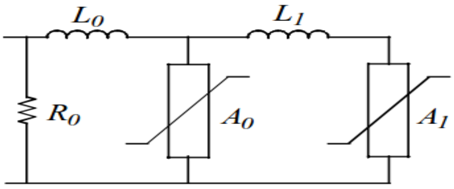

Fig. 2.a Simplified IEEE prepared by Pinceti.

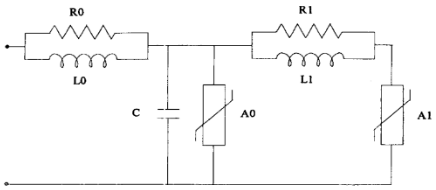

Fig. 2.b IEEE Frequency-Dependent Model.

E. Modelling of Voltage and Current transformers

The voltage and current transformers are simulated by their stray capacitance to ground which chosen to be 500 pF and 250 pF, respectively [14-15].

F. Modelling of Disconnecting Switch

The disconnecting switch is simulated by its stray capacitance to ground. The capacitance-to-ground is chosen to be 100 pF [14-15].

G. Modelling of Bus-Bar Support Insulator

The Bus-Bar support insulator is simulated by its stray capacitances to ground. The capacitance-to-ground is chosen to be 80 pF [14-15].

H. Modelling of Circuit Breaker

The circuit breaker is simulated by its stray capacitance to ground. The capacitance-to-ground value range is from (50 - 100) pF [14-15].Figure 3 shows the circuit breaker model and minimum capacitance values used in lightning studies for different types of substation equipment, when the actual data is not available. If the disconnector switches or circuit breakers have more than one support, appropriate capacitances should be added to the model [15].A 600 μΩ circuit breaker contact resistance is also added during the circuit breaker pole closing position.

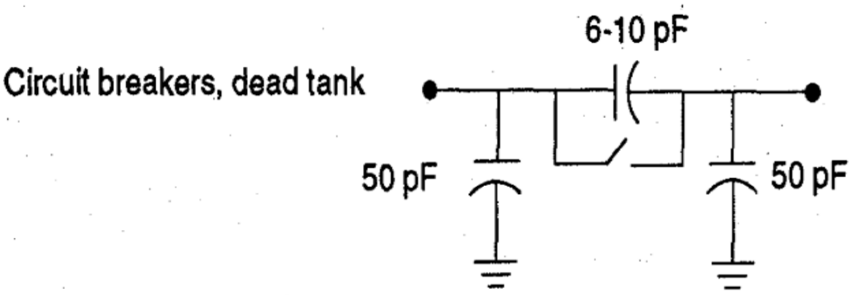

Fig. 3 Circuit breaker stray capacitance

Figure 4 shows one switchgear bay includes bus-bar, disconnecting switch, circuit breaker, current transformer, voltage transformer and SA as simulated in the PSCAD/ EMTCD model.

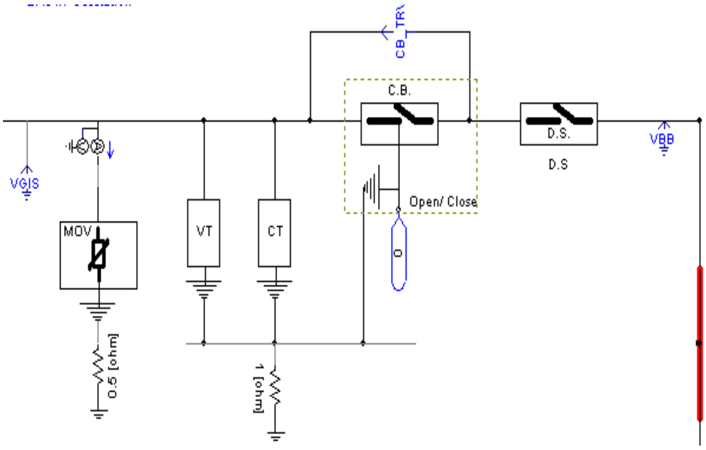

Fig. 4 PSCAD/EMTDC switchgear simulation.

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III. MODELLING BACK FLASHOVER

The probability distribution of negative lightning current amplitude recommended by CIGRE for lightning statistical studies is shown in figure 5.a [21]. The probability of back-flashover depends on this Graph. The formulae used for the calculations are based on Eriksson Weck, simplified procedures for determining representative substation impinging lightning over voltages [26]. Lightning stroke current waveforms by cloud-to-ground discharges can have a simplified description in terms of parameters such as peak current, rate of rise, rise time and tail time. Figure 5.b shows the simplified current source representation of the lightning surge used in this paper [27]. Lightning strikes the ground wires. The current discharges to ground through the tower and ‘tower footing resistance’. The resulting potential rise of the tower, stresses the line insulation. When the voltage across the insulator exceed the insulator voltage withstand capability, back flashover occurs (simulated by closing the parallel switch) [28].

Peak impulse current strike on ground wires is normally from (80 - 200) kA. A value of 190 kA is chosen in this paper according to [14]. Since the probability of occurrence for 190 kA peak is less than 1%, the lightning impulse is modelled as a current source with a simplified wave shape as shown in figure 5.b. It has 4.5 µs front time and 75 µs tail time as per worst case stroke event as mentioned in table1 [14]. When the magnitude of lightning stroke is more than 50kA, the back flashover on the tower insulators is always occurs with any tower footing resistances [4].

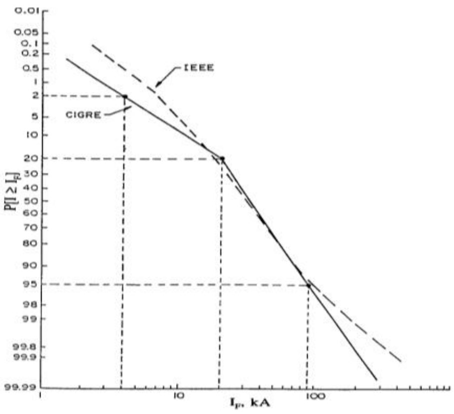

Fig. 5.a CIGRE and IEEE stroke current probability curves, first stroke negative downward flash

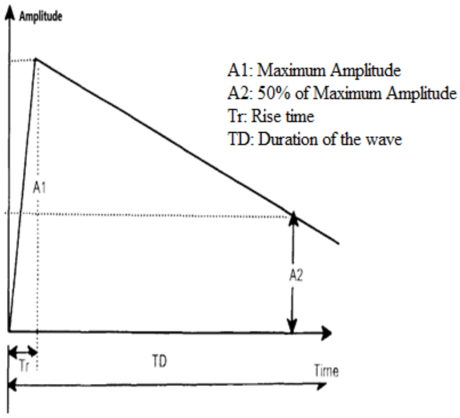

Fig. 5.b Simplified current source of the lightning surge

Figure 6.a shows the equivalent circuit of the tower during a lightning stroke [28].
The flashover occurs when V_t-V_{sys} > gap flashover voltage.

$$V_t = F\left(I_x, Z_t, Z_g\right) \tag{4}$$

Where:
V_t : Tower induced voltage
V_{sys} : System voltage
I_x : Lightning strikes Current
Z_t : Tower Surge impedance
Z_g : Footing grounding impedance

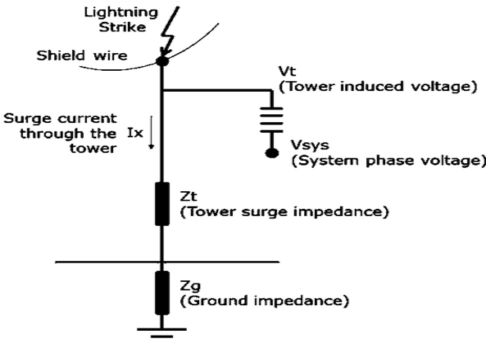

Fig. 6.a Back-flashover propagating.

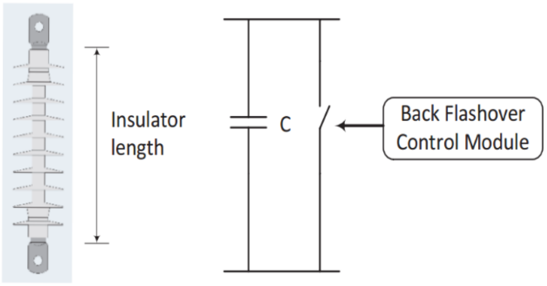

Fig. 6.b Back-flashover model

Back flashover occurs when a leader propagating from one electrode reaches the other, or when leaders propagating from both electrodes meet in the middle of the air gap [28]. Back-flashover is modelled by a bypass switch (Control Module) in parallel with the insulator capacitance as shown in figure 6.b [14].

Table 1 CIGRE concave wave shape parameters for stroke currents used in this study

Parameter	Stroke (worst case stroke event)
Peak current	190 kA (less than 1% probability the stroke exceeding this peak current)
Maximum front steepness	60 kA/µs
Equivalent front time	4.5 µs
Time to half	75 µs

IV. SIMULATION STUDIES

Computer Aided engineering software tools PSCAD/ EMTDC [29] is used for modelling and simulating the FF transient overvoltage to evaluate the likely overvoltage under various scenarios. High-Speed line traction system is considered. Currently, the most commonly used traction power system (TPS) is based on 25 kV nominal voltage at the power frequency [30]. It has 1 x 25 kV simple feeding conductor with rail return. The average distance between substations is (20 – 40) km, each substation connected to grid with nominal voltage either 132kV or 220kV and has two single-phase power transformers connected to the same two phases. The tracks are connected in parallel approximately every 10 km by use of disconnectors. The single-phase electrification system supplies trains by means of an overhead conductor system, known as Overhead Line Equipment (OLE). The system comprises a contact wire and suspension catenary, which is energized at a nominal system voltage of 25 kV to earth. Traction current drawn from the overhead contact wire returned through the running rails and overhead return conductor [31]. The rating of the lightning impulse withstands voltage (LIWV) of the substation equipment's are given as 200 kV [14]. To avoid insulation failure for the switchgear, the insulation level of the equipment (200 kV) must be higher than the magnitude of transient overvoltage that will appear on the system. It is assumed that 190 kA lightning stroke current hits the first tower which is located 40 meters away from the substation. The first tower is chosen to represent the worst induced overvoltages affect the substation apparatuses. It is worth mentioning that the induced voltage is inversely proportional to the striking distance [6].

The next three case studies show the effect of changing the earthing system for the first tower footing resistance and SA on the induced voltage due to back-flashover. The transient overvoltages appeared on the switchgear components are computed and compared with the BIL of the components.

A. Case 1 (effect of changing SA earthing resistance)

Designing the substation grounding resistance at steady state operation is almost satisfied. However, under transient conditions whether high fault current or lightning protection, there is no perfect ground resistance value [32]. As mentioned in 12.1 of IEEE Std 80-1986, the ground resistance in case of distribution substation shall be within limit of 5 Ω, whereas for transmission substation the same shall be within limit of 1 Ω [33]. Grounding resistance is measured near Gadong power station of Brunei Darussalam where it is found to be 6 Ω [34]. This case study shows the effect of changing SA resistance value on the transient overvoltages. Assuming all earthing resistance for the towers to be 40 Ω.

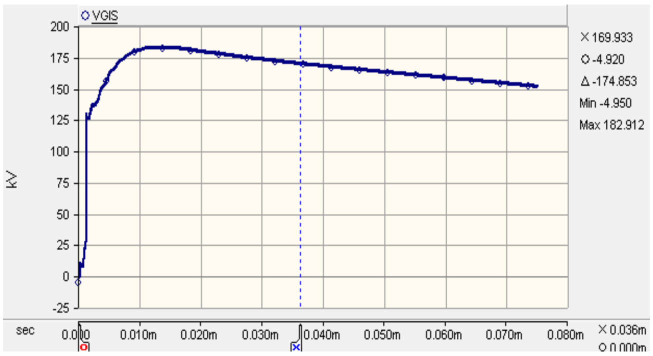

Fig. 7.a Switchgear transient overvoltage during 0.2 Ω S.A resistance

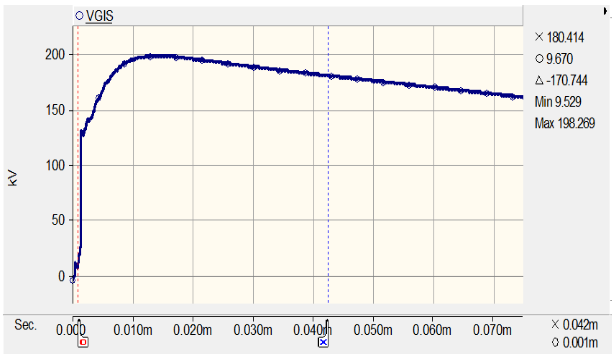

Fig. 7.b Switchgear transient overvoltage during 0.33 Ω (critical S.A resistance)

The earthing resistance of SA varies from (0.2 – 3.2) Ω. The transient overvoltages is calculated during the back-flashover at the first tower substation components. It is shown that the transient overvoltages on switchgear are largely affected by the SA earthing resistances. The overvoltages increase with the increasing of SA earthing resistances. Figures (7.a – 7.d) show the calculated transient overvoltages on the switchgear with SA having 0.2 Ω, 0.33 Ω, 0.33 Ω and 3.2 Ω earthing system resistance respectively where 0.33 Ω is the critical SA earthing resistance for safety operation. If the SA earthing system resistance higher than 0.33 Ω, the applied transient overvoltage exceeds the BIL (200 kV) of the substation components.

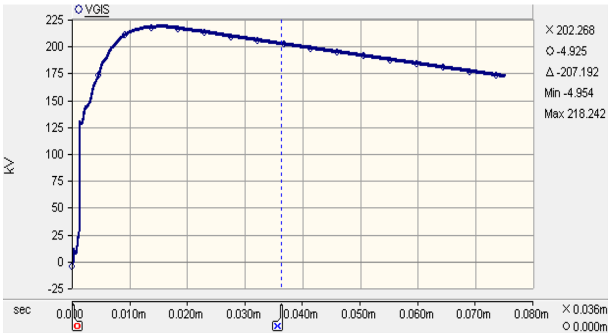

Fig.7.c Switchgear transient overvoltage during 0.5 Ω S.A resistance

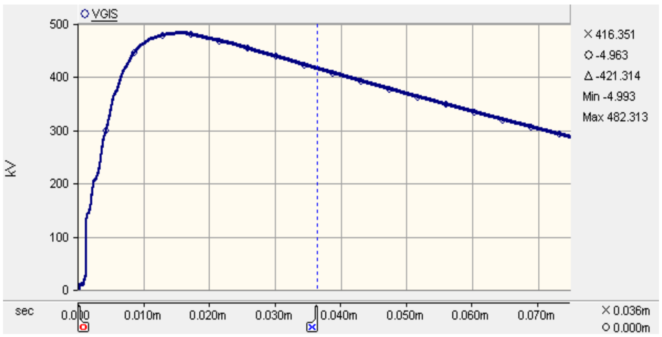

Fig. 7.c Switchgear transient overvoltage during 3.2 Ω S.A resistance

B. Case 2 (effect of changing first tower footing resistance)

The variation of tower footing resistance of the tower between 4-35 ohms is analysed for study the lightning surge propagation through power distribution networks and subsequent consumers [7]. This case study illustrates the effect of earthing resistance of the first gantry/ tower on the transient overvoltages during lightning stroke at first tower.

In this case, the earthing resistance for all remaining towers in this case is assumed to be 40 Ω, while its value for the first tower is varying from 0.5 up to 128 Ω and the SA earthing system resistance is increased at 1 Ω due to bad soil conditions, environments effects as temperature rise. Figures (8.a – 8.d) show the transient overvoltages on the switchgear for first tower earthing resistance 3.2 Ω, 4.4 Ω, 16 Ω and 128 Ω.

Fig. 8.a switchgear transient overvoltage during 3.2 Ω first tower earthing resistance

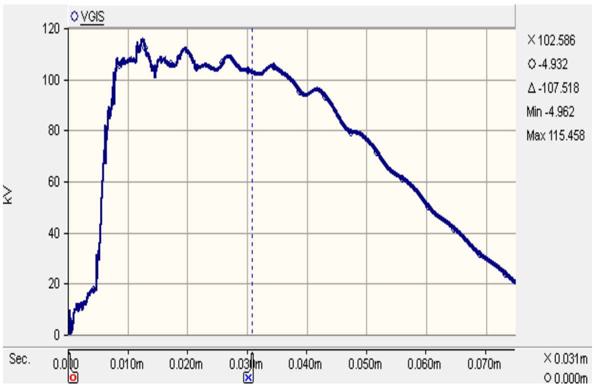

Fig. 8.b switchgear transient overvoltage during 4.4 Ω (critical first tower earthing resistance)

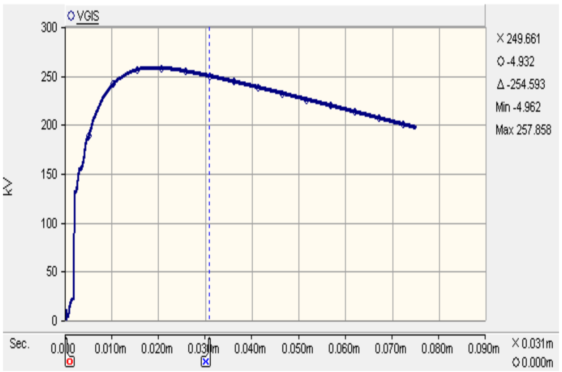

Fig. 8.c Switchgear transient overvoltage during 16 Ω first tower earthing resistance

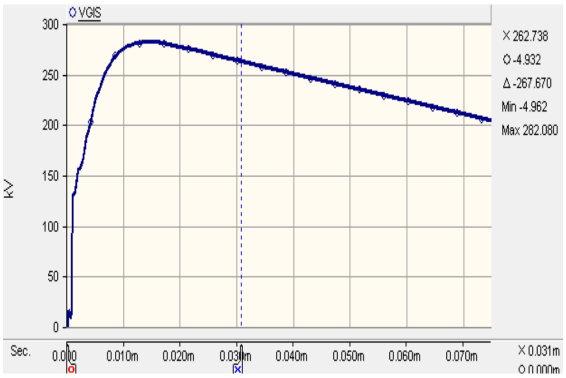

Fig. 8.d Switchgear transient overvoltage during 128 Ω first tower earthing resistance

It is clear from the figures that the transient overvoltages increase with increasing the earthing resistance of the first tower. It is noticed also that there is a critical value of earthing resistance of 4.4 Ω at which the transient overvoltage is equal to BIL of substation considering soil ionization.

C. Case 3 Improving earthing resistance by connection between the SA and first tower

Considering the grounding resistance of the substation (i.e. S.A earthing resistance) are increased to 4.4 Ω due to environmental conditions and increase in temperature degrees. As mentioned in [35] the soil resistivity varies widely by region and changes seasonally due to the variations in the soil's electrolytic content and temperature. The soil resistivity may vary with high resistivity values in the dry season. Assume the earthing resistance of all towers are constant at 40 Ω except the first tower.

In this case study we will connect ground wire between the substation earthing system and the first tower earthing system. The earthing system resistance for both SA and the first tower is assumed to be varied from (0.5-10) Ω.

Figure 9.a shows the variation of the calculated transient overvoltage on the substation with variation of earthing resistance for SA and first tower. Fig. 9.b shows switchgear transient overvoltage during 4.4 Ω for the earthing systems of both SA and first tower.

As always, the first tower will be near the substation so, in this case study we will connect ground wire between the substation earthing system and the first tower earthing system. The value of transient overvoltage is improved to be 324kV which is within the acceptable range. Figure 9 shows the switchgear transient overvoltage with connection ground wire between the SA earthing system and first tower earthing system.

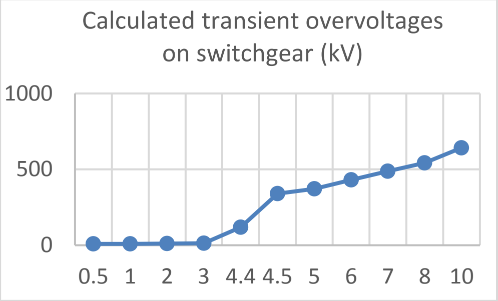

Fig. 9.a Variation of transient overvoltages with earthing resistance for SA and first tower

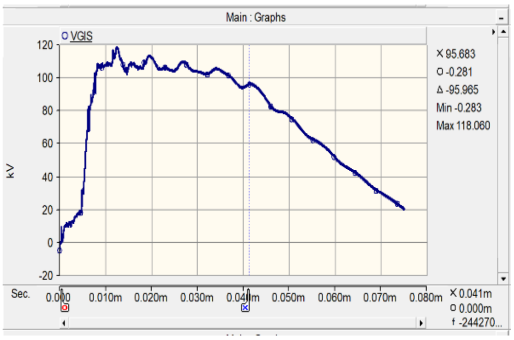

Fig. 9.b Switchgear transient overvoltage during 4.4 Ω for the earthing systems of both SA and first tower

V. CONCLUSION

In this paper, three cases were studied to illustrate the effect of system earthing resistance on fast front back flashover. From the results, the higher earthing resistances for the SA and for the first tower, the higher the calculated transient overvoltage. When the earthing resistances for the SA are less than 0.33 Ω, all the values of calculated transient overvoltage are within acceptable limits. When the SA earthing system resistance is increased to 4.4 Ω due to environments seasonal effects, the values of calculated transient overvoltages exceed the acceptable limits. By connection between the earthing systems of both SA and first tower then achieving earthing resistance 4.4 Ω, the problem is solved. So that at short distances between the first tower and substation, it is highly recommended to connect the earthing of first tower with substation earthing system for improvement the transient overvoltage and it is recommended to connect between them by two ground wires for higher reliability.

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