Air-Insulated Substation – Comparison Between Two Lightning Model Approaches

A. L. P. da Cruz, W. L. A. Neves

***Abstract*—Electromagnetic transient simulations using Alternative Transients Program – ATP were carried out in a 500 kV air-insulated substation owned by Chesf, an utility company from Brazil. Two modeling approaches were analyzed. In the first approach, lightning was modeled by a voltage source entering the substation and the lightning struck Transmission Line (TL), substation equipment, and busbar were modeled as a single-phase network. In the second modeling approach, a three-phase representation is used and lightning was represented as a current source. It accounts for three-phase models of substation components, as well as, lightning hit TL tower surge impedance, grounding system and, insulator string flashover models. Preliminary results have showed that modeling lightning surge as a voltage source originates higher overvoltages than those observed in the current source model. Both modeling approaches have great impact on station insulation coordination and care must be taken when deciding which one should be used.**

***Keywords*—ATP, backflashover, insulation coordination, lightning.**

I. Introduction

When performing lightning insulation coordination studies for new substations, Brazilian utilities and some consulting companies use a simplified approach [1], [2], [3], [4]. In this regard, lightning striking a transmission line is modeled as a voltage source whose amplitude is equal to the TL Critical Flashover Voltage (CFO) plus three standard-deviation, 3σ, which is assumed to be the maximum insulator string withstand voltage. Only the struck phase conductor is simulated (ground wires are neglected) and transmission line hit by lightning is modeled by a Constant Parameter Distributed Line (CPDL) model which takes into account its positive sequence surge impedance, and surge propagation velocity. Lightning struck point is 500 m away from the substation entrance, which is the line length of the TL span modeled by the CPDL.

This simplified approach neglects important phenomena that contribute to the lightning surge overvoltage computation entering a substation, such as travelling waves along the struck transmission line tower, reflected waves from its grounding system surge impedance and adjacent towers, transmission line flashover behavior and, coupling effects among phase conductors and ground wires. It is worth mentioning that modeling those phenomena is recommended by IEEE, IEC, and Cigré guidelines [5], [6], [7], [8] and by other publications, e.g. [9].

Both modeling methods may have different impact on a station insulation coordination. In order to verify the main differences between them, ATP/ATPDraw lightning electromagnetic transient simulations were carried out in a 500 kV air-insulated substation owned by Chesf, an electrical generation and transmission company of the Northeast of Brazil. This paper aims to present the main simulations results considering both methods. By varying some model parameters, a sensitivity analysis is also presented to investigate which of them has a major effect on lightning overvoltage. Apparently, such a comparison analysis hasn't been done.

II. Modeling Approaches

In the following paragraphs, the two modeling methods are described taking into account only backflashover analyses due to first return stroke currents.

A. Modeling lightning surge as a voltage source

This method will be referred to as Voltage Source Modeling Approach - VSMA. In VSMA, for backflashover simulation, it is assumed that lightning overvoltage across insulator string rises until a certain breakdown value occurs. This is assumed to be the maximum insulator string withstand voltage, $V_{3\sigma}$, which can be obtained by (1) [10].

$$V_{3\sigma} = CFO(1 + 3\sigma) \quad (1)$$

In (1), CFO is the insulator string 50% probability withstand voltage and σ is the standard-deviation and equals 3% of the CFO [10].

Theoretically, after the backflashover occurrence, a surge voltage with "an infinite" rate of rise travels towards the substation. Due to corona effects, 500 m away from the station entrance, the surge front time increases to 0.5 μs. Here, the surge voltage tail time is assumed to be 50 μs. The situation described above is simulated in the ATP by modeling lightning as a voltage source whose magnitude is equal to $2V_{3\sigma}$.

A matching resistance, equal to the TL positive-sequence surge impedance, is connected in series with this voltage source to avoid reflected waves returning to the substation entrance. In the present case, lightning struck TL has a CFO of 2000 kV and applying (1) yields $V_{3\sigma}$ = 2180 kV. A double ramp type voltage source [11] is used as shown in Fig. 1.

In the VSMA, transmission line and also substation components such as, busbars, lead conductors and high voltage equipments are modeled in a single phase basis which means that only the flashovered phase is considered. Conductors

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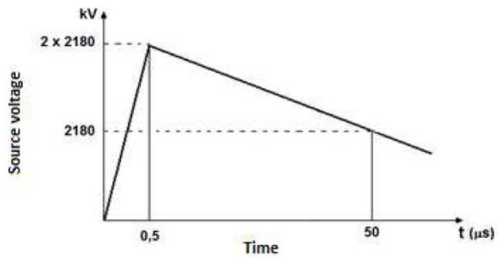


Fig. 1. VSMA - Voltage source waveshape for modeling lightning impinging surge.

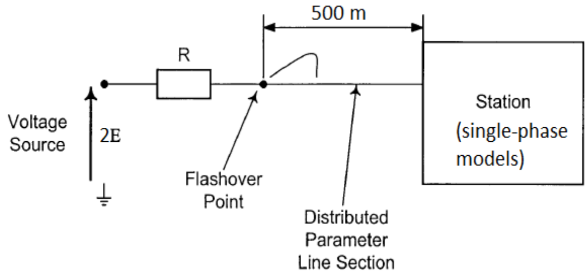


Fig. 2. VSMA - Simplified diagram (adapted from [12]).

mutual effects, TL tower hit by lightning, substation gantry and their grounding systems, as well as, insulator string flashover models are neglected. Fig. 2 shows a simplified diagram of the VSMA.

B. Modeling lightning surge by a current source

The second modeling approach accounts for three-phase models of substation components, as well as, lightning hit TL tower surge impedance, grounding surge impedance and, insulator string flashover models, all of them according to the main modeling guidelines [5], [6], [7], [8]. Throughout the paper, this method will be referred to as Current Source Modeling Approach (CSMA). It must be said that, for this approach, as there are several models for each TL component, a reference case was considered and only the models used in this case are described in details.

In the CSMA, lightning is modeled as a current source by means of the ATP slope-ramp source type (type 13). Its waveform is the same as that shown in Fig. 1 used in the VSMA, with amplitude, I, front time, t_f, and tail time, t_h. These parameters are statistical in nature and can be estimated by log-normal probability distributions [13]. Correlations factors between amplitude, I, and front time, t_f, are also given [8], [13]. The one used in this work is that shown in (2) [8]. So, based on (2), for a given amplitude I, the front time, t_f, can be estimated:

$$t_f = 0.154 I^{0.624}. \tag{2}$$

According to [14], for a 500 kV system, a 150 kA lightning current amplitude is adopted in Japan and this value was also used here. Thus, by using (2), for I = 150 kA, t_f = 3.5 μs.

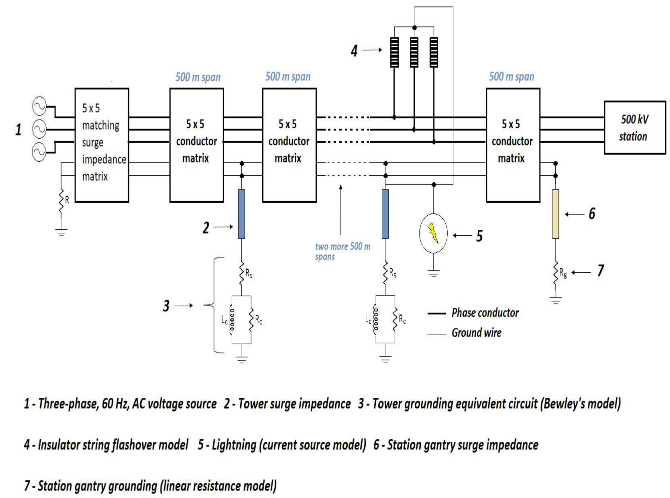


Fig. 3. CSMA: Simplified diagram.

For the tail time, t_h, a value of 75 μs was adopted. According to [13], this is the 50% probability value of being exceeded.

The slope-ramp source type used to simulate the lightning current in the reference case was connected to the ground wires at the first tower after substation gantry, 500 m away apart, as can be seen in Fig. 3. Lightning current channel impedance was neglected.

Transmission line hit by lightning was modeled by a 5 x 5 matrix (3 phase conductors and 2 ground wires) including their mutual coupling. The ATP untransposed, K. C. Lee TL model was used, taking into account modal transformation theory [11]. In both methods, line parameters were calculated at 500 kHz [9], and 1000 Ωm ground resistivity. Five spans near substation were represented, each of which with 500 m length. Station busbars and conductors between high-voltage equipments were modeled by their positive and zero sequence parameters.

Transmission line towers and substation gantry were modeled by single phase, lossless CPDL model. The main models proposed are summarized in [9]. Transmission line and substation gantry dimensions are shown in Fig. 4.

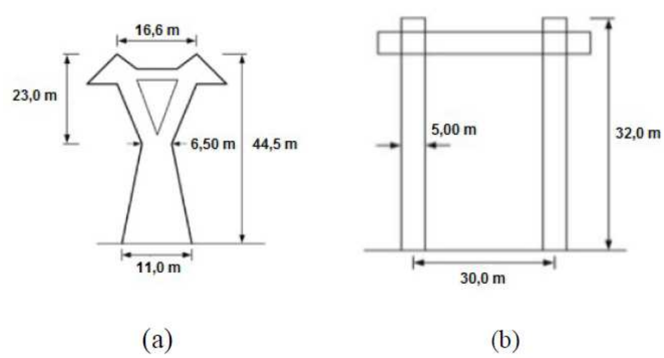


Fig. 4. Transmission line tower (a) and substation gantry (b) dimensions.

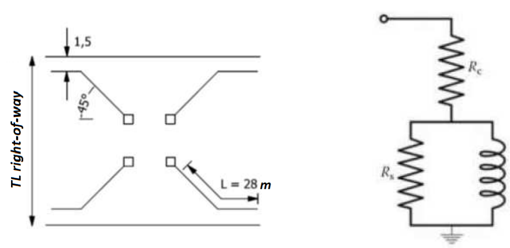
Insulator flashover model plays an important role in lightning studies. Some of the proposed models are voltage-controlled switch, volt-time curves [15], and integration methods [16]. They can be easily modeled in EMTP-type programs by using a switch and the control logic that generates the flashover signal [17]. Leader development models are based on the physics breakdown process and can be implemented in ATP with ease, as well [18].

The model used in the CSMA reference case was the one based on the disruptive effect concept (integral method), whose expression is given in (3).

$$DE^* = \int_{t_0}^{t} [v(t) - U_0]^k dt \tag{3}$$

In the above expression, $v(t)$ is the voltage applied to the insulator string, DE is the surge disruptive effect ($kV^k\mu$s), t_0 is the time by which $v(t)$ exceeds U_0, t is the time elapsed since voltage application, k is a constant, and DE^* is the critical value of DE. During the simulation, the integral is calculated whenever $v(t)$ exceeds U_0 and, if its value is greater than DE^*, a switch closes to simulate a flashover on the insulator string.

For modeling TL tower-footing grounding system, for the present case, counterpoises are used in a four 5.19 mm diameter conductor configuration as shown in Fig.5a. Bewley has proposed an RL equivalent circuit in order to take into account the transient performance of counterpoises when hit by high frequency currents [19]. This model is shown in Fig.5b and was the one used in the CMSA simulations. Soil ionization, which tends to decrease the grounding resistance [9], was not modeled.



(a) (b)

Fig. 5. Lightning struck TL tower-footing grounding system (a) and equivalent circuit (b).

Substation gantry grounding was modeled by a 0.5 Ω linear resistance, since it is connected to the substation grounding grid, which is designed for such a low resistance value.

C. Common models to both approaches

In both modeling approaches, high-voltage substation equipments were modeled by their stray capacitances whose values are shown in Table I.

TABLE I
EHV EQUIPMENT STRAY CAPACITANCES.

EHV 550 kV Equipment	CVT	CB	DS	CT	RE
Capacitance (pF)	4000	107	152	347	4000

In Table I, CVT means Capacitive Voltage Transformer, CB, Circuit Breaker, DS, Disconnect Switch, CT, Current Transformer, and RE, Shunt Reactor. Autotransformers (ATR) were also represented by their stray capacitances as shown in Table II.

TABLE II
EHV EQUIPMENT STRAY CAPACITANCES.

ATR Terminals	HV - MV	HV - gnd	MV - gnd
Capacitance (pF)	6314	6116	23407

In Table II, HV is the High Voltage ATR winding (550 kV), MV is its Medium Voltage (230 kV) winding and gnd is the ATR ground terminal.

In order to take into account the high frequency surge arrester behavior for surges with front times up to 8.0 μs, Pinceti and Giannettoni [20] surge arrester model was used in the VSMA as well as in the CSMA. Its parameters are shown in Table III.

Power frequency voltage was included in the simulations by the use of the ATP sinusoidal voltage source, Type 14 [11]. Three AC voltage values were taken into account at instant of lightning strike: zero, -Vph, and +Vph, where Vph is equal to 449 kV. In the VSMA, a single-phase AC source was used, while in the CSMA a 3-phase AC source was used. Thevénin equivalent impedance is connected in series with the AC voltage source in order to represent the remainder of the power system not modeled in fast front transient simulations [7], [8].

In Table IV, the parameters of the models used in both modeling approaches are shown. Transmission line and busbar conductors data are given, as well as, transmission line CFO.

III. Camaçari IV Substation and EHV Equipment Insulation Levels

Camaçari IV substation was designed in breaker-and-a-half arrangement. There are 2 transmission lines and two 500/230 kV, 2400 MVA, autotransformer banks, as well as a 150 MVA line shunt reactor. Substation one line diagram is shown in Fig.6. Lightning struck TL is also shown in this figure.

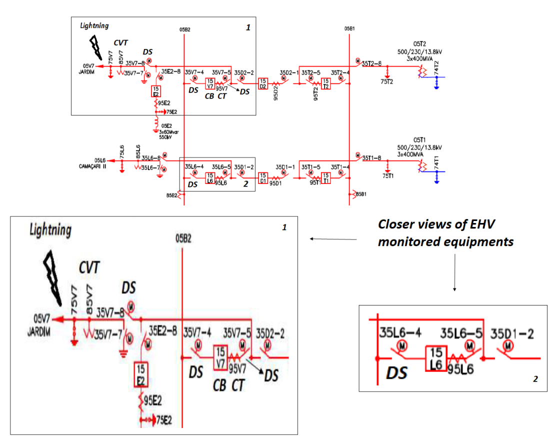


Fig. 6. Camaçari IV 500 kV One Line Diagram Substation.

In order to seek for the highest overvoltage levels, 4 substation configurations were simulated. They are:

TABLE III
VSMA AND CSMA MODELS AND THEIR PARAMETERS.

Component	Method	
	VSMA	CSMA
Lightning	Voltage source: t_f/t_h = 0.5/50 µs Amplitude: 2180 kV	Current source: t_f/t_h = 3.5/75 µs Amplitude: 150 kA
Transmission line	Single-phase; Surge impedance: 214 Ω Span: 1 x 500 m	Three-phase; 5 x 5 matrix Modal parameters 5 spans of 500 m, each
	Phase conductors: 4 x Grosbeak, 636 MCM, regular bundle of 457 mm Ground wires: 2 x 176,9 MCM, Dotterel	
Substation busbar/ lead conductors	2 x Sagebrusch, 2250 MCM, 457 mm apart/1 x Tulip, 336 MCM	
TL tower	Not modeled	Waist tower: surge impedance/travel time - 97.5 Ω/0.175 µs
Substation gantry	Not modeled	H-frame tower: surge impedance/travel time - 82 Ω/0.140 µs
Insulator string flashover model	Not modeled	Integral method: DE* = 983 kV. µs; U_0 = 1800 kV K = 1 Lentgh: 4.42 m
Tower grounding	Not modeled	Bewley's RL circuit: Rc = 14.5 Ω Rs = 19.7 Ω Lc = 1102 µH
Gantry grounding	Not modeled	60 Hz, linear resistance: R = 0.5 Ω
Substation equipments	Stray capacitances: see Tables I and II for their values	
Surge arresters	Pincetti and Gianettoni model: L_0 = 5.25 µH L_1 = 15.8 µH R = 1.0 M Ω V_{10kA} = 966 kV	
60 Hz, AC voltage	Single-phase: 449 kV peak voltage, phase-to-ground	Three-phase: 449 kV peak voltage, phase-to-ground
Matching impedance	Single resistance: 214 Ω	5 x 5 surge impedance matrix (based on line parameters at 500 kHz, 1000 Ωm)

1) Full operation - all substation components connected (in operation)
2) Camaçari IV – Camaçari II TL out of service
3) 500/230 kV, 05T2 ATR out of service
4) Camaçari IV – Camaçari II TL, 05T2 ATR, and 05B1 busbar out of service.

The lowest EHV equipment basic impulse level (BIL) is 1550 kV. A safety margin of 10% was adopted, which means that the maximum overvoltage should not exceed V_{max}, equal to 1395 kV.

IV. SIMULATION RESULTS

Based on the models and their parameters as shown in Table III, simulations were carried out taking into account the 4 configurations outlined. For both modeling approaches, configurations 2 and 3 have resulted in the most severe overvoltages.

In the CSMA, three t_f/t_h pairs were adopted: 0.5/50 μs, identical to that used in the VSMA voltage source, 1.0/70 μs recommended in [14], and 3.5/75 μs, with t_f based on the lightning current amplitude, I [8] (150 kA), and t_h being the median value of the corresponding log-normal distribution.

Figure 7 shows the maximum overvoltages at the terminals of equipments at Jardim - Camaçari IV line entrance (the most severe ones), with a double ramp (DR) current source and the 3 values of t_f/t_h as mentioned above for the CSMA. VSMA results are also shown. It can be seen that, in the VSMA, the majority of the overvoltages are above the maximum allowable value (1395 kV), while in the CSMA the overvoltage levels are strongly dependent upon the lightning current t_f value. So, the greatest values were those related to 0.5 μs for t_f, whilst the lesser ones were those associated with a front-time of 3.5 μs. It is interesting to note that, most of the values obtained in the VSMA are higher than those resulted with the CSMA.

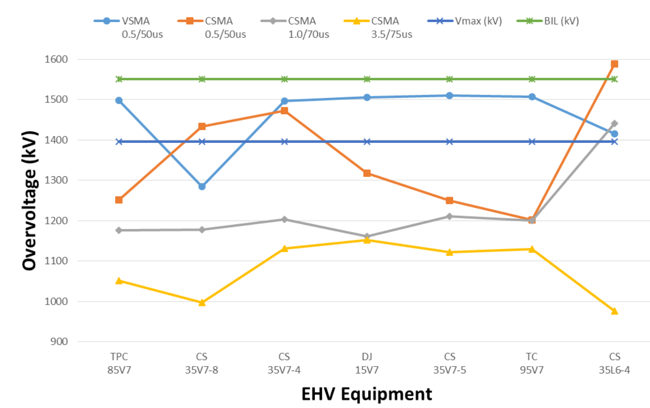


Fig. 7. VSMA x CSMA: maximum overvoltages.

Three tower models were also tested: waist, conical and cylindrical. Figure 8 shows the results for each tower model with a DR current source, 0.5/50 μs waveshape. VSMA results are also shown. In the CSMA, at least 2 overvoltage values are higher than the maximum allowable value, but most of them are lesser than those obtained in the VSMA. Although not shown in Figure 8, a DR current source, 3.5/75 μs waveshape was simulated and none of the overvoltages was higher than 1395 kV.

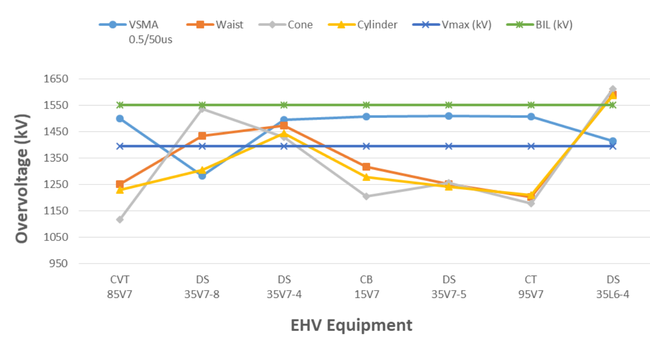


Fig. 8. VSMA x CSMA: maximum overvoltages for 3 tower models: waist, cone and cylinder – t_f/t_h = 0,5/50 μs.

Finally, 3 insulator string flashover models were tested: v-t curve, disruptive effect (integral) and LPM (Cigré model). Two front-times were considered: 0.5 μs and 3.5 μs. Main results are shown in Figure 9 (only for t_f = 0.5 μs), which also shows the VSMA results. It can be observed that backflashover was not observed when the v-t model was used, since overvoltage values are very low, roughly, 600 kV .The integral model has resulted in the most severe overvoltages, some of them higher than the limit. This was not observed when the Cigré LPM model was used. For t_f = 3.5 μs, no overvoltage above 1395 kV has been observed.

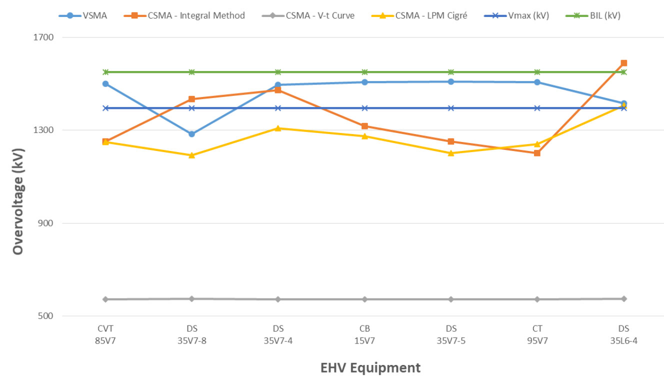


Fig. 9. VSMA x CSMA: maximum overvoltages for 3 insulator string flashover models: v-t curve, integral method, and LPM Cigré model – t_f/t_h = 0,5/50 μs.

V. Comments on the Results

The VSMA has resulted in overvoltage values greater than those observed in the CSMA, even taking into account a front-time value of 0.5 μs for the current source in the CSMA. In the VSMA, the lightning hit TL towers are not modeled. This is an important aspect, since, as can be seen in Fig. 10, the traveling surge is reduced as it passes along each tower.

In Fig. 10, a surge e_1 impinges on the ground wire conductor with surge impedance Z_1, connected to a tower whose grounding resistance is R. As e_1 passes along the tower, it originates a transmitted voltage, $e"_1$, which is a fraction of e_1 and travels until it reaches the next tower, and so on. It is interesting to note that, not only the ground wire transmitted surge is reduced, but also the induced voltage $e"_2$ on the phase conductor, with surge impedance Z_2. The reduction factor, as can be seen in Fig. 10, depends on the mutual surge impedance between the ground wire and the phase conductor, Z_{12}. The greater Z_{12} is, the lesser will be the value of $e"_2$. A high value of Z_{12} means a close proximity between the ground wire and the phase conductor. Thus, modeling coupling between conductors is another important issue in the CSMA, since a reduction in overvoltages can be obtained.

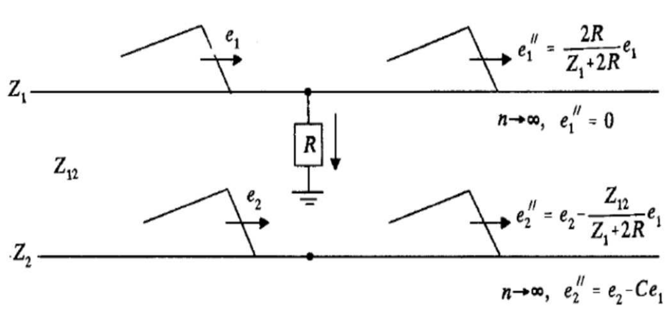


Fig. 10. Voltage surge reduction after passing a tower [21].

The current source front-time in the CSMA is also important. The 0.5 μs value is very conservative and, along with a 150 kA lightning amplitude current, has a very low probability of occurrence [13]. The same comments apply for the 1.0 μs front-time value. It was previously shown that these front-time in the CSMA resulted in overvoltages higher than the maximum allowable value. The exception were the 3.5 μs case results, whose values are lesser than the limit. Such a time-front was obtained by using the following correlation expression [8] with a 150 kA lightning current amplitude:

$$t_f = 0.154 I^{0.624} \tag{4}$$

The front-time has a great impact on the tower top voltage, as can be seen in (5) [21]:

$$V_{TT} = \left(R_e + \alpha_T Z_T \frac{T_T}{t_f} \right) I \tag{5}$$

In (5), V_{TT} is the crest value of the tower top voltage, R_e is an equivalent impedance which accounts for the parallel combination of the tower surge impedance, Z_T, and the ground wire surge impedance, α_T is the reflection coefficient at the tower ground, and T_T is the surge transit time along the tower. Thus, the lesser the value of t_f is, the greater the tower top voltage will be. After the backflashover occurrence, this voltage will be equal to the phase conductor one, and will travel toward the substation. In order to equalize those values at the tower, the voltage at the ground wire decreases, while the voltage at the phase conductor is considerably increased, as shown in Fig. 11, for the 3 values simulated for t_f. It can be seen that, the voltage peak at the phase conductor for t_f = 3.5 μs is the lesser one, since the corresponding increase in the tower top voltage is reduced as compared to those for 0.5 μs and 1.0 μs front-time values

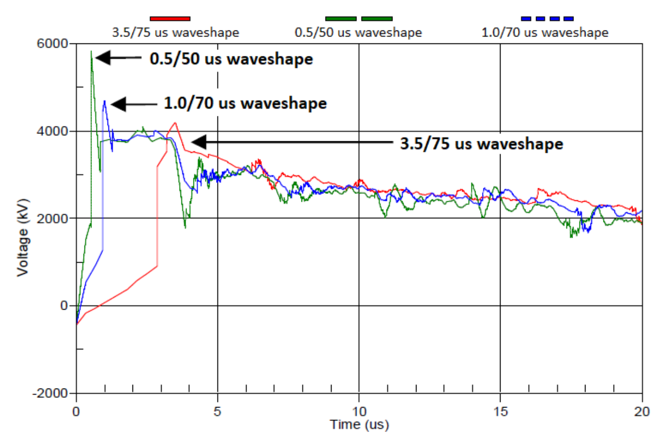


Fig. 11. Transmission line voltage for the 3 t_f/t_h simulated values.

As regard the three tower models simulated, results have showed that the greatest overvoltages have occurred for t_f = 0.5 μs, being t_f the dominant parameter, for the present case, as compared to the tower surge impedances.

Although not shown, all overvoltages obtained in the 3.5 μs time-front waveshape case were smaller than 1395 kV, for the 3 tower models tested. The same can be stated for the 3 string insulator flashover models.

VI. Conclusion

A comparison analysis between two modeling approaches for lightning backflashover simulations in a Brazilian system 500 kV air-insulated substation was made. The first method models lightning surge by using a voltage source and all components represented in a single-phase basis. The second approach models lightning surge by a current source and all conductors (phase and ground wires) are represented (three-phase modeling). TL tower, grounding impedance, and insulator string flashover models are also considered.

For the present case, simulation results using ATP have showed that the voltage source modeling approach (VSMA) was more conservative than the current source modeling approach (CSMA), since overvoltages greater than the maximum allowable voltage level were produced.

Differences in values are mainly due to mutual effects among ground wires and phase conductors, which decrease the maximum overvoltage across insulator string, and surge reduction due to opposite polarity reflected waves produced by the parallel combination of ground wires and TL tower surge impedances. Grounding system surge impedance has a great influence on this phenomenon, as well. These components, which are not present in the VSMA, are represented in the CSMA.

For the CSMA, a sensitivity analyses was carried out by taking 3 different tower and insulator string flashover models. Results so obtained are strongly dependent on the current source time-front values and the maximum overvoltages were greater than the maximum allowable for t_f values equal to 0,5 μs e a 1,0 μs. Favorable results were observed for t_f = 3,5 μs.

The different results for both approaches (VSMA and CSMA) have a great impact on the station insulation coordination and the method used must be carefully chosen so that unnecessary actions be taken based on a method that disregards important effects in the backflashover process. In the CSMA, the choice of the lightning current front-time value must also be done with care, in order to avoid an unlikely combination of this parameter with the return stroke current amplitude, e.g., very low values of t_f and very high ones of I. According to correlation factors expressions given in [13], a direct relation do exist between those parameters.

If these factors are neglected and high lightning current amplitudes are used in association with very low front times, CSMA may result in very high overvoltage values, greater than that observed in the VSMA. Should a more conservative method is required for lightning insulation coordination study, VSMA can be used for a first approximation, since it is simpler than the CSMA. Otherwise, the CSMA should be the preferred method.

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