STATISTICAL STUDY OF THE LIGHTNING OVERVOLTAGES AT A GAS INSULATED STATION TRANSFORMER

M. Fernandes M.T. Correia de Barros M.E. Almeida

IST-Universidade Técnica de Lisboa/Instituto da Energia-INTERG
1096 Lisboa Codex, Portugal

Abstract - In order to establish the application procedures for substation insulation coordination, a detailed lightning overvoltage study is needed. Computer simulation is an important tool for such studies. This requires to establish an accurate representation of the relevant network parameters.

In order to evaluate the overvoltages at a station transformer, lightning statistical studies are performed using the ElectroMagnetic Transients Program (EMTP). The data files are created automatically by a dedicated routine, able to generate lightning events: the lightning stroke parameters, the place it hits the incoming transmission line, and the phase angle of the power frequency voltage at the striking time. A Monte-Carlo simulation is used to generate these events, and severity selection criteria applied. The analysed lighning activity time span is established according to the MTBF (mean time between failures) acceptable for the station transformer. A sensitivity study showing the influence of different modelling parameters on the computed results is performed.

I. INTRODUCTION

For insulation coordination, it is necessary to analyze accurately various overvoltages generated internally or externally to the power system. Among these, lightning surge overvoltages are very important, as they are a main factor to determine the insulation and protection levels.

Lightning surge analysis is performed for various parts of the power system. The most frequently, for substations, since the lightning surge has great influence on substation insulation design, and the standardization of substation layout is difficult, thus leading to the analysis of each specific case.

To perform the insulation and protection design, it is necessary to model the circuit elements adequately, and to analyze overvoltages at different locations. Experimental results being difficult to obtain, computer simulation is an important tool for insulation coordination studies.

Station insulation coordination studies require to establish an addequate representation of the lightning events striking the incoming transmission lines, and an accurate representation of the relevant network components. The sensitivity of the results with respect to the selected models has to be evaluated. For modelling the lightning event, either a deterministic or a statistical approach can be followed. The first requires that a representative lightning event is identified. The latest can give a more correct view of the lightning performance of the analysed system, but it is time consumimg.

Different overviews on the methods for estimating the lightning performance of power systems are available in the literature [1-6]. Particular emphasys is given to the analysis of transmission lines.

This paper presents a statistical study of the overvoltages at a GIS transformer, following backflashover events on the incoming transmission line. The addopted modelling techniques follow, in general, the Gigré guidelines [4]. The influence of different modelling parameters on the computed results is performed.

II. LIGHTNING EVENTS GENERATION

The generation of lightning events is based on a Monte-Carlo simulation, taking into account the ground flash density in the region where the substation is located. In the absence of directly measured ground flash density, the relation established by Anderson et al [7] is considered:

$$N_g = 0.04 T_d^{1.25} \qquad (1)$$

where Td is the average annual thunderstorm day.

Each lightning stroke is considered to be represented by an ideal current source of infinite source impedance. The lightning current parameters (amplitude, time-to-crest, steepness and duration) follow log-normal distribution of variables, the median value M and the logarithmic standard deviation β having the values addopted in [4].The incidence to the line, including phase conductors, shielding-wires and towers, is evaluated using the average attractive radius R_a concept [8]:

$$N_L = N_g (2R_a + b)/10 \qquad (2)$$

where b is the distance between the shielding-wires, N_L giving the expected average incidence of strikes per 100 km-line, per year. The fraction of them which go to the phase conductors is evaluated using the modified electrogeometric model developed in [9]. The remaining strokes obviously hit the towers and the shield wire(s). The latest are represented by lightning currents injected at the top of the closest tower. It is proved that the effect of strokes within the span may be represented by a 60%-equivalent, if injected at the adjacent towers [4].

A statistical insulation coordination study requires that the analysed lightning activity time span is chosen, according to the accepted MTBF (mean time between failures). For GIS, depending on the importance of the substation, the accepted MTBF is 300 to 1,000 years [3]. The limits of the confidence interval for an estimation of MTBF can be calculated with a certain precision if the number of observed failures is high. For that reason, a period of more than ten times the MTBF has to be considered, thus occuring a very high number of ligtning events that hit the line during that period. However, only a very small fraction of them will have the characteristics possibly leading to flashover on the transmission line. Therefore, a severity selection criteria is necessary, in order that resonable computation times are met. The implemented selection criteria follows the Gigré guidelines [4].

III. BASE-CASE STUDY

The network in Fig. 1 is considered.

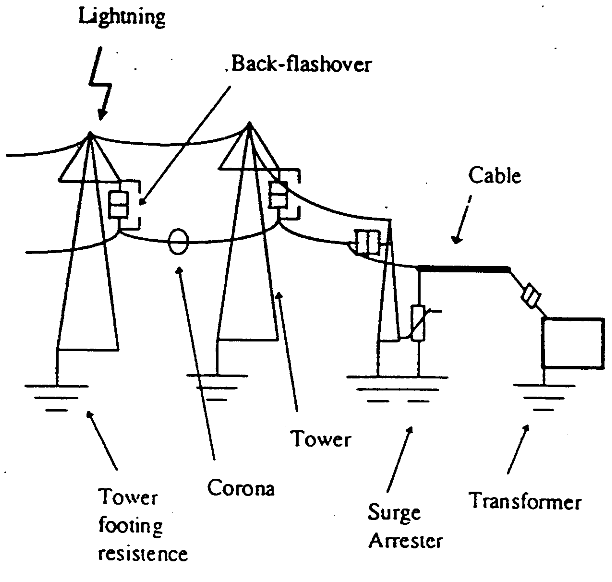

Fig. 1 - Case-study network.

A stretch of 880 m (5 towers / 207.7-m x 4 spans + 50-m x 1 span) of the 220 kV line entering the substation is considered, as flashes at a greater distance are not dangerous for the substation. The line configuration is vertical, lateral to the tower, and the earth wire occupies a central position (fig. 2). The K C LEE model is considered for representing the line. The line parameters are evaluated at 50 kHz using the LINE CONSTANTS routine. The effect of corona on the travelling surges is negleted for the base-case study.

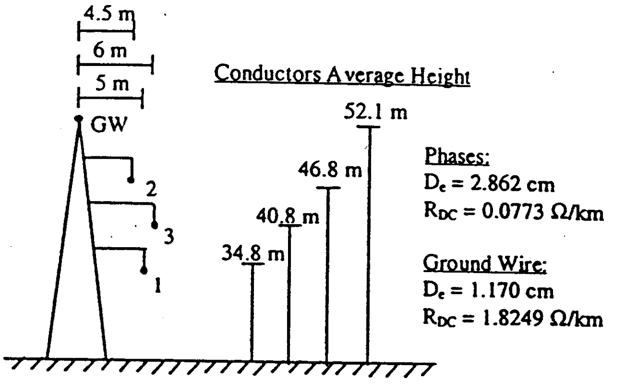

Fig. 2 - Transmission tower and line geometry.

The towers are represented by the distributed parameters Z_T = 150 Ω and v = 300 m/μs. For backflashover studies, the tower footing modelling is very important, in particular its nonlinear behaviour, related to soil ionisation. The model addopted by both Cigré [4] and IEEE [5] is addopted, considering a 80 Ω - d.c. resistance value, a 720 Ωm - non-ionized soil resistivity, and a 400 kV/m - ionization threshold field. The tower/earth electrode connections are represented by lumped inductances of 1 μH/m.

To represent the air-gap at the insulators string, the leader progression model is used for taking into account non-standard lightning impulses [4]. Backflashover is represented by a time-depndent arc resistance, decreasing from 1 kΩ to 1 Ω in .2 μs, and to .5 Ω in 1.0 s.

A v(i) curve is considered for modeling the ZnO surge arresters at the line entrance, and the inherent inductances taken into account [10].

The transformer is represented by a 4.2 nF pure capacitance, evaluated according to [11], and is connected to the entrance by a 75 m cable, represented by lossless transposed transmission line model: Z_W = 65 Ω and v = 300 m/μs.

Lightning events corresponding to 10,000 years of lightning activity have been generated, the targeted MTBF being set at 800 years. This aims at no failure during the life time of the equipment (40 years), with a confidence level of 95%. The annual thunderstorm-day value being considered equal to 50 (N_g = 5.318 flashes/km^2), 14,459 strokes are found to hit the line stretch during the 10,000 years observation time span. For the considered simulation conditions, only two shielding failure events are observed. By applying the severity selection criteria to the other events, it is found that 53 are prone to cause backflasover. The corresponding EMTP simulations were performed, considering a concave front in the lightning current, as recommended in [4].

The histogram in figure 3 shows the computed overvoltage distribution at the different phases of the station transformer.

Results show that the higher stresses appear on the phase that corresponds to the lower line conductor, the one with the lowest coupling factor with the shielding-wire. These conclusions agree with a study presented in [4] where lightning currents with different rising times were injected on the top of a tower belonging to a similar line. For the shortest rising times, breakdown occured on the top phase and for longer times on the bottom one. The times-to-crest considered in the present study are mostly long, so the results agree with reference [4]. Furthermore, multiple flashovers occur (phase 1 and 2), explaining the level of overvoltages that stress phase 2 of the station transformer.

IV. PARAMETER SENSITIVITY STUDY

Starting from the the base-case study described above, the sensitivity of the computed overvoltages to different modelling parameters is evaluated.

Soil ionisation - Results obtained when considering a 80 Ω constant tower footing resistance are shown in figure 4.

As it is well known, soil ionisation acts to decrease the tower footing resistance above a threshold field, and therefore plays a positive role regarding backflashover.

Consequently, when soil ionisation is disregarded, significantly more severe overvoltages are found at the station transformer, as indead it is plain when comparing figures 3 and 4.

A detailed analisys of the backflashover events shows that an increase on the number of multiple flashovers occurs on the hitted tower as well as on the adjacent ones, when soil ionisation is not taken into account.

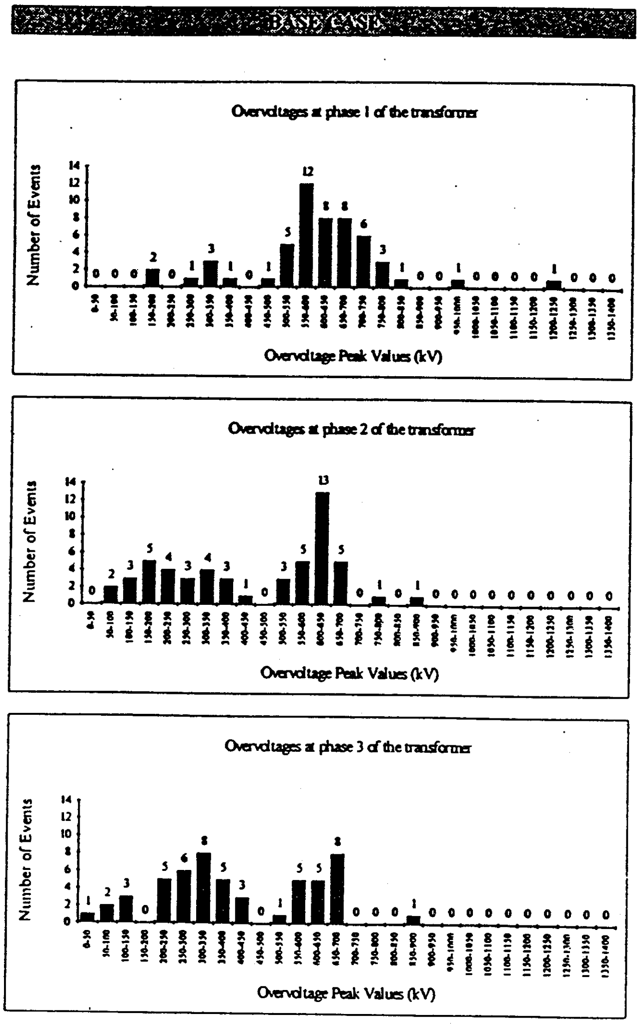

Fig. 3 - Overvoltages distribution, corresponding to the base-case study.

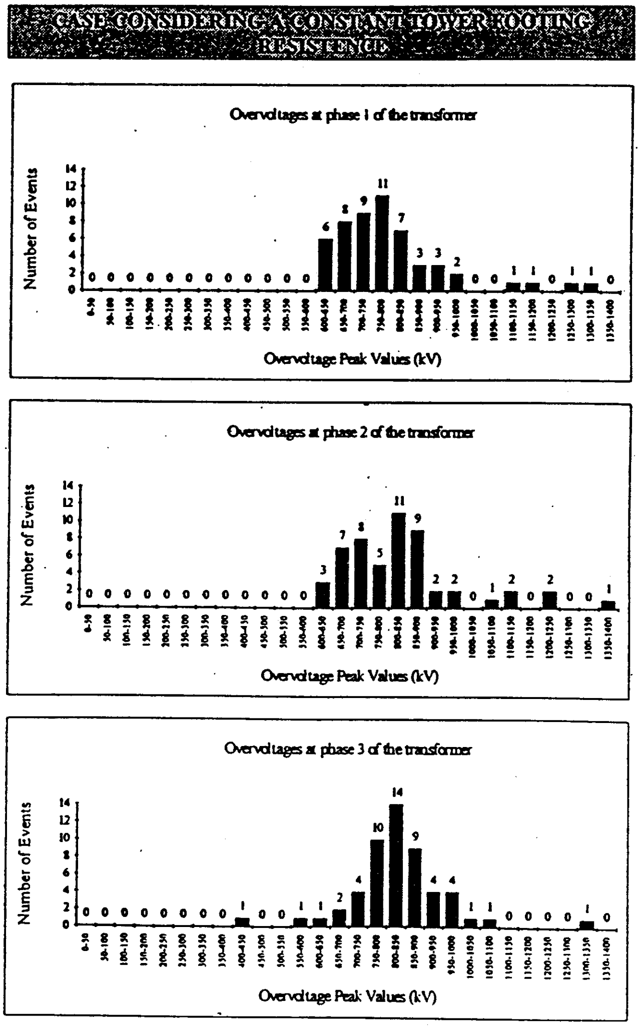

Fig. 4 - Overvoltages distribution. Computed results obtained by neglecting soil ionisation.

Tower modelling - Results shown in figure 5 were obtained considering the tower represented by a connection of lumped inductances (0.5 µH/m), according to the tower geometry. Comparision of the results presented in figures 3 and 5 show that modelling the tower by distributed or by lumped parameters does not affect significantly the statistical distribution, because time to crest of injected currents are long compared with tower propagation time. Notwithstanding, one should notice that in both cases the tower losses have not been considered.

Corona - Corona is taken into account by modifying the capacitance coefficients of the transmission line [12], according to:

$$C_{ij} = C_{0ij} + \sum_k \frac{C_{0ik} C_{0kj}}{C_{0kk}} (\gamma_k - 1) \qquad (3)$$

where the value of γ_k, at each line segment, is controlled by the electric field. This is evaluated at each time time step, taking into account the current values of the voltages and space-charges at each line segment. In the example presented here, γ_k, above the threshold field, is considered equal to 3 for the phase conductors and equal to 2 for the shielding-wire. The threshold field was set at E=25.34 kV/cm for the phase conductors and E=28.26 kV/cm for the shielding-wire. In any case, $\gamma_k = 1$, if corona is not active. In order to allow taking into account the distributed non-linear effect of corona on the wave propagation, the transmission line model presented in [13] was used.

The results obtained when taking corona into account are shown in figure 6 and are somehow surprising, because one would expect a decrease of the overvoltages at the station transformer. However, remembering that corona effect decreases the wave impedance, lower reflections occur when the overvoltage reachs the cable, increasing the peak values at the station transformer. On the other hand, corona, by affecting the coupling, also decreases the number of multiple flashovers, and the effect of this can be observed comparing phase 2 overvoltages in figure 3 and 6.

CASE CONSIDERING A CONCENTRATED PARAMETER TOWER

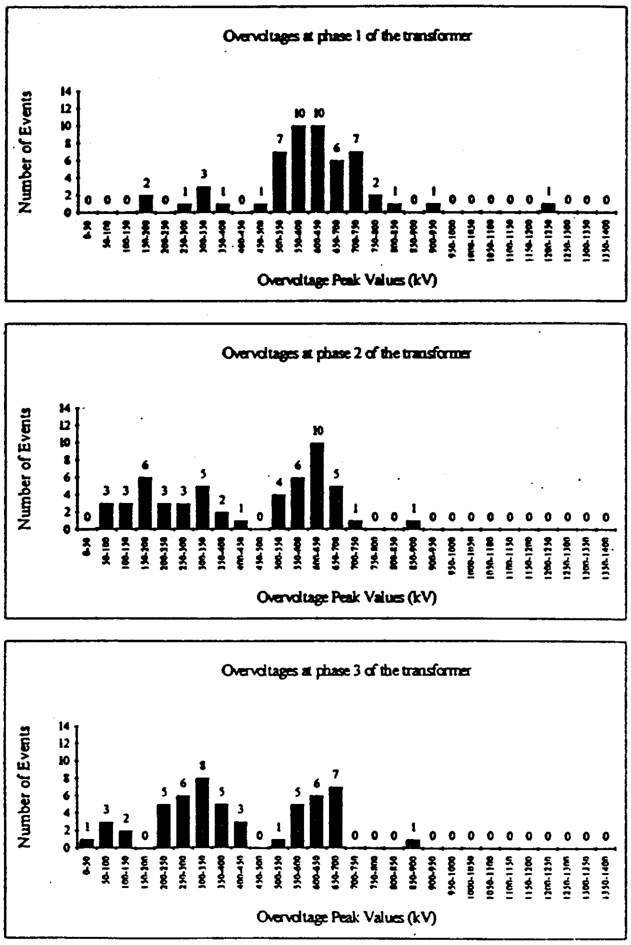

Fig. 5 - Overvoltages distribution. Computed results obtained by representing the tower as a lumped parameter.

CASE TAKING CORONA ON THE TRANSMISSION LINE INTO ACCOUNT

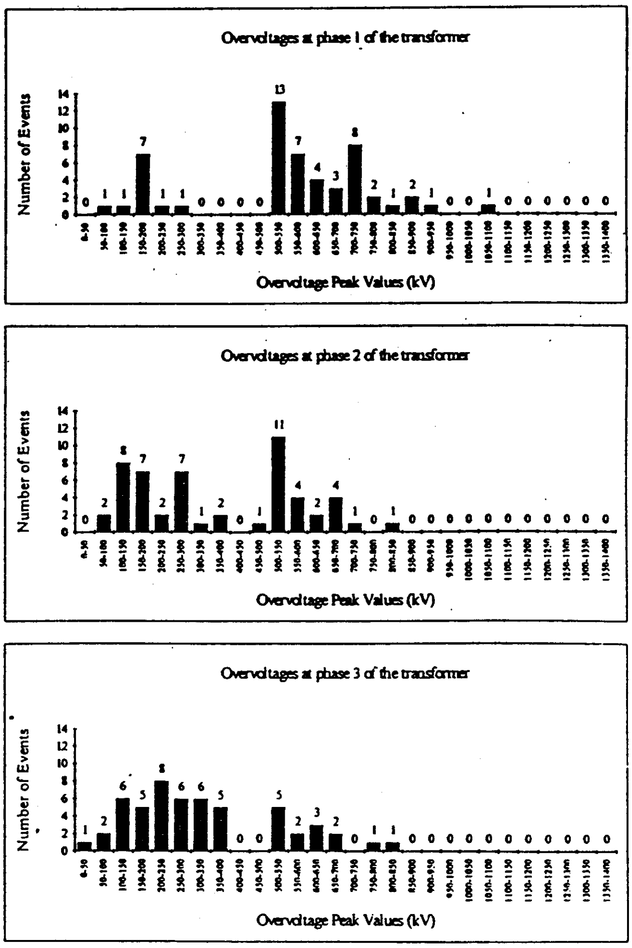

Fig. 6 - Overvoltages distribution. Computed results obtained by taking corona into account.

Transformer capacitance - It is generally accepted that the transformer can be modelled, for high frequencies, as a pure capacitance connected to each phase. However, the accurate values of these capacitances are difficult to obtain . Aproximate values are given in [11], according to the power and type of the transformer. For the present case, a value of 4.2 nF for the station transformer was obtained, and considered on the base case study. In order to evaluate the influence of these capacitance values on the overvoltages distribution, a value of 2.1 nF is also considered, and the corresponding results plotted in figure 7. Comparing these results with figure 3, we conclude that the overvoltages at the transformer do not change much. This can be explained if we remember that in both cases the transformer is close to an open circuit, even for high frequencies, due to the low value of the capacitance.

Shape of the lightning current front - A linearized lightning current front is considered, its stepness being given by the highest steepness of the concave front, as shown in figure 9. The corresponding computed overvoltage distribution is plotted in figure 8. These results, compared to the base case overvoltage distribution show that higher overvoltages are obtained using a linearized front. However, we must notice that a different linearization criteria may lead to different results. A linear rising front current causes higher overvoltages at the tower top than its equivalent concave form (figure 9), because its steepness is always equal to the highest steepness of the concave front. Therefore, comparing figure 8 with figure 3, we observe higher overvoltages at the transformer using a linear rising front. However, the difference is not significant.

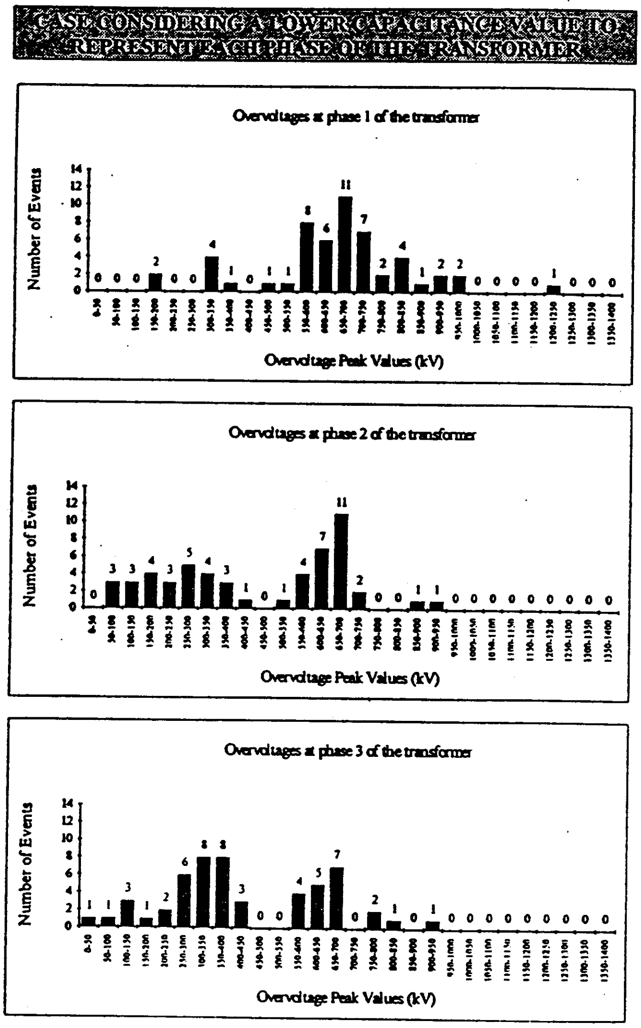

Fig. 7 - Overvoltages distribution. Computed results obtained for a lower value of the station transformer equivalent capacitance.

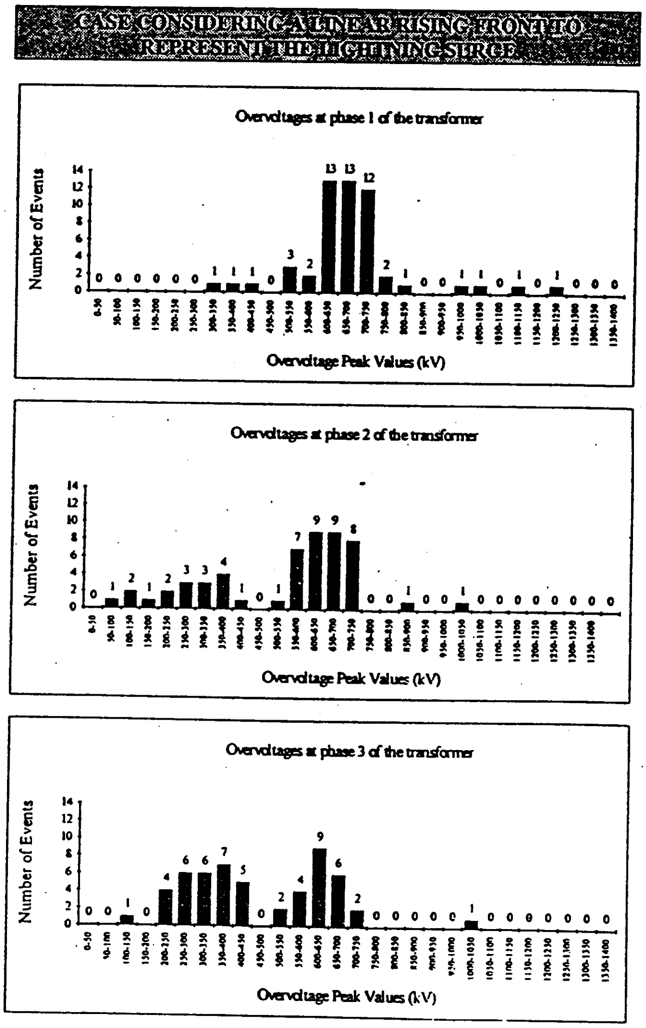

Fig. 8 - Overvoltages distribution. Computed results obtained for a linearized lightning current front.

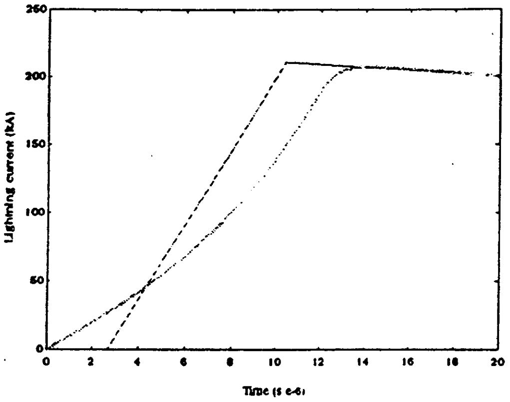

Fig. 9 - Concave lightning current fornt and its equivalent linearized waveform.

V. CONCLUSIONS

A Monte-Carlo based statistical study was performed for the overvoltages at a GIS transformer, using EMTP. The data files are automatically generated by selecting the lightning events prone to cause backflashover on the incoming line. A sensitivity study showing the influence of different modelling parameters on the computed results was performed. Results show that the farmost important parameter affecting the results is the tower footing resistence. No significant influence has been observed for the tower model, the transformer capacitance and the shape of the lightning current front. Futhermore, it was shown that corona has a complex effect, as it affects simultaneously the coupling between conductors (shield wires and phase conductors), the wave attenuation and the reflection factor at the entrance of the substation.

VI. ACKNOWLEDGMENT

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