ANALYSIS OF CONDUCTIVE, CAPACITIVE AND INDUCTIVE COUPLINGS IN HV TRANSMISSION LINES IN FREQUENCY AND TIME DOMAIN

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AUTHOR BIOGRAPHICAL NOTES

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ABSTRACT

The aim of this work is to study the physical behaviour of an HV transmission line (composed by phase conductors, towers and earth-wire overhead line) connected to the earth by earthing systems of the power substations located at its end points.
The analysis is carried out both when an earth fault occurs (frequency domain simulation) and when a lightning strokes directly the line earth-wire (time domain simulation).
In the first case the current distribution along the whole system is determined (in particular the current leaked by the grounding system of towers) and shows an interesting phenomena due to the change in phase angle of the fault current along the line.
In the second case time distribution of current, scalar potential and electromagnetic field are computed either at important points of the system or in the surrounding medium.
The analysis above described is carried out by means of a new computer code called AGSA (Aerial and Grounding System Analysis) which is able to simulate the physical behaviour of a conductor system, located indifferently in air and/or in the soil, having complex geometry.
The current distribution along the conductors and in the earth and the distribution of electromagnetic field and scalar potential in the surrounding medium can be computed.
The algorithm which has been implemented in AGSA make it able to operate both in frequency (almost up to 2 MHz) and in time domain (by means of FFT) . Therefore, it can be used to carry out an accurate analysis for electric power systems both under normal operating conditions (50÷60 Hz and harmonics) and when they are stroked, directly or indirectly, by a lightning.

INTRODUCTION

Under normal operating conditions of a power system, the currents flowing along the earth-wires of overhead lines are only those induced because of inductive coupling between these and the phase conductors. For the same reason, currents dispersed into the soil are small, and no hazardous situations are of concern in this case. Generated electromagnetic fields are also of minor interest. However, under fault conditions, that is either when an unsimmetrical fault occur or when a lightning strikes a transmission line, both earth-wires and soil may be interested by large currents which could lead, for particular conditions, to potentially dangerous situations. The preventive analysis of these effects, in particular the computation of the fault current distribution along the earth-wire and inside the soil as well as the connected effects (i.e. potential distribution and electromagnetic fields), becomes then very useful.
Some examples of this kind of analysis are presented in this paper, showing some sample results obtained by means of a specifically developed software called AGSA (Aerial and Grounding System Analysis), with which any system having complex geometry and various characteristics may be considered. This tool results very useful for studying practical cases, at the same time dealing with rigorous theoretical aspects which have been considered for implementing the numerical routines, as shown in the paper.
For a complete description of the numerical procedure, the reader may refer to the suggested literature.

LOW FREQUENCY PHENOMENA (50 Hz)

Generally, the study of the current distribution in an electrical system under ground faults conditions is rather laborious because phase conductors, earth-wire and soil are involved at the same time.
In the case of a power substation where two or more transmission lines are connected, a simplified approach can be adopted. The n 'active' lines which contribute to the fault current, have a different physical behaviour from the m "passive" lines whose contribute to the fault current is null.
Because of the inductive coupling between circuits composed by phase conductors and earth return and the circuits constituted by earth-wires and earth return, each earth-wire of an active lines is affected by a bigger portion of fault current. Obviously this is true only if the earth-wire is connected to the earthing system of the power substation.
Let Igi represent the contribution to the total fault current Ig supplied from the i line and Iti the remaining portion of the current flowing in the earthing system of the power substation. The reduction factor is defined as follow:

$r_i = It_i / Ig_i$

The current which flows along the earth-wire because of the inductive effect is then:

$Iw_{i1} = (1 - r_i) Ig_i$.

The reduction factor r depends on several parameters such as: material of the earth-wire and its zero-sequence impedance, distance between earth-wires and phase conductors, earth resistance of line towers and earth resistance of the connected power substation, earth resistivity etc...
If the power substation is connected to n active lines then:

$$It = \sum_{i=1}^{n} It_i = \sum_{i=1}^{n} r_i Ig_i$$

Both active and passive lines (that is connected to the earthing system of the power substation) participate to the drainage of a part of the fault current since they represent an auxiliary grounding system in parallel to the main grounding system of the power substation. The equivalent impedance of the system composed by tower and earth-wires can be calculated as:

$$Zp = \frac{Zw}{2} + \sqrt{ZwRs + \frac{Zw^2}{4}}$$

where Zw represents the zero sequence impedance of one span of the earth-wire and Rs the earth resistance of a tower. The total earth impedance of the system composed by power substation and earth-wires is then:

$$Zt = \frac{1}{\frac{1}{Rt} + \sum_{i=1}^{n+m} \frac{1}{Zp_i}}$$

From the value of the total earth voltage, calculated as $Ut = ZtIt$, it is easy to compute the current which flows along the earth-wire line as follows:

$$Iw_{i2} = \frac{Ut}{Zp_i}$$

Consequently, the total current which flows through the earth-wire of an active line is:

$$Iw_i = Iw_{i1} + Iw_{i2}$$

By means of AGSA it is possible to compute any electromagnetic parameters either along a profile or over a surface as defined by the user. As input data, AGSA require only the physical data of the system (geometry and material characteristics), the topology of the electrical connections between conductors and the characteristics of the sources that feed the conductor system.
A simplified electrical system composed by a power substation and two connected lines (the first active and the second passive) is considered (Fig. 1).

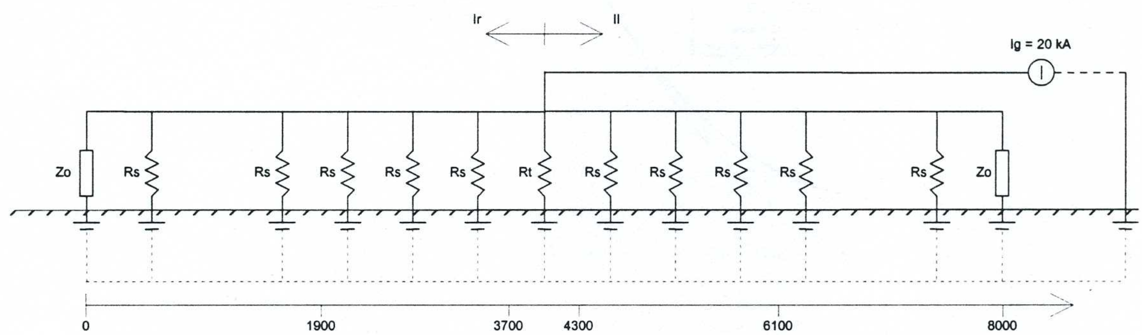

Fig. 1 System under studied with AGSA

As an example a 4 km length has been chosen for both lines with an adaptation impedance at each receiving end which is equivalent to consider two infinite length lines. Both lines have identical physical characteristics (identical geometry of the spans, towers etc) aiming at showing that inductive coupling in an active lines has an important role in the earth-wire current distribution.
In Fig. 2, the current distribution along earth-wire calculated by AGSA is presented.
Although the potential at the sending end of the two earth-wires is the same, current distributions in the two cases are completely different. The current on the active line earth-wire is greater because of the mutual inductive coupling between phase conductors affected by the fault current (zero sequence component) and respective earth-wire. The mutual inductive coupling produces an induced voltage which increase the current along the earth-wire. It is important to notice that AGSA considers all the phenomena above mentioned and provides for each point of the system the current and potential values. For example the potential distribution along the earth-wire is shown in Fig 3.
Furthermore AGSA enable to calculate electromagnetic parameters generated by electric power systems in the surrounding medium (see Fig 4 and Fig 5)
The distribution of the potential on the earth surface along the line axis is due to leakage current from the tower.
Because of the effect of the inductive coupling, the leakage currents and the potential distribution are more uniform in the case of an active line and then it is possible to have hazard because of touch and step voltages also in correspondence to towers far from the power substation where the fault has occurred.

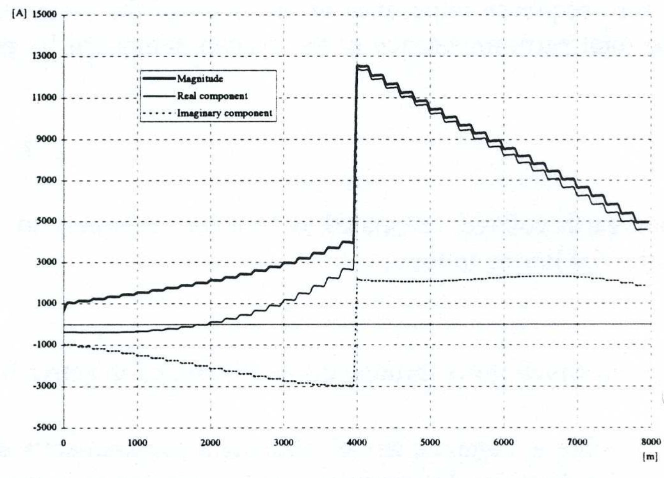

Fig. 2 Distributions of the current along earth-wire on the system of Fig 1.

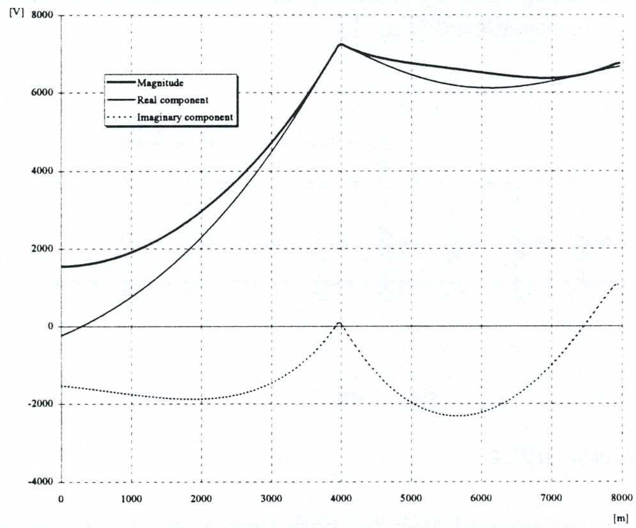

Fig. 3 Distributions of the potential along the earth-wire on the system of Fig. 1

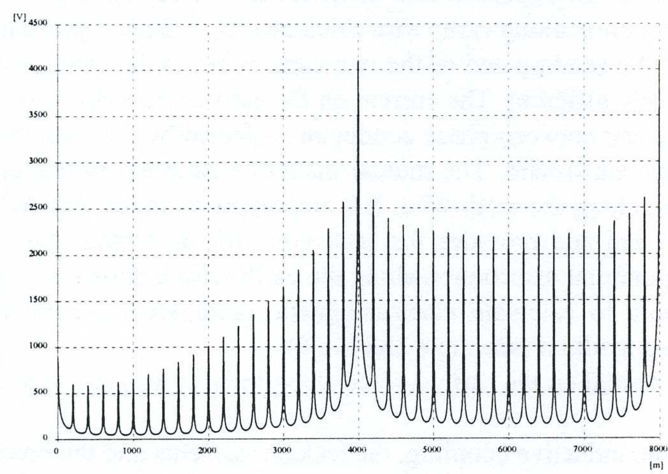

Fig. 4 Distributions of the earth potential along the axis of the line on the system of Fig. 1

As may be seen in Fig 5, the magnetic field is maximum in correspondence of the line axis. Furthermore, magnetic field is particularly strong far away from the fault section and in correspondence of the active line. In this section the field value exceeds the 40 A/m against maximum values of field that under normal operating conditions are about 15 and 17 A/m for 220 and 380 kV lines respectively.

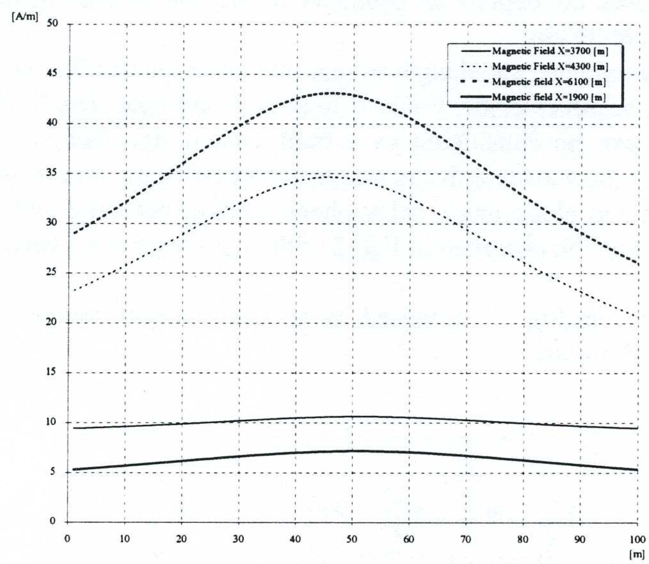

Fig. 5 Distributions of magnetic field in correspondence to some sections on the system of Fig. 1

Some comments may be done upon the behaviour of the currents drained by the passive line earth-wire in order to show a particular phenomena, due to the phase variation of the voltage and current phasors along the earth-wire. This is usually dealt with an analytical approach, which may find its correspondence by means of AGSA.
Let x an axis along a generic line between sending and receiving end s and r (Fig. 6).

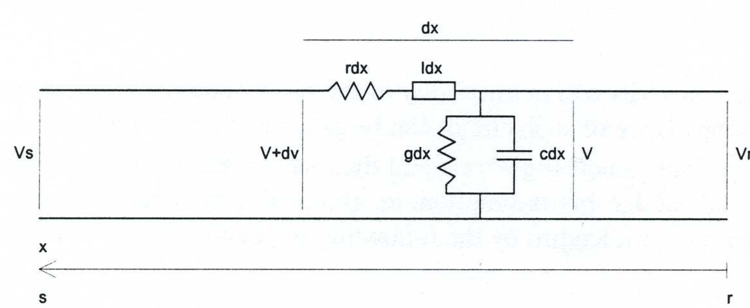

Fig. 6 Equivalent circuit of a transmission line

Potential and currents along an adapted line are given by the following equations:

$$\dot{V}(x) = \dot{V}r\, e^{\dot{k}x}$$

$$\dot{I}(x) = \frac{\dot{V}r}{\dot{Z}o} e^{\dot{k}x}$$

where $\dot{k} = \sqrt{\dot{z}\dot{y}}$ indicates the transmission constant, $\dot{Z}o = \sqrt{\dot{z}/\dot{y}}$ the characteristic impedance, and where $\dot{z} = r + j\omega l$ and $\dot{y} = g + j\omega c$ indicate the longitudinal impedance and transversal conductance per unit length respectively.
The magnitude and phase angle of potential and current decrease with the distance x in an exponential way which depends on the real and imaginary component of the transmission constant

respectively. The line wavelength λ can be defined as the portion of line in correspondence of which the phase angle delay is 2π.
In the case of an ideal line ($r = 0,\ g = 0$) the wavelength can be calculated as:

$$\lambda = \frac{2\pi}{\mathrm{Im}(\dot{k})} = \frac{2\pi}{\omega\sqrt{lc}}$$

In such case $lc = \mu\varepsilon$ and does not depend on geometry of the line. In case of line insulated in air at 50 Hz wavelength is about 6000 km.
Because of dissipative phenomena, wavelength in real line becomes smaller, however the magnitude and phase angle changing becomes evident only if long lines are considered. The system composed by tower and earth-wire can be considered as a transmission line having a big value of shunt conductance. Consequently the wavelength can assume values of some tens kilometres. In such case, the magnitude attenuation and phase angle delay phenomena of potential and of currents are more evident. Such phenomena may be observed in Fig. 2, although they can be verified in a better way if a longer line is considered.
Let us consider the system in Fig. 7 composed by an ideal current source, tower and earth-wire closed to the earth at its end points.

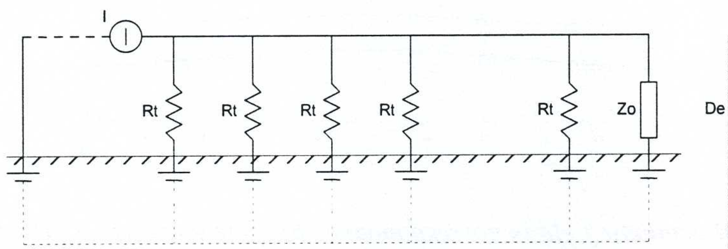

Fig. 7 System composed by tower and earth-wire closed to the earth at its end points

Based on Carson's theory, the effects of the current flowing through the soil can be evaluated considering an image conductor located in the soil at a distance from the earth-wire given by the following expression:

$$De = 0{,}74\sqrt{\frac{\rho}{f\mu}}$$

where ρ and μ indicate resistivity and permeability of the soil respectively. The transmission constant and the characteristic impedance of such circuit can be calculated once *r* and g are known.
In practical cases (at low frequencies) g >> ωc and then the capacitive coupling between earth-wire and soil can be neglected. Under this assumption, longitudinal impedance and transversal admittance of the system are given (per unit length) by the following expressions:

$$\dot{z} = r + \frac{1}{4}\mu\pi f + j\mu f \ln\frac{De}{d/2}$$

$$\dot{y} \cong \frac{1}{Rs\ ls}$$

where *d* is the earth-wire diameter, *Rs* is the earth resistance of tower and *ls* is the span length.
Once determined the longitudinal impedance and transversal admittance, it is easy to obtain $\dot{k}$ and then the wavelength λ.
An example can be useful.
Let us consider an alumoweld earth-wire having 160 mm^2 section, 16.5 mm diameter and 0.224 Ω/km resistance (at 20 °C). The average span length is 200 m, tower grounding resistance 15 Ω and 100 Ωm earth resistivity. The resulting distance from the earth-wire and the image conductor is De = 933m.
Consequently we obtain:

$$\dot{z} = 0{,}224 + 0{,}0493 + j0{,}0628 \ln \frac{933}{16{,}5\,10^{-3}/2} = 0{,}273 + j0{,}731 \frac{\Omega}{km}$$

$$\dot{y} = 0{,}333 \frac{S}{km}$$

$$\dot{Z}o = 1{,}26 + j0{,}870 \frac{\Omega}{km}$$

$$\dot{k} = 0{,}420 + j0{,}290 \frac{1}{km}$$

$$\lambda \cong \frac{2\pi}{0{,}290} = 21{,}6\,km$$

In other words, potential and current phase angle variation per unit length is approximately 16.6 deg/km. If the current injected in the system lies on the real axis and the line is adapted, then the phase angle difference between potential and current at the sending end of the line is equal to the argument of the characteristic impedance.

Along the earth-wire the phase angle of the potential and current change with a rate of 16.6 deg/km

Furthermore potential and current magnitude decrease with the distance x exponentially depending on the real part of the transmission constant of the line (see Fig. 8).

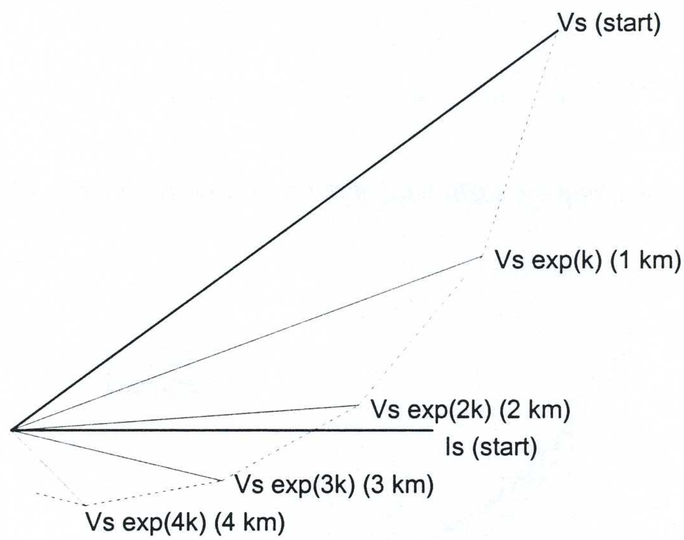

Fig. 8 Potential along the earth-wire

The current leakage in the soil from the tower can be calculated as:

$$\dot{I}l(x) = \frac{\dot{V}(x)}{Rt}$$

The leakage current has the same phase angle of the potential.

Consequently leakage current at a distance equal to $\lambda/2$ is not injected in the soil but on the contrary it is 'captured' from the earth.

The theoretical predictions are confirmed from the simulations carried out by AGSA.

The distribution of potential shown in Fig. 9 are referred to a 8 km long line.

The earth-wire, tower and soil have the same characteristics above indicated. The earth-wire is adapted to its end section and 10 kA current is injected at the begin of the line.

From analytical expression it is possible to state that the imaginary component of the potential of the earth-wire became zero in correspondence of the section situated at a distance x given by the following expression:

$$x = \frac{\angle \dot{Z}o}{\Im(\dot{k})} \cong 2{,}1 \quad km$$

This is confirmed, with a good approximation, also by the simulation carried out by AGSA (see Fig. 9). Fig. 10 shows the current distribution along the earth-wire. The distribution presents discontinuity in correspondence of each tower.

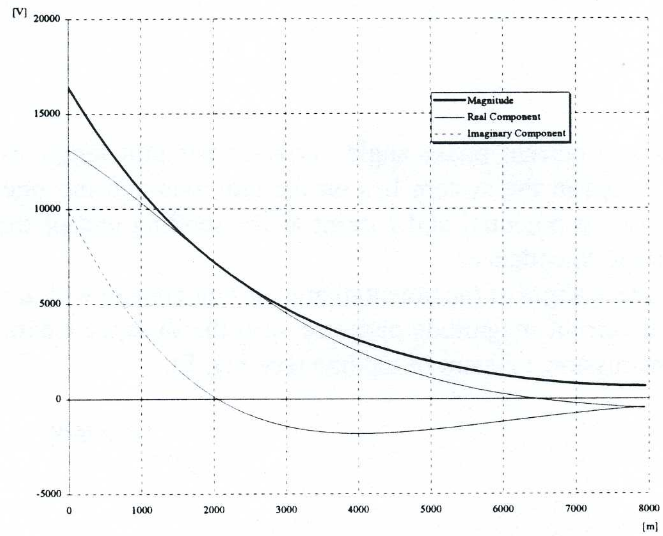

Fig. 9 Potential distribution along the earth-wire of the system represented in Fig. 7

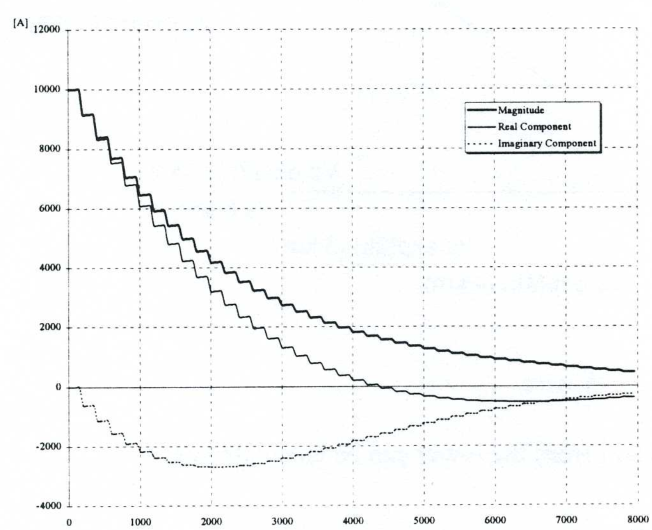

Fig. 10 Currents distribution along the earth-wire of the system represented in Fig. 7.

The result obtained with AGSA are consistent with the theoretical predictions. AGSA can be successfully used also in more complex and practical cases while an analytical approach can be considered only for simple and often theoretic studies.

HIGH FREQUENCY PHENOMENA (LIGHTNING IMPULSE)

Transients associated to lightning discharges are different one to each other and, in any case, they are very fast.

It is usual to distinguish negative and positive lightning (which are originate from lower and upper part of the clouds respectively). Negative lightning occurs more frequently than the positive ones (about 80%), are normally multiple and respect to positive lightning they have a lower total charge and a faster front rise.

Fundamental frequencies associated to the lightning current are in the 1÷100 kHz range for negative lightning and in the 0,3÷100 kHz range for the positive ones. Frequency spectrum associated to lightning discharge can be extended up to some MHz.

Typical lightning waveform exhibit a 0.2 to 1.5 μs rise time and persist for 50 to 200 μs for negative and positive cases respectively.

For testing and standardisation purposes, a standard lightning wave has been established, the so called 1,2/50 μs waveform. Since the speed propagation of transient along transmission lines is about 300 m/μs and the transmission lines are usually very long it is necessary to consider their equivalent distributed parameters circuits.

To demonstrate the usefulness of the code AGSA also for analysis of systems stroked by a lightning the following example is considered.

The earth-wire aim consists to shield the below phase conductors from the lightning discharge.

Generally only a small percentage of lightnings (< 5%) stroked directly the phase conductors.

Normally lightnings can stroke directly the earth-wire or more frequently the top of the tower.

Let us consider this second case: a portion of the lightning current is leakage to the earth from the ground tower while the remaining portion flow along the earth-wire with two wave travelling in opposite direction.

When travelling wave meet the discontinuity they will be partially reflected and partially transmitted and after a time equal to that necessary for the propagation of the wave along two spans they come back to the stroked point.

If the span is 200 m long then the first reflected wave come back to stroked point approximately after 1.3 μs.

If a standard 1.2/50 μs waveform is considered when the reflected wave came back to the stroked point the peak value of the potential wave is already reached and its value is given by the following expression:

$$Vs = \frac{Rs\,Zg/2}{Rs + Zg/2} If$$

where Zg represents the characteristic impedance of the earth-wire (normally in the 400 ÷ 500 Ω range) and If is the peak value of the lighting current.

The potential difference applied to the line insulators can be computed as:

$$Vps = kVps$$

where k represents a reduction coefficient due to the capacitive and inductive mutual coupling between earth-wire and phase conductor and its value is normally in the 0.7 ÷ 0.9 range.

Normally line insulator are designed in such way to be proof against lightning having typical parameters. Only the strongest lightning (which occur with a known percentage) are able to cause the breakdown discharge in the insulator.

Let us consider the system shown in Fig. 11.

At the indicated point in the Fig. 11 a typical double exponential current waveform is injected. In Fig.12, the current time distribution at the middle section of the earth-wire span and in the middle section of the stroked tower are shown.

As shown in Fig 12 current time distribution present evident oscillations overall in the initial portion. Such oscillation occur with a time period corresponding to the time require to the travelling wave to cover a distance equal to twice of the span length (1,3+1,3 = 2,6 μs).

It is possible to confirm this fact considering the same system with a 400 m spans length

In Fig.13 current time distribution at the middle section of the span when the same lightning of the previous case is injected in correspondence to the same tower shows is shown.

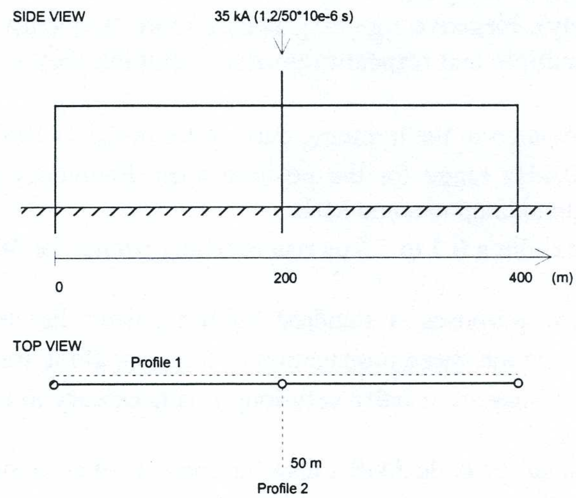

Fig. 11 Geometry of the system studied by AGSA

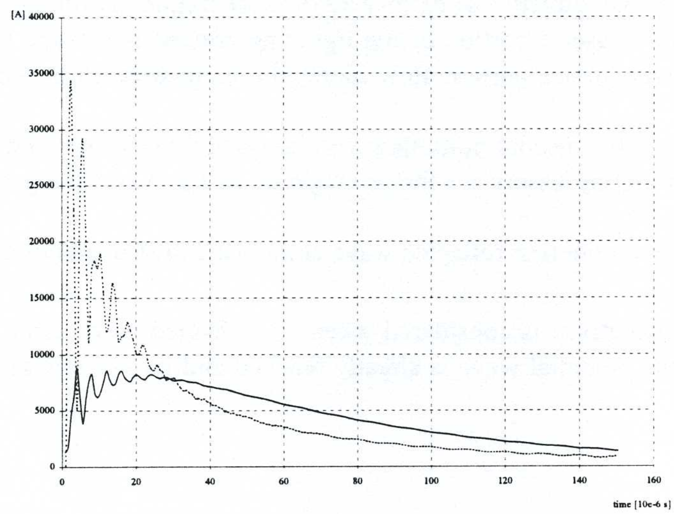

Fig. 12 Current time distribution as a function of time (continuous line: earth wire – dot line: stroked tower)

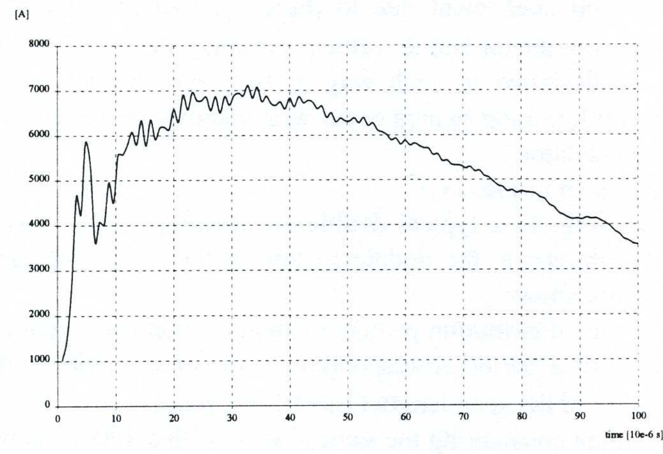

Fig. 13 Current time distribution as a function of time

Finally, Figs. 14, 15 and 16 represent the earth potential distribution computed along profile 1, and magnetic and electric field distribution calculated along profile 2 respectively (profile 1 and 2 are defined in Fig 11).

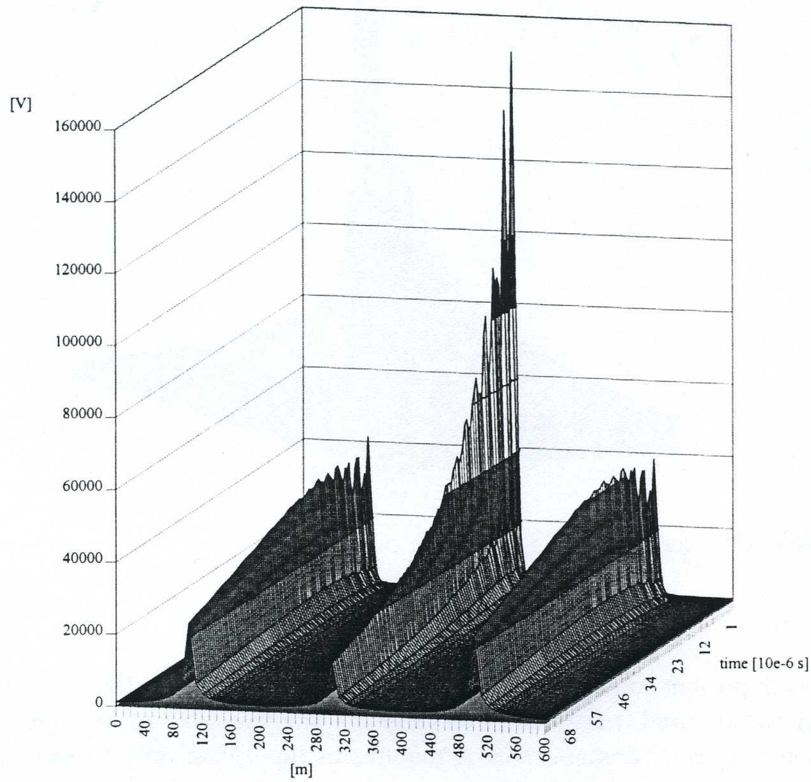

Fig. 14 Earth potential along profile 1 Fig. 11

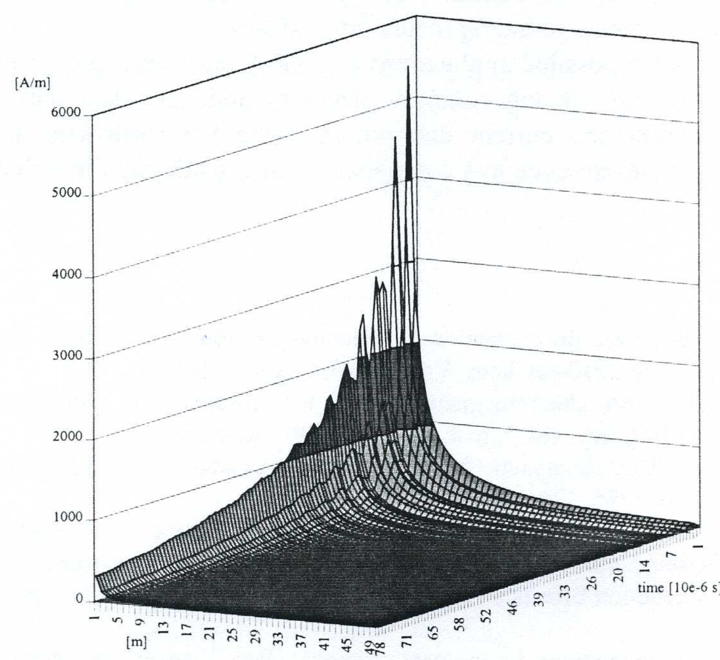

Fig. 15 Electric field along profile 2 Fig. 11