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Current and Potential Rise Distribution in Ground Structures Along an Energized H.V. Transmission Line

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Abstract – In this paper a new study is presented to determine the transient induced current distribution and the transient ground potential rise of the grounding structures along an energized H.V. transmission line (at no-load or in short-circuit). The method is based on modelling of power system elements in direct phase quantities. The method consists to represent each line span by a number of Π sections in cascade with mutual coupling between conductors included. Each tower is represented by an equivalent inductance calculated by its surge impedance and its propagation time. A computer program and simulation have been done to compute, transient currents in any element and segment of the network, transient ground potentials rise (TGPR) of the grounding structures and the peak values of these currents and TGPR.

1. INTRODUCTION

Energization creates a transient on the transmission line at the breaker which propagates at nearly the velocity of light to the open end. The propagation of currents and voltages creates induced transient currents on the ground wires. The currents return to the source station through the grounding structures (towers, ground rods, ground mats, etc.) and through ground (earth). The currents which flow into the ground through the grounding structures, raise the potential of these structures with respect to remote ground. This potential difference is called ground potential rise (GPR), and it is equal to the grounding structure impedance times the current flowing into ground through the grounding structure.

The primary design objective of electric power grounding systems is to ensure safety of persons and animals from electric shocks and ensure the protection of installations and electrical equipments, by the minimization or confinement of ground structure GPR within safe limits.

It is very important to know the magnitude and the waveform of the currents flowing through the grounding structures, through ground wires or neutral conductor and in each element of the network, for the following reasons:

1. To calculate accurately the electromagnetic interference between power line and nearby telecommunication lines.
2. To calculate the potential rise of stations and grounding structures which are used to compute step, touch and transfer voltages which may cause electric shocks. These voltages are used to evaluate the performance and reliability of existing grounding structures and to design safe grounding systems.

This paper presentes a new study to compute in transient, the current distribution in the grounding structures and the potential rise of these structures along an energized H.V. transmission line. The line may be at no-load, in fault or in short-circuit for line maintenance while safety grounds are in place. A computer program and simulation have been done to determine the current and voltage waveformes in the the grounding structures and the peak values of these waveformes.

2. PROPOSED METHOD

2.1 General considerations

The analysis of the transient current distribution in each element of the line and ground structures is very difficult mainly due to the complexity and number of influencing factors. These factors are: soil resistivity which vary along the line, conductors arrangement on the tower, number and material of conductors, source impedances and especially the accurate model of each element in transient (lines, towers, ground rods, ground grids, etc.) and the impedance values of these elements.

The general network configuration considered in this study consist of an single circuit three phase overhead transmission line with one ground wire. The line is energized from a terminal station (source) by a circuit breaker (see figure 1). The line can be assumed for both transposed and untransposed configurations. The source at the station may be a generator or may represent the external power system represented by the equivalent Thevenin impedance in series with an ideal voltage source. The station is assumed to be grounded with a grounding mat or grid, the towers with a ground rod. The neutral transformer of the station may be isolated, connected directly or by an impedance to soil. The closure of the circuit breaker may be simultaneous or non-simultaneous with closing resistors or not. The fault or the short-circuit may be any type and at any location of the line.

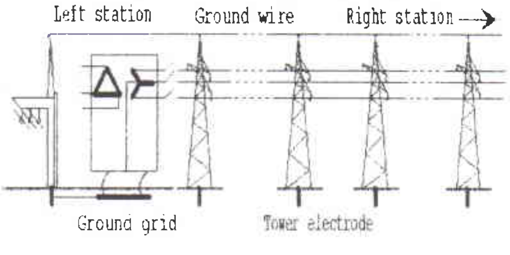

Fig. 1 Study system

2.2 Equivalent circuit and models

2.2.1 Line model

The proposed equivalent scheme of a line span (segment line between two neighboring towers) is represented in figure 2. Each line span is represented by a number of three phases Π sections with coupled parameters connected in cascade of different lengths [1].

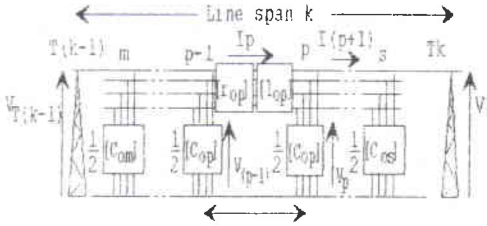

Fig. 2 Equivalent scheme of a line span

Applying Kirchhoff laws, the differential equations at the p^{th} line section are:

$$\frac{d}{dt}[I_p]_j = -[l_{op}]_j^{-1}\left([r_{op}]_j[I_p]_j + [V_{(p-1)}]_j - [V_p]_j\right) \quad (1)$$

$$\frac{d}{dt}[V_p]_j = 2\left[c_{op} + c_{o(p+1)}\right]_j^{-1}\left([I_p]_j - [I_{(p+1)}]_j\right) \quad (2)$$

where
$j = 1, 2, 3$ and g, represents the phases, and ground wire; respectively.
$[l_{op}]_j$, $[r_{op}]_j$, $[c_{op}]_j$ are the p line section inductance, resistance and capacitance matrices 4×4, respectively.
$[I_p]_j$ is the current column vector in the p^{th} line section.
$[V_p]_j$ is the voltage column vector at node p.
The line parameters are computed using Carson's formula expressed in terms of frequency, line configuration and ground resistivity [2]. The line parameters are computed for a frequency around 1000 Hz which is the average dominant frequency of the transient.

2.2.2 Tower, station grounding grid and tower electrode models

At the transient frequencies present in this study, it is adequate to represent the towers by a lumped inductance (Fig. 3). The inductance is given by the following expression [3]:

$$L_T = Z_T \times t \quad (3)$$

where Z_T is the characteristic impedance and t is the travel time through the tower.

For the ground grid, the resistance is given by the following expression [4]:

$$R_G = \rho\left(\frac{1}{4r} + \frac{1}{L}\right) \quad (4)$$

where
ρ: soil resistivity in Ωm,
L: total length of grid conductors in m,
r: radius of circle with area equal to that of grid in m.
For the tower electrode, the resistance (Fig. 3) can be expressed as [5]:

$$R_T = \rho\frac{1}{2\pi r_o} \quad (5)$$

where r_o is the radius of an equivalent hemispherical electrode having the same ground resistance as the tower, this radius is in the order of two to three meters for an average single or double circuit tower.

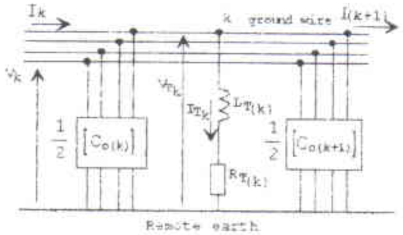

Fig. 3 Tower and tower electrode models

$R_T(k)$ is the electrode resistance of tower Tk,
$L_T(k)$ is the inductance of tower Tk.

2.3 Resolution method and computer program implementation

By writing the differential equations of currents (1) and voltages (2) at each section and each tower and at the source, we obtain a system of first order differential equations. The system is solved with the fourth order Runge-Kutta method. The initial conditions are zero, we suppose the line initially at rest. A computer program has been established, written in Fortran language. The program is flexible and can be used for various network configurations.

3. APPLICATION AND RESULTS

For this calculations, the line voltage is of 345 kV, where the configuration is represented in figure 4 [5]. The line is assumed of 50 km long, supported by 201 towers and represented by 600 Π sections in cascade. The soil resistivity is assumed to be 100 Ωm throughout the entire length of the transmission line. The tower spacing and tower footing resistances along the line are assumed to be uniform and they are equal to 250 m and 20 Ω, respectively. The characteristic impedance and the travel time through the tower for all towers are equal to 140 Ω and 96 ns. respectively. The ground wire is connected to the ground grid by a terminal tower of characteristic impedance and travel tower equal to 100 Ω and 86 ns. respectively. The neutral of transformer is connected directly to the ground grid. The ground grid resistance of the station is supposed equal to 0.3 Ω. The breaker pole of phase 1 closes at time $t = 0$ s, phase 2 closes 3 ms later and phase 3 closes 5 ms later, The closing resistors are set to 300 Ω with an insertion time of 8 ms. The source parameters are :

Generator : 15 kV, 160 MVA, $X_d'' = 0.185$ pu.
Transformer : 15 kV/345 kV, 200 MVA, $x_d = 0.1$ pu.

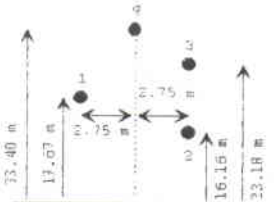

Fig. 4 Tower configuration

3.1 Energization of the no-load line

3.1.1 Currents distribution in towers

Fig. 5 shows the transient current in the first tower (and tower electrode).

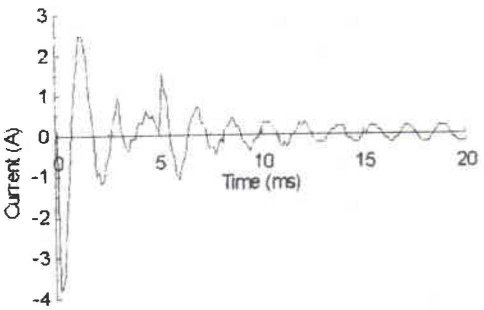

Fig. 5 Currents (A) in the first tower

Fig. 6 shows the peak values distribution of these currents.

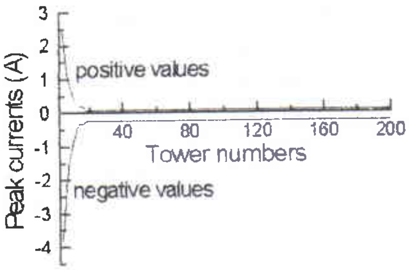

Fig. 6 Peak values of currents in towers

3.1.2 Voltages distribution in tower electrodes

Fig. 7 shows the transient voltages in the first tower electrode.

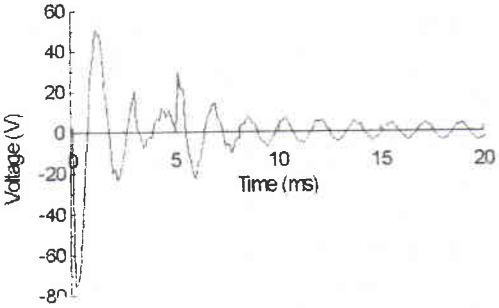

Fig. 7 Voltage (V) in the first tower electrode

Fig. 8 shows the peak values distribution of these voltages.

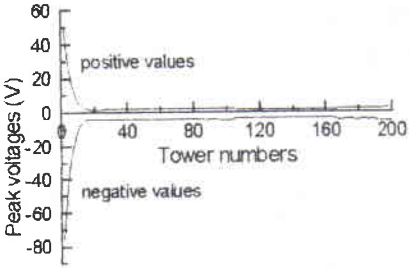

Fig. 8 Peak values of tower electrode voltages

3.1.3 Ground wire currents distribution in spans

Fig. 9 shows the transient ground wire current distribution in the first span.

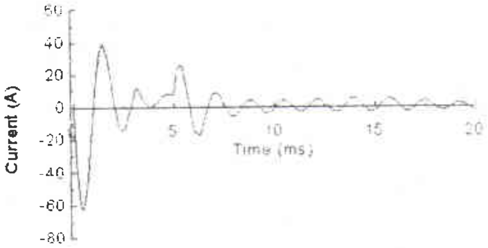

Fig. 9 Ground wire currents (A) in the first span

Fig. 10 shows the peak values distribution of these currents.

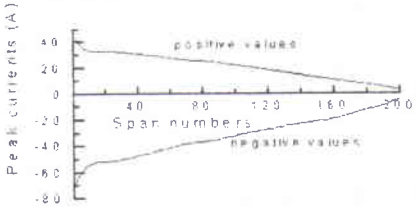

Fig. 10 Peak values of the ground wire currents in spans

3.1.4 Ground grid voltage

Fig. 11 shows the station ground grid voltage waveform.

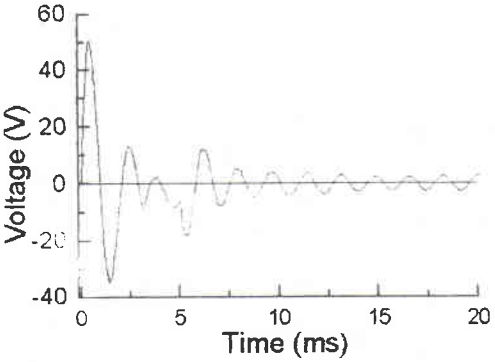

Fig. 11 Station ground grid voltage

The results obtained show that the biggest values of the peak currents in towers and the peak voltages in tower electrodes are obtained at the first tower, -3.8 A and -75.4 V respectively. The currents and voltages decrease to attain the zero value. The same thing for the ground wire currents in spans, the big maximum value (-69 A) is obtained at the first span.

3.1.5 Effect of the connection of the ground wire at the station ground grid

Figs. 12 and 13 show respectively the distribution of the peak values of the currents in towers (and tower electrodes) and of the tower electrode voltages when the ground wire is connected or not at the station ground grid. The results show that the peak values decrease rapidly to a negligible value and the peak values in the case where the ground wire is connected a the station ground grid are lower than in the case where the later is disconnected.

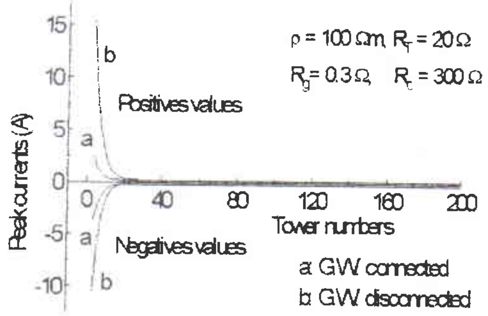

Fig. 12 Peak values of currents in towers

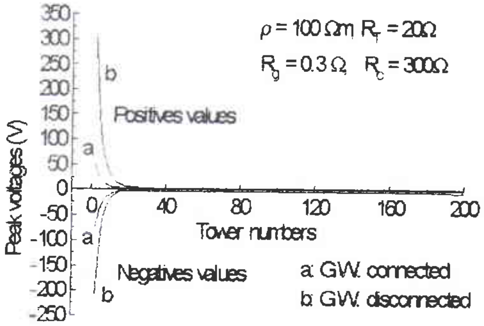

Fig. 13 Peak values of tower electrode voltages

Fig. 14 show the distribution of the peak values of the ground wire current in spans when the ground wire is connected or not at the station ground grid. The results show that the peak values decrease along the line. At the first span, the peak values in the case where the ground wire is connected a the station ground grid are greater than in the case where the later is disconnected .

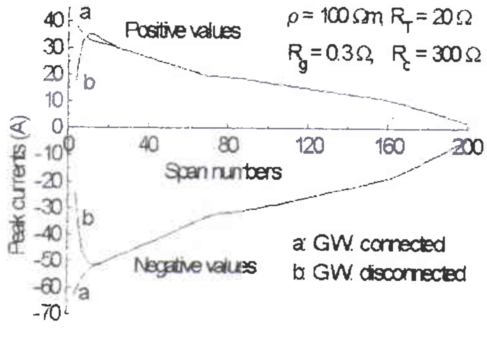

Fig. 14 Peak values of the ground wire currents in spans

3.2 Energization of the line in short-circuit

Energization of a line in short-circuit is accidental while safety grounds are in place (short-circuit of the conductors to soil) for line maitenance, or the line is in fault. We suppose that the short-circuit is three-phase with the *72nd* tower from the station.

3.2.1 Currents distribution in towers

Fig. 15 shows the current waveform at the *72nd* tower. Fig. 16 shows the positive and negative peak values distribution of the currents in the towers.

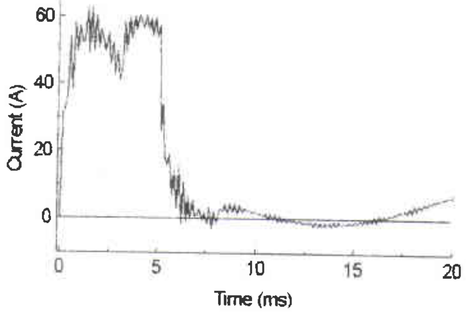

Fig. 15 Currents in the 72nd tower

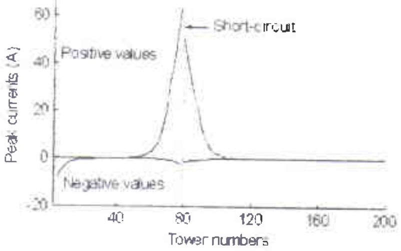

Fig. 16 Peak values of currents in towers

The results obtained show that the positive biggest value of the peak currents (63.3 A) is obtained at the short-circuit location (*72nd* tower). The peak currents decrease rapidly on the both sides of the short-circuit to a negligible value from the *60th* tower at the left side and from the *100th* tower at the right side. The negative peak values are smaller than the positive peak values and decrease rapidly to a negligible value from the first tower.

3.2.2 Voltages distribution in tower electrodes

Fig. 17 shows the voltage waveform at the *72nd* tower electrode. Fig. 18 shows the positive and negative peak values distribution of the tower electrode voltages.

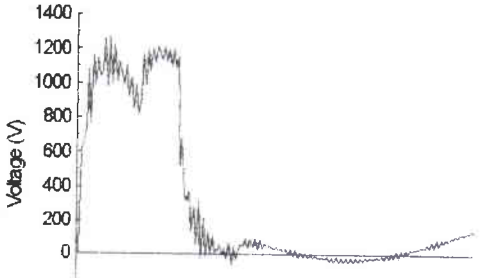

Fig. 17 Voltage in the 72nd tower electrode

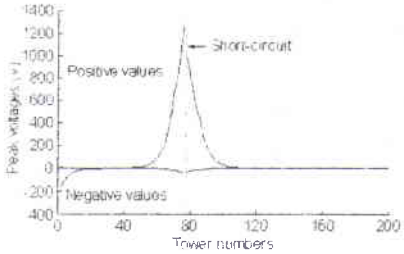

Fig. 18 Peak values of tower electrode voltages

The results obtained show that the positive biggest value of the peak voltages (1266.6 V) is obtained at the short-circuit location ($72nd$ tower). The peak voltages decrease rapidly on the both sides of the short-circuit to a negligible value from the $60th$ tower at the left side and from the $100th$ tower at the right side. The negative peak values are smaller than the positive peak values and decrease rapidly to a negligible value from the first tower.

3.2.3 Ground wire currents distribution in spans

Fig. 19 shows the current waveforms at the $72nd$ and the $73rd$ span.

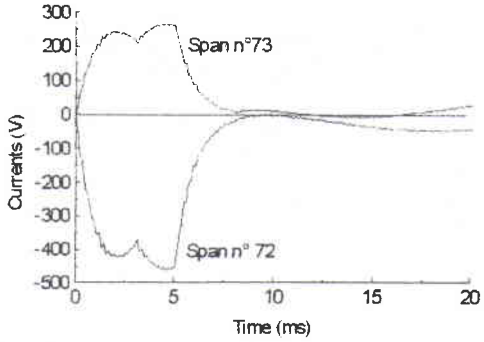

Fig. 19 Ground wire currents in the 72nd and the 73rd span

Fig. 20 shows the positive and negative peak values distribution of the ground wire current in spans.

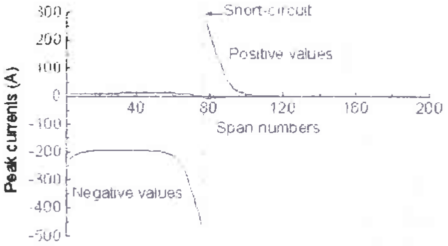

Fig. 20 Peak values of the ground wire currents in spans

The results obtained show that the positive (266.8 A) and negative (-461 A) biggest values of the peak currents are obtained at the short-circuit location ($72nd$ tower). The positive peak currents decrease rapidly to a negligible value from the $100th$ tower at the right side. The negative peak currents decrease to value (194 A) from the $60th$ tower at the left side.

3.2.4 Ground grid voltage

Fig. 21 shows the station ground grid voltage waveform for both cases of the circuit breaker, with and without closing resistors.

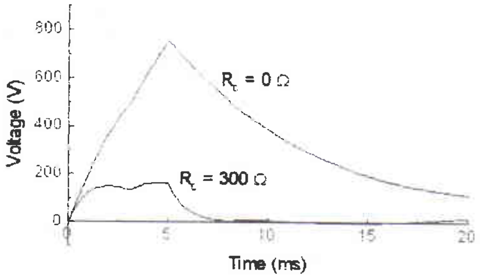

Fig. 21 Station ground grid voltage

4. CONCLUSION

A new study has been presented for the determination of the current distribution and the TGPR in grounding structures of an energized H.V. line (at no-load or in short-circuit). The transmission line is represented by a large number of Π sections in cascade in three phase quantities with mutual coupling. The line can be evaluated for both transposed and untransposed configurations. The circuit breaker can be equipped or not by closing resistors and with a simultaneous or non-simultaneous closing. In this study, we have determined at the same time with a reduced calculation time:

1. all phase current and phase voltage waveforms at any point of the line,
2. transient voltages distribution in towers and tower electrodes,
3. transient currents distribution in towers and ground wire.

The method can be used for various network configurations.

The results showed that the biggest values of the peak currents and the peak voltages are obtained at the first tower and in the first span ground wire for the no-load line. For the line in short-circuit the biggest values are obtained at the short-circuit location and decrease on the both sides of the short-circuit to a small value.

5. REFERENCES

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