A Comparative Parametric Analysis of the Ground Fault Current Distribution on Overhead Transmission Lines

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***Abstract*—The ground fault current distribution in an effectively grounded power network is affected by various factors, such as: tower footing impedances, spans lengths, configuration and parameters of overhead ground wires and power conductors, soil resistivity etc. In this paper, we comparatively analyze, using different models, the ground fault current distribution in a single circuit transmission line with one ground wire. A parametric comparative analysis was done in order to study the effects of the non-uniformity of the towers footing impedances, number of power lines spans, soil resistivity, grounding systems resistances of the terminal substations etc., on the ground fault current distribution. There are presented some useful qualitative and quantitative results obtained through a complex dedicated developed MATLAB 7.0 program.**

***Index Terms*—fault currents, power system faults, transmission lines.**

I. Introduction

A ground fault that appears anywhere in a power system causes fault currents through the grounding systems of all substations with grounded neutrals. When the fault occurs at any tower of an overhead transmission line in an effectively grounded power network, the fault current returns to the grounded neutral through the towers, ground return path and ground wires. The estimation of the ground fault current distribution is an important step to design a safe substation grounding grid and the associated line's grounding systems, and it had been undertaken by many researches and numerous analytical methods have been published [1-16]. Rudenberg [2] introduce an analytical method based on Kirchoff's theorems, in order to determine the ground fault current distribution in effectively grounded power network. This method did not include the mutual coupling between the ground wire and the faulted phase. In Endrenyi's [3] approach, considering a series of identical spans, the tower impedances and overhead ground wires are reduced to an equivalent lumped impedance. Verma and Mukhedkar [4] included the mutual coupling between the neutral conductors and the phase conductors. All the above three cited works have considered only uniform span lengths and uniform tower resistances, too. Sebo [5] introduce an analytical method which is valid for non-uniform span lengths and non-uniform tower resistances. Goci and Sebo [6] presented an improved method through the current distribution is calculated based on the driving point impedance computation. Other methods which permit varying tower resistances along a transmission line have been described by Dawalibi [7, 8]. These methods were implemented in some complex software frameworks, too. Popovic introduced an analytical procedure which enables evaluation of the significant parts of the ground fault current, for a fault at any tower of a transmission line of an arbitrary number of spans, single or double circuit parallel lines [9, 10]. His work is focused on the critical fault position's determination. In contrast, we focused on the distribution of the ground fault current in ground wires and return paths. Nahman introduced a mathematical model and equivalent schemes for zero-sequence components for overhead transmission lines with non-uniform span lengths and non-uniform tower resistance [11, 12]. This approach is focused on the effects of voltage drops in the grounding systems formed by the ground wire and towers, and ground electrodes of the terminal substations.

In our previous works there were presented some analytical methods in order to determine the ground fault current distribution in effectively grounded power networks, for a ground fault located anywhere along the transmission line [17-20]. In all these cases it was assumed uniform spans lengths and towers impedances. But usually these parameters are not the same on the entirely transmission line.

In this paper, we comparatively analyze, using different models, the ground fault current distribution in a single circuit transmission line with one ground wire. We consider the case when the section of the line between the faulted tower and the source station is finite, thus it must take into consideration the termination of the network. Also we will treat both cases: uniform, respectively non-uniform spans lengths and towers impedances. Therefore, the new significant contributions of this work comparing with our previous ones [17-20] are the followings: presenting a complex analytical model treating the more realistic case of the non-uniform spans lengths and towers impedances; comparing in a quantitative manner, based on some laborious numerical simulations, this model with the previous ones, focused on uniform spans lengths and towers impedances.

The calculation methods are based on the following assumptions: the impedances are lumped parameters in each span of the transmission line; the line's capacitances are neglected; the contact resistance between the tower and the ground wire, the contact resistance between the tower and the faulted phase, are all neglected; the network is

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considered linear in the sinusoidal steady-state, state and only the fundamental frequency is considered.

II. Ground Fault Current Distribution

Let's consider a single circuit transmission line with one ground wire connected to the ground at every tower of the line, each transmission tower having its own grounding electrode or grid and let’s assume that a single line-to-ground fault appears at one tower of this transmission line. The fault current returns to the grounded neutral through the ground wires, towers and ground return paths. The fault divides the line into two sections, each extending from the fault towards one end of the line. Depending of the number of towers between the faulted tower and the stations, respectively of the distance between the towers, these two sections of the line may be considered infinite or they may be regarded as finite. In the first case, ground fault current distribution is independent on the termination of the network. In the second case, the ground fault current distribution may significantly depend on the termination of the network [3].

On the other hand, the ground fault current distribution is affected by the towers and ground wire impedances. It may be possible that considering uniform spans lengths and towers resistances to result in wrong values because usually, these parameters are not the same on the entirely transmission line.

A. Model 1. Uniform Spans Lengths and Tower Resistances

As a first step and without loosing the approach’s generality, it is assumed that the fault occurs at the last tower (tower no. *0* in Fig. 1). It is considered that the transmission line has N towers. Fig. 1 presents the connection of a ground wire to earth through transmission towers. It is assumed that all the transmission towers have the same ground impedance Z_t and the distance between towers is long enough to avoid the influence between their grounding electrodes. The self-impedance of the ground wire connected between two grounded towers, called the self-impedance per span, was noted with Z_w. It was assumed that the distance between two consecutive towers is the same for every span. Z_m represents the mutual-impedance between the ground wire and the faulted phase conductor, per span. The station C grounding system resistance is R_s.

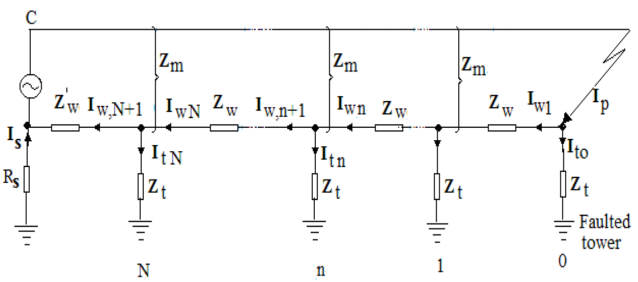

Figure 1. Ground fault current distribution in case of a fault at the last tower of the transmission line

As it was already presented in [17-20], considering the n-th tower, as counted from the terminal tower, the current flowing to ground through it, has an exponential variation and it is given by the next expression [2], [4]:

$$I_{tn} = Ae^{\alpha n} + Be^{-\alpha n} \tag{1}$$

A and B in expression (1) are arbitrary parameters and they could be obtained from the boundary conditions; parameter α in the solution (1) is given by the next expression:

$$\alpha \approx \sqrt{\frac{Z_w}{Z_t}} \tag{2}$$

The current in the ground wire is given by the following expression:

$$I_{wn} = A\frac{e^{\alpha n}}{1-e^{\alpha}} + B\frac{e^{-\alpha n}}{1-e^{-\alpha}} + \nu \cdot I_p \tag{3}$$

ν in expression (3) represents the coupling factor between the overhead phase and ground wire ($\nu = \dfrac{Z_m}{Z_w}$) and I_p represents the fault current. The boundary condition (condition for $n=0$) at the terminal tower of Fig. 1 is:

$$I_p = I_{w1} + I_{t0} \tag{4},$$

where I_{t0} represents the current in the faulted tower and I_{w1} represents the current in the first span of the ground wire.

1) Long Line

If the line is sufficiently long so that, after some distance, the varying portion of the current exponentially decays to zero, then the parameter $A \to 0$. In this case only the parameter B must be determined from the boundary conditions [4]. According to relations (1) and (3), it results:

$$I_{tn} = Be^{-\alpha n} \tag{5}$$

$$I_{wn} = B(e^{-\alpha n}/1-e^{-\alpha}) + \nu \cdot I_p \tag{6}$$

Substituting these expressions in (4), with $n=0$ for I_{tn} and $n=1$ for I_{wn}, it could be obtained the parameter *B*.

Usually, the terminal tower is connected through an extra span Z'_w to the station grounding grid (Fig. 2). As a consequence, the ladder network representing the transmission line must be closed by a resistance representing the grounding system of the station resistance.

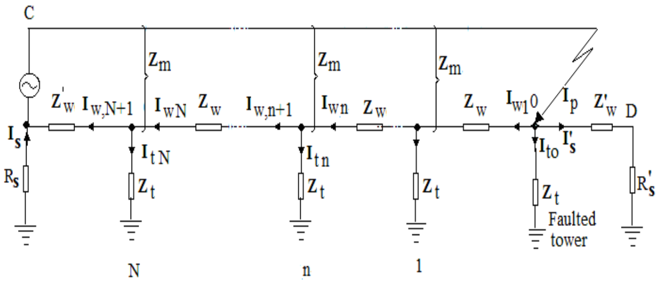

Figure 2. Ground fault current distribution considering the resistance of station grounding system

R'_s in Fig. 2 represents the grounding system resistance of the station *D*.

In this case, a part of the total ground fault current will flow through the station ground resistance $R_s^{'}$.

In order to use the previous results, it is enough to replace the current I_p with $I_p^{'} = I_p - I_s^{'}$, where $I_s^{'}$ represents the current through the station *D* grounding grid resistance and it is given by the next expression:

$$I_s^{'} = I_p \frac{Z}{Z + Z_s^{'}} \quad (7),$$

where with $Z_s^{'}$ was noted the sum between $Z_w^{'}$ and $R_s^{'}$ ($Z_s^{'} = R_s^{'} + Z_w^{'}$) and Z represents the resultant impedance of the ladder network looking back from the fault.

In case the values of $Z_s^{'}$ and Z are known, $I_s^{'}$ can be computed from relation (7).

$I_p^{'}$ is given then by the next expression:

$$I_p^{'} = I_p - I_s^{'} = I_p - I_p \frac{Z}{Z + Z_s^{'}} = I_{w1} + I_{t0} \quad (8)$$

Next, it will be found the *n*-th tower, as counted from the terminal tower, where the current gets reduced to 1% then that traversing the terminal tower [2].

From equation (5) it is obtained:

$$Be^{-\alpha n} = \frac{1}{100} B \Rightarrow n = \frac{\ln 100}{\alpha} \approx 4{,}6\sqrt{\frac{Z_t}{Z_w}} \quad (9)$$

For $\frac{Z_w}{Z_t} = 0.03$, it will get *n*=26.5. It takes at least 26 towers from the fault to get a current reduced to 1% then that traversing the terminal tower.

If the number of the towers is at least equal with the number given by expression (9), then it is possible to consider *A*=0 in the expressions (1) and (3).

2) Short Line

If the line cannot be considered long enough regarding to the expression (9), then parameters *A* and *B* will be determined from the boundary conditions.

The boundary condition at the faulted tower is:

$$I_p = I_s^{'} + I_{t0} + I_{w1} = I_{w1} + I_{t0} + I_{t0}\frac{Z_t}{Z_s^{'}} \quad (10)$$

At the left terminal of the line we have (see Fig. 2):

$$\begin{cases} I_p = I_s + I_{w,N+1} \\ I_{tN} Z_t + I_s R_s - I_{w,N+1} Z_w^{'} + \nu I_p Z_w^{'} = 0 \end{cases} \quad (11)$$

Taking into account the above boundary conditions, according to (1) and (3), parameters *A* and *B* will get the next expressions [7, 18, 19]:

$$A = \frac{I_p(1-\nu)e^{-\alpha N}\left[\frac{e^{-\alpha}}{1-e^{-\alpha}}\left(1+\frac{Z_w^{'}}{R_w}\right)-\frac{Z_t}{R_s}\right]-\left(\frac{1}{1-e^{-\alpha}}+\frac{Z_t}{Z_s^{'}}\right)}{e^{-\alpha N}\left[\frac{e^{-\alpha}}{1-e^{-\alpha}}\left(1+\frac{Z_w^{'}}{R_w}\right)-\frac{Z_t}{R_s}\right]\cdot\left(\frac{1}{1-e^{\alpha}}+\frac{Z_t}{Z_s^{'}}\right)-e^{\alpha N}\left[\frac{e^{\alpha}}{1-e^{\alpha}}\left(1+\frac{Z_w^{'}}{R_w}\right)-\frac{Z_t}{R_s}\right]\cdot\left(\frac{1}{1-e^{-\alpha}}+\frac{Z_t}{Z_s^{'}}\right)} \quad (12)$$

$$B = \frac{I_p(1-\nu)\left\{\left(\frac{1}{1-e^{\alpha}}+\frac{Z_t}{Z_s^{'}}\right)-e^{\alpha N}\left[\frac{e^{\alpha}}{1-e^{\alpha}}\left(1+\frac{Z_w^{'}}{R_w}\right)-\frac{Z_t}{R_s}\right]\right\}}{e^{-\alpha N}\left[\frac{e^{-\alpha}}{1-e^{-\alpha}}\left(1+\frac{Z_w^{'}}{R_w}\right)-\frac{Z_t}{R_s}\right]\cdot\left(\frac{1}{1-e^{\alpha}}+\frac{Z_t}{Z_s^{'}}\right)-e^{\alpha N}\left[\frac{e^{\alpha}}{1-e^{\alpha}}\left(1+\frac{Z_w^{'}}{R_w}\right)-\frac{Z_t}{R_s}\right]\cdot\left(\frac{1}{1-e^{-\alpha}}+\frac{Z_t}{Z_s^{'}}\right)} \quad (13)$$

B. Model 2. Non-Uniform Spans Lengths and Tower Resistances

In order to evaluate the ground fault current distribution in substations, overhead ground wires and towers, a mathematical model inspired by Sebo's work [5] is described.

Fig. 3 presents the connection of the ground wire connected to earth through transmission towers and the ground fault current distribution when a single line-to-ground fault appears at the last tower.

It is considered that the transmission line has *N* towers between the faulted tower and the source station, and that the span lengths $l_{(k)}$ and tower resistances $Z_{t(k)}$ are non-uniform (*k* is the number of considered span).

The self-impedance of the ground wire connected between two grounded towers, called the self-impedance per span, was noted with $Z_{w(k)}$.

The self-impedance of the faulted phase conductor per span was noted with $Z_p(k)$.

$Z_{m(k)}$ represents the mutual-impedance between the ground wire and the faulted phase conductor, per span.

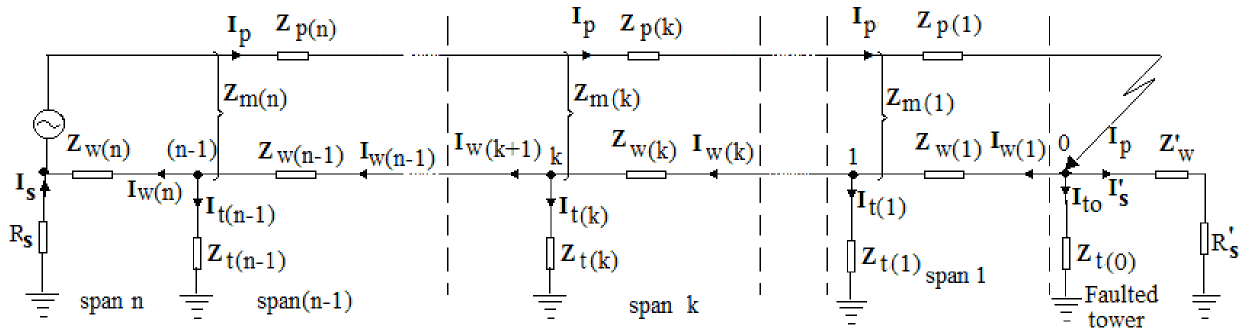

Figure 3. Fault current distribution on a single circuit transmission line

The source station grounding system resistance is R_s and $R_s^{'}$ represents the grounding system resistance of the distribution station.

Considering span number k between two consecutive towers (see Fig. 4), the following expressions, written in a matrix form, which relate the left-side quantities $U_{p(k+1)}$, $U_{w(k+1)}$, $I_{w(k+1)}$ and $I_{p(k+1)}$ of the span with its right-side quantities $U_{p(k)}$, $U_{w(k)}$, $I_{w(k)}$ and $I_{p(k)}$, can be written [5]:

$$[M_{(k+1)}]=[E_{(k)}]\cdot[N_{(k)}] \qquad (14)$$

Or:

$$\begin{bmatrix} U_{p(k+1)} \\ I_p \\ U_{w(k+1)} \\ I_{w(k+1)} \end{bmatrix} = \begin{bmatrix} 1 & Z_{p(k)} & 0 & -Z_{m(k)} \\ 0 & 1 & 0 & 0 \\ 0 & Z_{m(k)} & 1 & -Z_{m(k)} \\ 0 & -\dfrac{Z_{m(k)}}{Z_{t(k)}} & -\dfrac{1}{Z_{t(k)}} & (1+\dfrac{Z_{w(k)}}{Z_{t(k)}}) \end{bmatrix} \cdot \begin{bmatrix} U_{p(k)} \\ I_p \\ U_{w(k)} \\ I_{w(k)} \end{bmatrix} \qquad (15)$$

where:

$$M_{(k+1)} = \begin{bmatrix} U_{p(k+1)} \\ I_p \\ U_{w(k+1)} \\ I_{w(k+1)} \end{bmatrix} \quad N_{(k)} = \begin{bmatrix} U_{p(k)} \\ I_p \\ U_{w(k)} \\ I_{w(k)} \end{bmatrix} \quad E_{(k)} = \begin{bmatrix} 1 & Z_{p(k)} & 0 & -Z_{m(k)} \\ 0 & 1 & 0 & 0 \\ 0 & Z_{m(k)} & 1 & -Z_{m(k)} \\ 0 & -\dfrac{Z_{m(k)}}{Z_{t(k)}} & -\dfrac{1}{Z_{t(k)}} & (1+\dfrac{Z_{w(k)}}{Z_{t(k)}}) \end{bmatrix} \qquad (16)$$

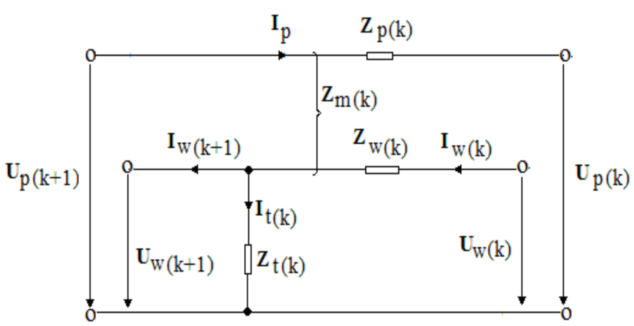

Figure 4. Span k between two towers

In the same way, the right-side quantities of the span no. k could be expressed as a function of the left-side quantities of the same span:

$$[N_{(k)}]=[E_k^{-1}]\cdot[M_{(k+1)}] \qquad (17),$$

where $[E_k^{-1}]$ is inverse matrix of $[E_k]$. Recurrently applying expression (14) for all the transmission line spans, it will be obtained:

$$\begin{aligned} &[M_{(2)}] = [E_{(1)}]\cdot[N_{(1)}] \\ &[M_{(3)}] = [E_{(2)}]\cdot[N_{(2)}] = [E_{(2)}]\cdot[E_{(1)}]\cdot[N_{(1)}] \\ &.... \\ &[M_{(n+1)}] = [E_{(n)}]\cdot[E_{(n-1)}]\cdot..\cdot[E_{(1)}]\cdot[N_{(1)}] = \\ &\qquad = [E^{(n)}]\cdot[N_{(1)}] \end{aligned} \qquad (18)$$

In order to determine all the unknowns' quantities in Fig. 3, the following boundary conditions are necessary.

At the faulted tower, on the right side of the first span, the faulted phase conductor and the ground wire are connected by the phase-to-ground fault, thus $U_{p(1)}=U_{w(1)}$.

The column vector $[N_{(1)}]$ will be:

$$[N_{(1)}] = \begin{bmatrix} (I_p - I_{w(1)}) \cdot Z_e \\ I_p \\ (I_p - I_{w(1)}) \cdot Z_e \\ I_{w(1)} \end{bmatrix} \quad (19),$$

where Z_e represents the resultant impedance of the ladder network extended beyond the fault.

At the left terminal $I_s = I_p - I_{w(n)}$; therefore the column vector will be:

$$[M_{(n)}] = \begin{bmatrix} U_{p(n+1)} \\ I_p \\ (I_{w(n)} - I_p) \cdot R_s \\ I_p \end{bmatrix} \quad (20)$$

The expression (17) is applied to the (*n*-1) span, which contains the last tower of the transmission line (see Fig. 3) and the following matrix equation ca be written:

$$[M_{(n-1)}] = [E^{(n-1)}] \cdot [N_{(1)}] \quad (21),$$

where:

$$[M_{(n-1)}] = \begin{bmatrix} U_{p(n)} \\ I_p \\ (I_{w(n-1)} - I_{w(n)}) \cdot Z_{t(n-1)} \\ I_{w(n)} \end{bmatrix} \quad (22)$$

$[E^{(n-1)}]$ will be computed as in expression (18).

Additionally, in order to gain the necessary number of equations, for the last span (span *n*) the next expressions could be written:

$$R_s \cdot I_s - I_{w(n)} \cdot Z_{w(n)} + I_p \cdot Z_{m(n)} + U_{w(n)} = 0 \quad (23)$$

$$\begin{cases} I_p = I_{w(n)} + I_s \\ U_{w(n)} = I_{t(n-1)} \cdot Z_{t(n-1)} \\ I_{t(n-1)} = I_{w(n-1)} - I_{w(n)} \end{cases} \quad (24)$$

Taking into account relations (24), expression (23) became:

$$I_p(R_s + Z_{m(n)}) - I_{w(n)}(Z_{t(n-1)} + R_s + Z_{w(n)}) + \\ + I_{w(n-1)} Z_{t(n-1)} = 0 \quad (25)$$

Considering the boundary conditions, for the case of the fault fed from one side, all the unknowns quantities $U_{p(n)}$, I_p, $I_{w(1)}$, $I_{w(n-1)}$ and $I_{w(n)}$ can be computed from expressions (21) and (25).

By choosing I_p as the given reference value, all the currents are obtained as per-unit complex values referred to the pure reference quantity of I_p [5].

In order to obtain all the ground wires currents, in every span, it is enough to observe that:

$$[M_{(n-2)}] = [E^{-1}] \cdot [M_{(n-1)}] \quad (26),$$

Because $[M_{(n-1)}]$ is known from expressions (21), by proceeding toward the fault, all ground wires currents could now be determined.

III. RESULTS

In order to illustrate and validate the theoretical approaches outlined in the sections above, first it is considered that the line which connects those two stations is a 110 kV single circuit transmission line with aluminum-steel (*ACSR*) 185/32 *mm*^{2} phase conductors and one aluminum-steel (ACSR) 95/55 *mm*^{2} ground wire (Fig. 5).

Ground wire impedance per one span $Z_{w(k)}$ and the mutual impedances $Z_{m(k)}$ per one span between the ground wire and the faulted phase are calculated, for different values of the soil resistivity ρ, with formulas based on Carson's theory of the ground return path [1, 21].

Line impedances per one span are determined considering that the average length of the span is 250 m.

The fault was assumed to occur on the phase which is the furthest from the ground wire, because the lowest coupling between the phase and the ground wire will produce the highest tower voltage.

The total fault current I_p was chosen as the reference value given, thus all the currents are obtained as per-unit complex values referred to the pure reference quantity of I_p.

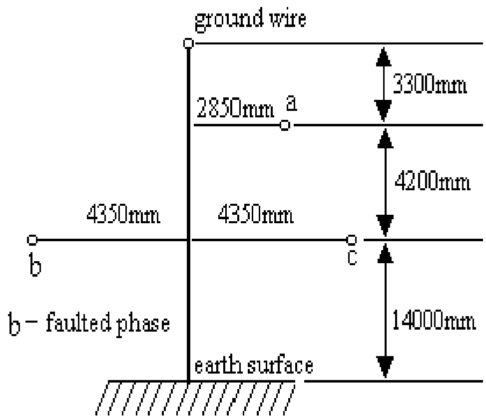

Figure 5. Disposition of line conductors

Fig. 6 shows the currents flowing in the ground wire in the case of a fault at the last tower of the line, considering a single circuit transmission line.

It was assumed that the line has 15 towers and tower impedances are uniform, first $Z_t = 5\ \Omega$ and then $Z_t = 10\ \Omega$. The values were computed considering the model for uniform tower impedances (Model 1 above) and then, the model for non-uniform tower impedances (Model 2 above).

The first model will be further called Model 1 and the second one will be further called Model 2.

It can be seen that in case of a uniform tower resistances the values are identical, confirming the correctness of the two models.

The values were obtained for soil resistivity

$\rho = 100\ \Omega m$, for the source station grounding system resistance $R_s = 0.001 \cdot \rho$ and for the grounding system resistance of the distribution station $R_s' = 0.01 \cdot \rho$ (both depending of soil resistivity).

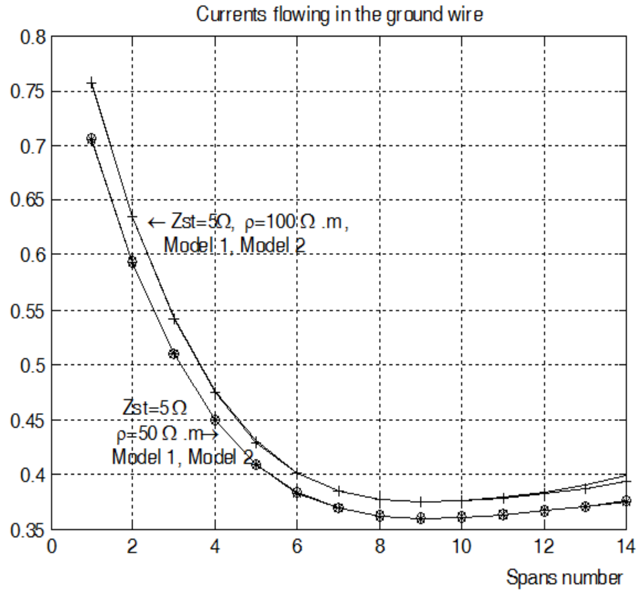

Figure 6. The currents flowing in the ground wire, uniform tower resistances

Fig. 7 shows the voltage rise of the faulted tower as a function of the soil resistivity. It was assumed that the line has 15 towers and tower impedances are uniform $Z_t = 5\ \Omega$. The values are obtained for $R_s = 0.01 \cdot \rho$ and $R_s' = 0.1 \cdot \rho$.

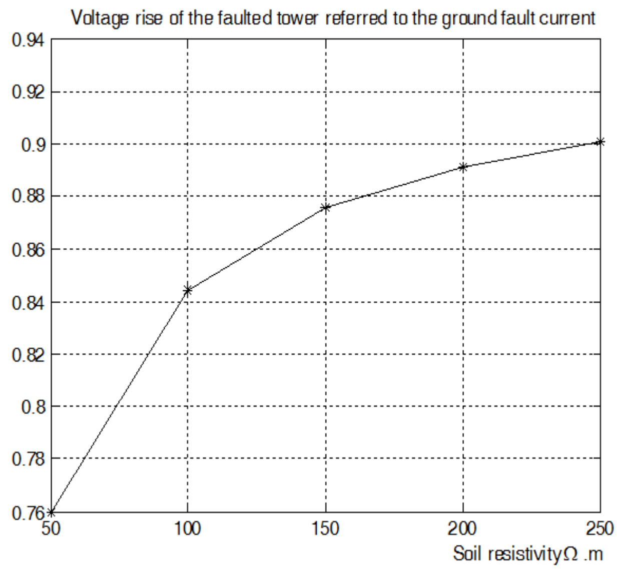

Figure 7. Voltage rise of the faulted tower as a function of the soil resistivity

Fig. 8 and Fig. 9 are showing the currents flowing in the ground wire in the case of a fault at the last tower of the line, considering a single circuit transmission line, for $\rho = 50\ \Omega m$, respectively for $\rho = 100\ \Omega m$. The values were computed using both Model 1 and Model 2. It was assumed that the line has 15 towers and tower impedances are uniform and respectively non-uniform.

In the last case (non-uniform impedances) it was assumed that first 7 towers have the same impedance values $Z_t = 5\ \Omega$, and the last 3 towers have $Z_t = 10\ \Omega$.

In order to use Model 1 for this computation, we developed two scenarios. In the first one we approximate all transmission towers' impedances with $Z_t = 5\ \Omega$, practically considering that the last 3 towers have the same impedance as the others. Then, in the second case, it was considered that all towers have the equivalent uniform impedance value $Z_t = 6{,}07\ \Omega$. The values are obtained for $R_s = 0.001 \cdot \rho$ and $R_s' = 0.01 \cdot \rho$.

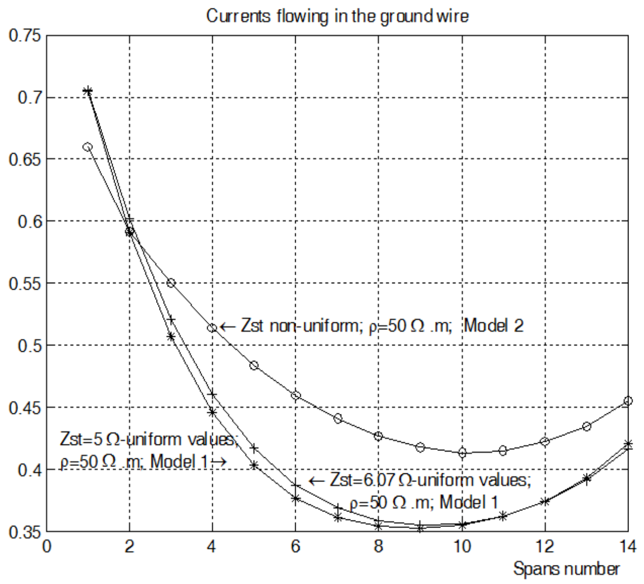

Figure 8. Ground wire currents for uniform, respective non-uniform tower resistances and for $\rho = 50 \Omega m$

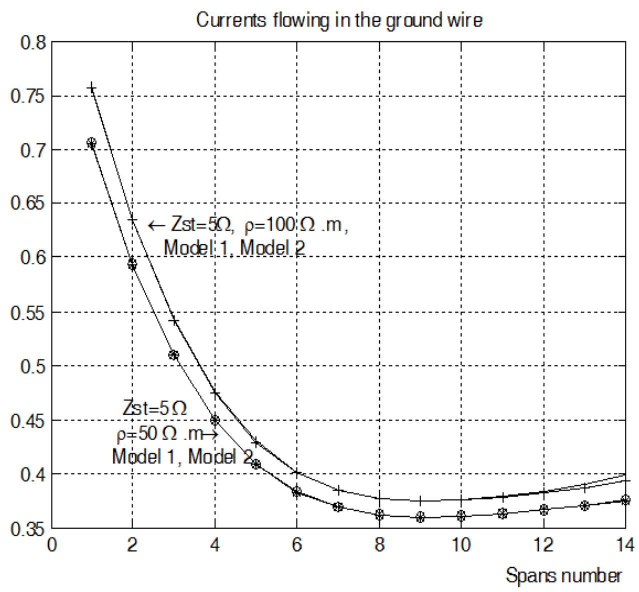

Figure 9. wire currents for uniform, respective non-uniform tower resistances and for $\rho = 100 \Omega m$

It can be seen that in this case the values are slightly different, the maximum error being of 2.24%. However, it is interesting to observe that Model 1 approximates the calculus under the above assumptions in an acceptable manner. Using in Model 1 the tower impedances' average value generates slightly more accurate results than using the minimum value.

In order to point out the influence of the stations grounding systems on the ground fault current distribution, Fig. 10 and Fig. 11 show the currents flowing in the ground wire, respectively in the transmission towers, in the case of a fault at the last tower of the line, considering a single circuit transmission line, for $\rho = 50\ \Omega m$, respectively for $\rho = 100\ \Omega m$, but this time the values were obtained for $R_s = 0.01 \cdot \rho$ and $R_s^{'} = 0.1 \cdot \rho$.

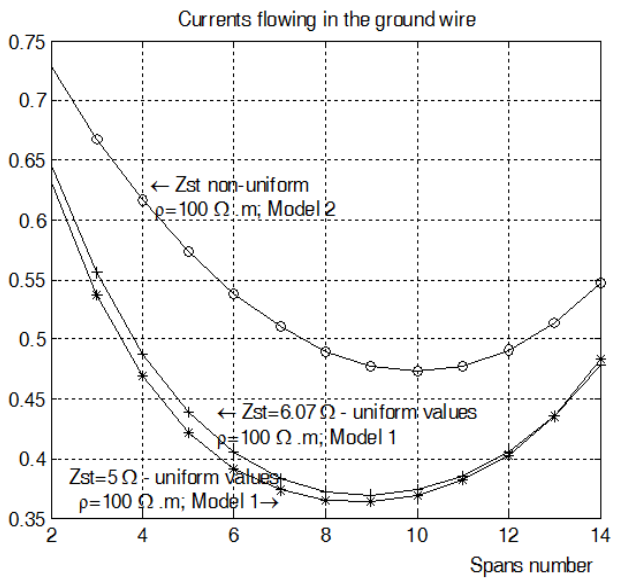

Figure 10. Ground wire currents for $R_s = 0.01 \cdot \rho$, $R_s^{'} = 0.1 \cdot \rho$

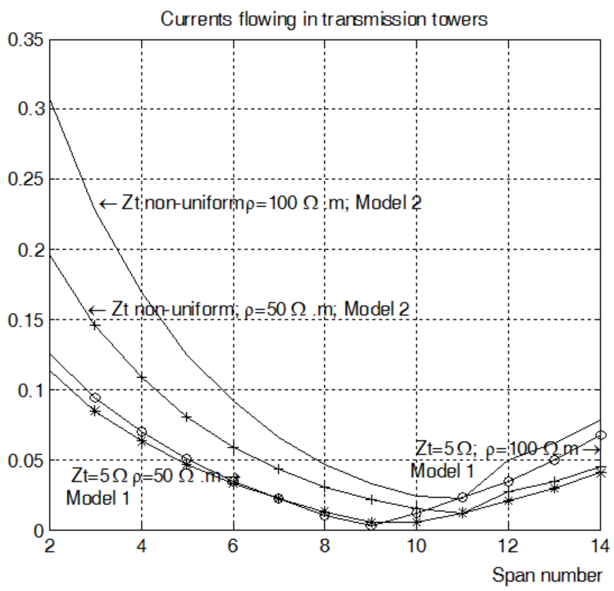

Figure 11. Currents flowing in transmission towers for $R_s = 0.01 \cdot \rho$, $R_s^{'} = 0.1 \cdot \rho$

It was assumed that the line has 15 towers and tower impedances are uniform ($Z_t = 10\ \Omega$) and respectively non-uniform. In the last case (non-uniform impedances) it was assumed that first 7 towers have the same impedance values $Z_t = 5\ \Omega$, and the last 3 towers have $Z_t = 10\ \Omega$.

IV. Conclusions

Two fundamental tendencies can be observed in the ground fault currents analysis methods: first, a continuous effort is developed in order to make these methods more convenient for applications - considering the great number of cases that should be solved, and second, the accuracy of these methods is improved by including new factors of lower significance. Unfortunately, some of the necessaries input data, like the footing resistance of each tower, can be found only when the transmission line is already built. But, the increased accuracy of these models has not a practical importance for most of the problems [9, 10].

In this paper, the ground fault current distribution is studied and evaluated for a typical electrical network with overhead transmission lines. It was considered an overhead transmission line with one ground wire, connected to the ground at every tower of the line and the fault appears at the terminal tower. There were presented the expressions of the currents flowing to ground through the towers and the currents in every span of the ground conductor in two cases: uniform, respectively non-uniform tower impedances and span lengths. In the first case, these currents are varying exponentially and their expressions contain two arbitrary parameters. For the long lines case, one of these parameters could be neglected. It was established the minimum number of towers that fulfill this request. For lines with a smaller number of towers, both the parameters must be determined. Based on the boundary conditions, there were obtained these parameters' expressions.

In the second case, a mathematical model inspired by Sebo's work [5] was described. The expressions of the currents flowing to ground through the towers and the currents in every span of the ground conductor could be computed taking into account the non-uniformity of the towers footing impedances, respectively of the power lines spans lengths.

A laborious parametric analysis was done in order to comparatively study the effects of the non-uniformity of the towers footing impedances, respectively of the lengths of spans of power lines and soil resistivity on the ground fault current distribution in substations, overhead ground wires and towers.

A complex MATLAB computer program fully implementing the presented mathematical methods has been developed. The models were simulated on different realistic validation cases, generating intuitive useful results for the designer.

The tower impedances and the transmission line impedances depend on the soil resistivity. It was studied the effect of the soil resistivity on the ground fault current distribution, by computing the impedances of the transmission line and ground wire with the formula based on Carson equation which contains the soil resistivity; the grounding systems of the terminal substation was also given as a function of a soil resistivity. Thus, from the above figures could be seen the strong influence of the soil resistivity on the ground fault currents distribution.

The currents which return through ground wires and transmission towers was computed and examined for various validation cases. It was shown that the non-uniformity of the transmission tower impedances might have considerable effects on the ground fault current distribution. The results clearly show that ignoring the ground return currents may lead to grounding over-design.

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