A New Method for Calculation of Main Performances of Grounding Cables System

Nikolce Acevski[1] and Risto Ackovski[2]

Abstract - **High voltage (HV) source transformer stations (TS) in urban areas usually supplies the middle voltage/low voltage (MV)/(LV) consumer's TS with electric power through underground classical IPO (NKBA) cables or single-core XLPE or PE insulated cables with copper metallic shields bonded to the earth electrodes of the HV/MV TS as well as the MV/LV TSs along the cables. In the case of line to ground short circuit in the power 3-phase power systems at the consumer's MV/LV TS, especially at HV/MV TS, dangerous voltages might be transferred along the shields to the MV/LV TS consumers. Main difficulty in modeling the classical steel armored lead shielded cables, as elements of the grounding system of a distribution network, is the steel armor in their construction, introducing nonlinearly in the parameters of the model. New model and method for accurate calculation this nonlinearly is proposed in this paper. The derived method also takes into consideration the mutual influence between all grounding electrodes, due to the resistive coupling through the soil. By means of the presented method it is possible to calculate the main grounding system performances, such as: earth electrode potentials under short circuit fault to ground conditions, earth fault current distribution in the whole grounding system, etc. The presented method is iterative and based on the admittance and current summation method, [11].**

Keywords - **cables, steel armor, model, grounding, resistive and inductive coupling, and reduction factor.**

I. INTRODUCTION

The grounding performances have been studied in the past by ignoring the proximity effects among the elements of the grounding system (GS) due to the resistive coupling through the soil. Because of such approximations, errors in calculation the GS performances may exceed couple of tenths %, what is quite unacceptable for practical purposes. The grounding systems of the MV distribution networks in the cities consists of great number of grounding elements, i.e. earth electrodes of the TSs, metal sheaths of the power cables, additional grounding elements etc. In order to make the model be more precise and realistic, each section of the cables should be divided into a bigger number of equal parts that makes this procedure be more complicated. Taking into consideration all mentioned effects leads to the problem of solving large number (maybe thousands) of complex nonlinear (or quasi linear) simultaneous equations (as in [6]). In that case memory and computational time requirements are, even for the contemporary computers, very great. The aim of this paper is to suggest a mathematical model enclosing all factors and relationships relevant for more exact evaluation of the GS performances. Another advantage in relation to the matrix ones is its speed, because of the avoiding operating with big reticular matrices. The proposed method is based on the admittance summation method application entirely exposed in [10] and [11]. It is convenient for solving the radial networks as well as networks with small number of loops (weakly meshed), where a special procedure for numeration the nodes and branches so-called "oriented ordering", is applied.

II. GROUNDING SYSTEM MODEL

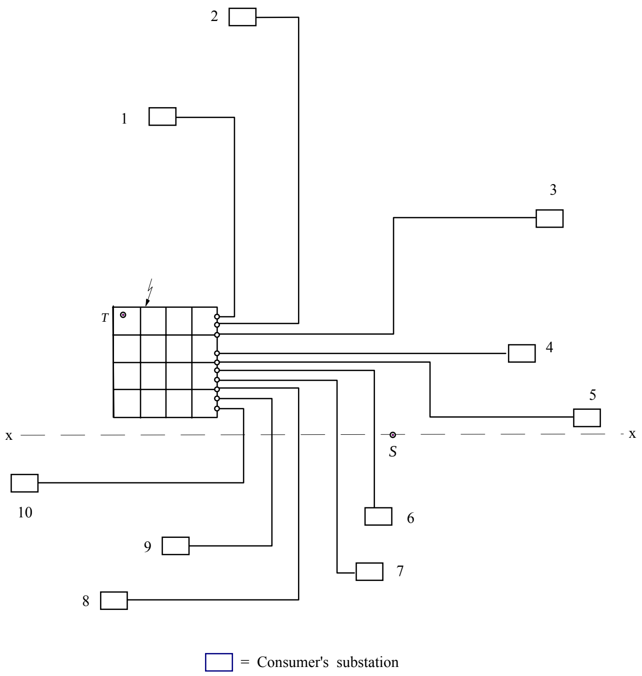

Figure 1. GS of a MV distribution network with one HV/MV TS and 10 outgoing cables

Fig. 1 presents GS of a MV distribution network with one HV/MV TS and 10 outgoing power cables. In the case of line to ground short circuit in the power 3-phase power systems at the consumer's MV/LV TS, especially at HV/MV TS, dangerous currents and voltages might be transferred along the shields to the MV/LV TS consumers. The problem is to evaluate potential and current distribution in the observed GS. It is also necessary to assess the potential distribution on the ground surface around the grounded objects and to evaluate the associated touch and step voltages.

---

[1] Nikolce Acevski is with the Faculty of Technical Sciences, Bitola, Macedonia, E_mail: nikola.acevski@uklo.edu.mk

[2] Risto Ackovski is with the Faculty of Electrotechnical Sciences, Skopje, Macedonia, E-mail: acko@ieee.org

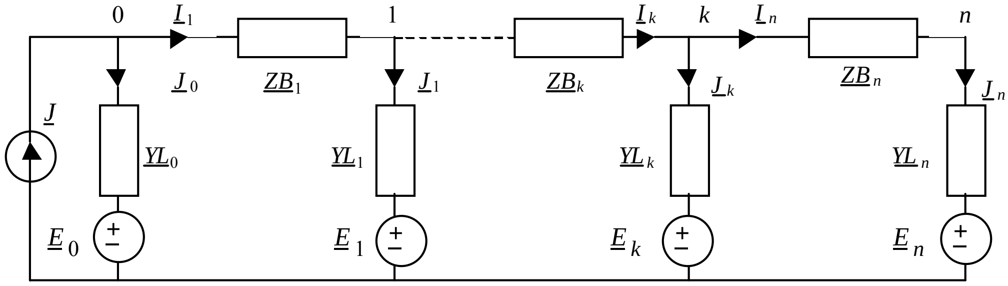

Figure 2. Equivalent circuit for a cable feeder, taking into consideration ground fault current $\underline{J}$ and induced voltages due to resistive coupling

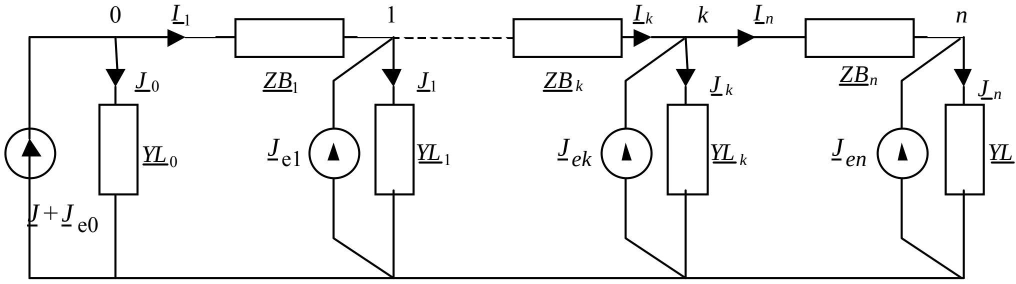

Figure 3. Equivalent circuit for a cable feeder, with equivalent current generators

Let us consider one of the power feeders, consist of couple sections (power cables), feeding several consumers MV/LV TS. Each section of this feeder is a line, connecting the neighboring TS. A G-equivalent circuit, as it is known, can represent the equivalent scheme of each section k, by impedance $\underline{ZB}_k$ and admittance $\underline{YL}_k$. That way, a ladder network can represent the whole feeder, as on figure 2. We can calculate these parameters easily by the well-known Carson's relations, entirely exposed in [2], [3], [4] and [7]. In that case, in the values of the parallel admittance of every node in which has MV/LV station, on appropriate way (parallel connection) we should take into consideration resistance to ground of that station, as well. If, between two neighboring MV/LV stations, have more than one cable, we should equivalent them as one by equivalent parameters. On such ways, all cable can be representing like ladder network, as on fig. 2. On this figure $\underline{J}$ is the fault to ground current in the node 0, (HV/MV station).

The proximity effects of the electrodes in the GS can be taken into account by introducing fictive voltage generators in all parallel branches of each section k of the network. They are result of the coupling of the current flowing into the earth from the grounding grid of the HV/MV station, and the coupling of all other leakage currents of the other grounding electrodes and cable shields in the GS, $\underline{J}_j$ (j = 1, n). The values of voltage generators also depend of the mutual resistances R_{ij} between the sections of the cable. R_{ij} are calculates by help of the Maxwell's relations, medium potentials method, and by Cetlin's relations, exposed in [1], [2], [3] and [4]. The mutual resistance's among electrodes of the grounding grid of the HV/MV station and cable's sections can be calculated in the same way or according [2], [8], and [9].

$$\underline{E}_i = \sum_{j=0, j\neq i}^{n} R_{ij}\cdot\underline{J}_j; i=1,n \qquad \underline{E}_0 = \sum_{j=1}^{n} R_{0j}\cdot\underline{J}_j \qquad (1)$$

III. ITERATIVE ADMITTANCE SUMMATION METHOD

Converting the voltage generators into equivalent source generators, the circuit from the fig. 2 converts into fig. 3.

$$\underline{J}_{ek} = \underline{E}_k\cdot\underline{YL}_k \qquad (2)$$

The number of nodes of the cable may be reduced as on figure 4. In that procedure we make reduction of the branches one by one, starting by the node with the highest number n and finishing by node 0. In that procedure, we sum admittances and currents. It is easy to prove that if the starting node of the branch n with ending node n is k in that case, the new values of the admittance's $\underline{YL}_{k(new)}$, as and new currents of the current sources $\underline{J}_{ek(new)}$ in the reduced circuit will be:

$$\underline{YL}_{k(new)} = \underline{YL}_k + \underline{D}_n\cdot\underline{YL}_n \qquad (3)$$

$$\underline{J}_{ek(new)} = \underline{J}_{ek} + \underline{D}_n\cdot\underline{J}_{en} \qquad (4)$$

$$\underline{D}_n = \frac{1}{1+\underline{ZB}_n\cdot\underline{YL}_n} \qquad (5)$$

This fictive removing is possible over subset of all branches α_{1-n} on path from the node n to 0. The new current will be:

$$(\underline{J}+\underline{J}_{e0})_{new} = \underline{J}+\underline{J}_{e0}+\underline{J}_{en}\cdot\prod_{l\in\alpha_{1-n}}\underline{D}_l \qquad (6)$$

But there are current generators in all nodes, so we should take them into consideration by the procedure of fictive removing of all current generators from the ending node n to the starting node 0. In this case the new current of the current generator, figure 5, as and apparent admittance's to ground of the feeder (viewed from node 0) are given by eq. (7) and (8).

$$(\underline{J}+\underline{J}_{e0})_{new} = \underline{J}+\underline{J}_{e0}+\sum_{k=n}^{1}\left(\underline{J}_{ek}\prod_{l\in\alpha_{1-k}}\underline{D}_l\right) \qquad (7)$$

$$\underline{YL}_{0(new)} = \underline{YL}_0+\sum_{k=n}^{1}\left(\underline{YL}_k\cdot\prod_{l\in\alpha_{1-k}}\underline{D}_l\right) \qquad (8)$$

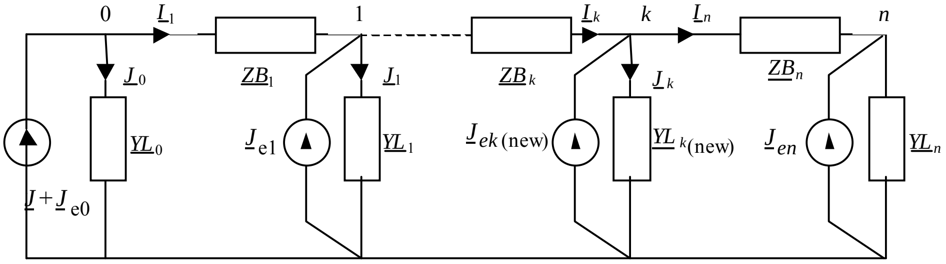

Figure 4. Equivalent circuit for a cable feeder, with reduced number of nodes

In them $l\in\alpha_{1-k}$ denotes that the branch l is an element of the subset of the branches on the path from the first node 1 to node k. After that the voltage in the sending node 0 will be:

$$\underline{U}_0=\frac{\left(\underline{J}+\underline{J}_{eo(new)}\right)}{\underline{YL}_{0(new)}} \tag{9}$$

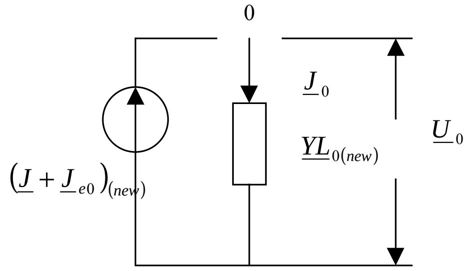

Figure 5. Apparent admittance to ground of the feeder

In general case the voltage of any node s which starting node is node i, will be:

$$\underline{U}_s=\underline{D}_s\left(\underline{U}_i-\underline{ZB}_s\cdot\sum_{k=n}^{s}\left(\underline{J}_{ek}\prod_{l\in\alpha_{1-k}}\underline{D}_l\right)\right) \tag{10}$$

In the first iteration, we suppose that there have not any mutual couplings among elements of the GS. Therefore, we can calculate the starting currents in all parallel branches:

$$\underline{J}_k=\underline{U}_k\cdot\underline{YL}_{k(old)} \tag{11}$$

By them and proposed procedure, we can calculate new voltages and currents in each iteration. Those computations should be repeated in an iterative process as long as necessary, because the currents $\underline{I}$ and $\underline{J}$ in the GS are unknown at the beginning of the iterative procedure. Based on the presented models, appropriate software has been produced for calculation of the GS performances. The number of iterations necessary for satisfactory accuracy of the solution is 5-10.

IV. MODEL - WHEN THE CABLES ARE CLASSICAL (IPO)

Main difficulty in modeling the classical steel armored lead sheath cables, as elements of the grounding system of a distribution network, is the steel armor in their construction, introducing nonlinearly in the model's parameters. The armor increase the strength of the magnetic field, which is result of the currents in the phase conductors and the metallic shield, and on a such a way decrease so-called reduction factor of the cable. The parameters by length of these cables have not stability value, because of the nonlinearly dependence of the magnetic permeability of the steel tapes $\underline{\mu}$ from the magnetic field $\underline{H}$ in the steel armor. That makes theirs modeling in big measure more difficult, and practically incompatible with classical models which are based on direct matrix calculations of the GS. New model for accurate calculation of this nonlinearly is proposed in this paper compatible with the proposed method. The serial impedance for k, is $\underline{ZB}_k=\underline{Z}_k\cdot l_k$:

$$\underline{Z}_k=\left(0{,}05+R_{pa}+r_{ak}\right)+j\left(X_k+x_{ak}\right) \tag{12}$$

The resistance per unit length of the shield and armor R_{pa} as and the self-inductive resistance per unit length X_k are calculate by well-known Carson's relations. In the last relation the real part r_{ak}, and the imaginary part x_{ak} of the complex impedance by which in the currents circles is taking into account the impact of the armor in the section k, depends of the magnetic flux in the armor $\underline{\Phi}_a$, where $\omega=2\pi f$.

$$\underline{Z}_{ak}\cdot l_k=\left(r_{ak}+jx_{ak}\right)\cdot l_k=\frac{j\omega\underline{\Phi}_a}{\underline{J}_k} \tag{13}$$

As a result of the inductive coupling as and of the changes of the current's value flowing into earth from every section of the GS, in every iteration the real part r_{ak} as and imaginary part x_{ak} from the complex impedance by which in the current's circles is taking into account the impact of the armor, are change, and by that in every iteration the impedance $\underline{ZB}_k$ is change, as in [4].

Let us suppose that the dependence $\mu(H)$ for the steel tapes, used for construction of cable's armor is known. On the beginning, in the first iteration, let us suppose that all fault to ground current flowing through cable's shield. So, there are not flowing currents into the earth, and there are not fictive voltage generators. According to [7], flux $\underline{\Phi}_\alpha$ in the armor as and the current $\underline{J}_i$ which flows into earth from every section i, depends from the magnetic field in the steel armor $\underline{H}$:

$$\underline{\Phi}_a=\underline{\mu}\cdot\underline{H}\cdot q_{Fe} \tag{14}$$

$$\underline{H}=\frac{\underline{J}_i}{\pi\cdot d_a} \tag{15}$$

$$\underline{\mu}=\mu'-j\mu''=\mu_0\cdot\left(\mu'_r-j\mu''_r\right) \tag{16}$$

In the last relation μ' shows inductive coupling to the steel armor, while imaginary part μ'', loses into magnetic material. For these starting conditions, $\underline{J}_i=0$, by (15) we can calculate the magnetic field $\underline{H}$ and read μ', μ''. According to [7] is valid:

$$q_{Fe}=n\cdot b_T\cdot d_T \tag{17}$$

n – number of tapes (usually two), b_T - tape's width, d_T - tape's depth, d_a -the armor's diameter. Furthermore will be:

$$r_a = \mu'' \frac{\omega \cdot n \cdot b_T \cdot d_T}{\pi \cdot d_a} \qquad x_a = \mu' \frac{\omega \cdot n \cdot b_T \cdot d_T}{\pi \cdot d_a} \qquad (18)$$

After calculation of the self impedance $\underline{ZB}_k$ of every section k for given beginning conditions, by help of the admittance's and currents summation method we can calculate voltage at the node 0, and after that voltages at all nodes, and currents in all branches of the model-network, as well.

V. EXAMPLE

Let from HV/MV station ten cables run out that supply MV/LV stations as on figure 1. Let the rectangular grounding grid of the HV/MV station be in form of square with side of 50m, with conductors diameter D=0,011m buried on depth 0,80m. The location and the length of the cables, as a comparison, are as in picture 8 from [6]. The voltage of touch U_t is calculated in point T, and the voltage of step U_s along the direction h-h. Let the cables be with a conveying butter shield of the type IP013 3X150 with a diameter over the shield D=0,05m, buried in depth of 0,80m. The specific resistance of the earth is homogenous with $\rho = 100\Omega m$. Let the injected current at HV/MV station be 1000A.

To compare the results of the example easily, we will introduce the values. These values are defined as follows:

$$|\underline{Z}_0| = \frac{\underline{U}_0}{\underline{J}_0} \qquad |\underline{\alpha}| = \frac{\underline{Z}_0}{r_0} \qquad |\underline{Z}_c| = \frac{\underline{U}_0}{\underline{I}_1} \qquad (19)$$

$\underline{Z}_0$-apparent impedance to ground of the source substation ground electrode

$\underline{Z}_c$-apparent impedance to ground of a cable sheath

$\underline{\alpha}$-source substation ground electrode impedance reduction factor

r_0 -substation ground electrode resistance to ground

The following results are obtained according:

ITERATIVE METHOD	MATRIX MODEL
$r_0 = 1{,}008\Omega$	$r_0 = 1{,}003\Omega$
$\lvert Z_0\rvert = 0{,}303\Omega$	$\lvert Z_0\rvert = 0{,}280\Omega$
$\lvert\alpha\rvert = 0{,}301$	$\lvert\alpha\rvert = 0{,}280$
$\lvert Z_c\rvert = 0{,}359\Omega$	$\lvert Z_c\rvert = 0{,}322\Omega$
$\lvert U_0\rvert = 303{,}113V$	$\lvert U_0\rvert = 279{,}6V$
$U_t = 67{,}656V = 22{,}32\%$	$U_t = 54{,}5V = 19{,}49\%$
$U_s = 8{,}135V = 2{,}627\%$	$U_s = 8{,}1V = 2{,}9\%$

The coordinates that the voltage of step is calculated for, almost cover the point on the picture 125,4 i.e. 126,4 meters along an x-axis. The voltage of touch (the point T) is taken with coordinates (0.71;49.29;0.0) i.e. at distance of 1 meter along the diagonal from the inner side. As a comparison, the total current in the cables is 84,478% from the current of earth connection, while in the example [6] it is 86,9%. The rectangular grounding grid with draws only 15,522% of the current. Generally, we can conclude that all other results don't differ for more than 10%, and the exposed method is quicker.

V. CONCLUSION

The paper presents a new model for the analysis of the performances of complex grounding systems built by a source HV/MV TS grounding grid, grounding electrodes of the associated consumer MV/LV TSs and by uncoated metal shielded cables (and/or steel armor, outgoing from the source substation. The proposed model takes into account all mutual interactions among cable shields and substation grounding electrode elements through the soil and among the parts of the same cable, as well. Main difficulty in modeling the classical steel armored lead shielded cables is the steel armor in their construction, introducing nonlinearly in the parameters of the model. In addition, a new model for accurate calculation this nonlinearly is proposed in this paper.

By means of the presented method it is possible to calculate the main grounding system performances, such as: earth electrode potentials under short circuit fault to ground conditions, earth fault current distribution in the whole complex grounding system, step and touch voltages in the nearness of the earthling electrodes dissipating the fault current in the earth, etc. The necessity of computing the simultaneous system of complex equations, proposed from the other existing models is avoided here by introducing an iterative procedure, which considerably reduces memory and time requirements and enables solving the complex GS such as those in the large urban areas.

REFERENCES

[1] Acevski, N., Ackovki, R., "Determining of galvanically separated grounding grids and grounding systems", MELECON 2000, Conference May 29-31 CYPRUS, IEEE Region 8.

[2] Ackovski, R., Acevski, N., "Method for Analysis of Complex Grounding Cables Systems", 3rd JBM Seminar on Applied Electromagnetic, September 15-17, 2000 Ohrid, Macedonia.

[3] Ackovski, R., Acevski, N., "Cables with isolation PE and XLPE, as elements of grounding systems", EIST, June 2001, Bitola, pp. 7-12.

[4] Ackovski, R., Acevski, N., "About reduction factor of classical cables", EIST, June 2001, Bitola, pp. 13-18.

[5] Ackovski, R., Rajicic, D., "New Method for Tower Potentials and Ground Wire Current Computation", Int.Conf. "Modeling and Simulation", Scottsdale, Arizona, March 1988.

[6] Nahman, J., Salamon, D., "Effects of the metal sheathed cables upon the performances of the distribution substations grounding systems", IEEE Trans. PWRD, Vol. 7, No. 3, July 1992, pp.1179-1185.

[7] Nahman, J., "Neutrals Grounding in the distribution networks", Beograd, 1980.

[8] Nahman, J., "Earthling Effects of Coated Underground Cables with Metallic Shields bonded to Earth Electrodes", IEE-Proc. Gener. Trans. Distrib. Vol. 144, No.1, Jan. 1997.

[9] Popovic, Lj., "Practical method for evaluating ground fault current distribution in station, towers and ground wire", IEEE/PES Winter Meeting, January 21-25, 1996.

[10] Rajicic, D., Taleski, R., "Two Novel Methods for Radial and Weakly Meshed Network Analysis", EPRI 48 (1998), pp. 79-87.

[11] Rajicic, D., Taleski, R., "Radial Distribution Systems Short Circuit Analysis Using Admittance Summation Method", Proceedings, Department of Electrical Engineering-Skopje, Vol. 19. No. 1-2, pp-11-14, 1996.