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Method for Analysis the Complex Grounding Cables Systems

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Abstract - A new iterative method for the analysis of the performances of the complex grounding systems (GS) in underground cable power networks with coated and/or uncoated metal sheathed cables is proposed in this paper. The analyzed grounding system consists of the grounding grid of a high voltage (HV) supplying transformer station (TS), middle voltage/low voltage (MV/LV) consumer TSs and arbitrary number of power cables, connecting them.

The derived method takes into consideration the drops of voltage in the cable sheets and the mutual influence among all earthing 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 complex grounding system, step and touch voltages in the nearness of the earthing electrodes dissipating the fault current in the earth, impedances (resistences) to ground of all possible fault locations, apparent shield impedances to ground of all power cables, e.t.c.

The proposed method is based on the addmitance summation method [1] and is appropriately extended, so that it takes into account resistive coupling between the elements that the GS.

Index Terms--cables, grounding systems, mutual influences, iterative method, admittances summation method.

1. Introduction

The need for a method providing fast and accurate analysis of currents and voltages in the complex grounding cable systems in case of an earth fault, has been present for a long time. At the beginning, the analysis of this problem had been carried out by means of the matrix models based on Maxwell's equations with numerous simplifications of the real physical model. The biggest approximation was that, it was considered that all the elements of a grounding system are on the same potential i.e it wasn't taken into consideration the drop of voltage along the elements of the GS (metal strips, ropes, metal sheaths of power cables etc.) Those elements are additional elements of the GS and as excellent grounding electrodes they dissipate a significant part of the fault current into the earth under fault conditions. Such grounding elements are the e.g. cables with paper isolation, lead sheath, and steel armature. It is also usually assumed

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that there is no resistive and magnetic coupling between the grounding grid of the HV/MV supplying TS and the cables that lead out of it, as well as that there is no mutual influence between the cables. Lately, models have been developed that take into consideration all these mutual influences, as well as the drops of the voltage along the cable sheaths, and this way the models of complex grounding cable systems approach to the physically real models, as in [3]. Grounding systems of the MV power networks in the cities may consist of hundreds or thousands of grounding elements. Out of HV/MV stations lead a great number of cables in different directions and in the models they are divided into many sections and segments. In order to achieve the model be realistic as much as possible, it is neccessary each section of the power cables in the model to be divided into a bigger number of equal parts, and doing this the procedure gets even more complicated.

In case of a matrix calculation of the problem, a long computing time is wasted because of the dimension of the matrices.

2. A short review to the method for admittance summation

The addmitance summation method, entirely exposed in [1] and [2], is dedicated for solving the radial distribution networks as well as weakly meshed networks. The MV power networks in urban areas are of this kind. In the case of meshed network, i.e. network with some number of contours, the meshed network should be opened, i.e. transformed into radial one. When transforming such networks into radial, a procedure of interruptions of the contours is introduced, break points and fictive nodes are introduced where the ideal current generators are plugged in. For the radial networks, a special procedure of ordering and numeration of branches and nodes of the network so-called "oriented ordering" is applied. By means of this procedure, the starting and ending node of each branch is easily defined. With no getting deeply into details of the modeling of elements that consist the radial branches of the network i.e. the connections between certain grounding elements of the TS, we can assume that each branch can be presented with an appropriate π - equivalent scheme.

Before the ordering process in the model-network starts, a starting point (node) is defined, and it is accompanied by an index 0. For that purpose, a point is usually selected, to which the excitation is plugged on (i.e. the injected current in the grounding system, which is a result of fault to ground) for example the grounding grid of HV/MV station). During the ordering, the parallel branches in the model network between the nodes of the model-network and the referent node (the earth) are not taken into account. These parallel branches represent the resistences to ground of the grounding electrodes of the MV/LV TS and the appropriate admittances of π equivalent schemes of the links between the grounding electrodes, are presented with. The parallel connection of all branches between a node of the model-network and the referent node, is presented with an equivalent parallel branch, with an admittance $\underline{YL}_k$ -attached to the node k. As the indexes of the ordered branches are equal to the indexes of the ending nodes of the branches (according to the rules for oriented ordering from [1] and [2]), the series branches will consist of an equivalent impedance. Eg. for the branch k which ending node is k the impedance will be $\underline{ZB}_k$, as in fig 1.

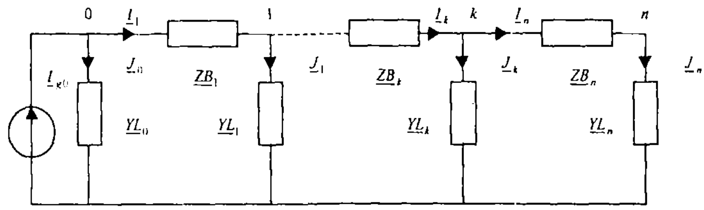

Figure 1. A scheme for a part of a MV network

To be explained easily, let the node 0 on fig. 1 presents HV/MV supply TS, while the rest of the nodes are MV/LV stations. They are connected and the links connecting them are realized with power cables. Firstly, two kinds of equivalent admittances are being determined (admittances of nodes and admittances of serial branches). The admittance $\underline{Y}_i$ associated to the branch i, that presents the admittance to ground on the part of the radial model-network, that is supplied through the branch i, taking into account the branch i, too. The admittance $\underline{YE}_i$ associated to the branch i, which presents an admittance to ground on the part of the radial model network, that is supplied through the node i, taking into account the parallel admittance at the node i, $\underline{YL}_i$. Those admittances are summed successively through a process where branch by branch is being processed, starting from the branch with the biggest index, and ending with the branch that has index 1. If n is the total number of nodes while processing the branch k, with a starting node i, is calculated:

$$\underline{Y}_k = \frac{1}{\underline{ZB}_k + \dfrac{1}{\underline{YE}_k}} = \frac{1}{1 + \underline{ZB}_k \cdot \underline{YE}_k} \cdot \underline{YE}_k = \underline{D}_k \cdot \underline{YE}_k \tag{1}$$

$$\underline{YE}_i = \underline{YE}_i + \underline{Y}_k ; \quad i=1,.....n \tag{2}$$

Then, the voltages of the nodes in the radial model-network are calculated, starting from the node 0:

$$\underline{U}_0 = \frac{\underline{I}_{g0}}{\underline{YE}_0} \tag{3}$$

where $\underline{I}_{g0}$ is a current of the only current generator between the node 0, where is the fault, and the referent node.

The procedure for calculation the voltages in the nodes is carried out first, starting from the first node, and ending with the node with the biggest index. The voltage of any node m is calculated according:

$$\underline{U}_m = \underline{U}_0 \cdot \prod_{l \in \alpha_{0-m}} \underline{D}_l \tag{4}$$

where α_{0-m} is a subset of branches that consist the path from the node 0 to the node m.

If there are current generators at some of the other nodes of the model-network, besides the ideal current generator at the node 0, the procedure for calculation of the voltages is changed, because the impact of the other current generators should be taken into account, through the procedure so-called 'removing of the current generators', described in details in [1] and [2]. The current generator with current $\underline{I}_{gk}$, attached to the node k is transformed into a voltage one, which is then again transformed into a current generator. This way, a fictive removing through each branch on the way from the node k to the node 0, is carried out. Let the last branch on that way be m with a starting node 0 and an ending node m. The current of the 'removed' current generator will be:

$$\underline{I}_{gm(k)} = \underline{I}_{gk} \cdot \prod_{l \in \alpha_{k-m}} \underline{D}_l \tag{5}$$

where α_{k-m} is a subset of branches that consist the path from the node k to the node m.

If there are more current generators with different currents that are plugged in at different nodes, in the part of the network which is supplied through the branch m, is valid:

$$\underline{U}_m = \underline{D}_m \cdot \left(\underline{U}_0 + \underline{ZB}_m \cdot \sum_{i \in \beta_m} \underline{I}_{gm(i)} \right) \tag{6}$$

β_m - a subset of nodes that are supplied through the node m, where the current generators are plugged in.

This way, the calculated voltages are equal to the potentials of the appropriate grounding elements of the grounding system, assuming that the approximation effect of certain grounding elements is neglective. The currents in the parallel branches, can easily be determined according to:

$$\underline{J}_k = \underline{U}_k \cdot \underline{YL}_k \tag{7}$$

3. Extension of the admittance summation method

In the previous case, the radial network was calculated directly in two steps: the first one, summation the admittances bacwards, from the node with the biggest index towards the first node, and the second one, a calculation of the voltages in the network, starting from the node with index 0 to the node with the biggest index. To the actual extension of the method, the latter method is only a zero iteration, which is valid for starting conditions, when all mutual influences in the grounding system are neglected.

In the practice, the mutual impact between the grounding elements should be taken into consideration, because a grounding element is very often in a potential funnel of another grounding element(s). If we don't consider this impact, especially if short distances between the grounding elements of a grounding system are in question, drastic differences can occur between the calculated values of the characteristics of certain grounding elements, and the measured ones. In some cases, these differences can exceed 50%. These mutual couplings are especially strong between the grounding grid of HV/MV TS and the shields of the cables running out the TS, between the sheaths of different cables, as well as between parts of a same cable. The closer are two parts of a same cable to each other, the expressed in this influence.

These mutual impacts can be taken into account by introducing fictive voltage generators in all parallel branches of the network, as well as in the node 0. It is necessary here to emphasize that further on, the nodes don't have to represent only points where the grounding of MV/LV stations are plugged in. If cables are longer than 100 m, for more exact calculation, it is necessary to divide each cable into more straight lined parts with shorter lengths, but not exceeding 50 m. Further on, each part of the cable is presented by π - equivalent scheme in the model-network i.e. represents a branch with a starting and an ending node. The voltage generator, plugged in the parallel branch of the 0 node which represents the grounding grid of HV/MV station, can be calculated by a superposition of the impacts of the currents in the parallel branches of all parts n of all cables s that run out of the determined HV/MV station, while the voltage generators in any of the other nodes $i=1,\ldots,ns$ are result of the impact of the current that led out of the grounding grid of HV/MV station, and the impact of all other currents from the transversal in all nodes of the radial network (relation (8)).

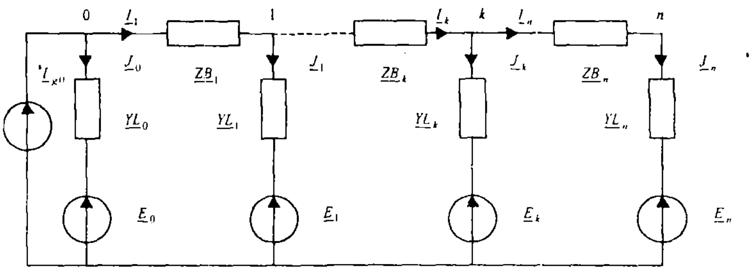

Figure 2. A scheme of the same section from fig. 1- the proximity effect is taken into account

$$\underline{E}_0 = \sum_{i=1}^{n \cdot s} R_{0i} \cdot \underline{J}_i$$
$$\underline{E}_i = R_{0i} \cdot \underline{J}_0 + \sum_{\substack{j=1 \\ j \neq i}}^{n \cdot s} R_{ji} \cdot \underline{J}_j \qquad (8)$$

To explain the procedure easily, a part of a MV power network has been presented on figure 2, i.e. a first section of the cable feeder from the HV/MV supply TS to the first MV/LV station. In that case the cable is divided into n parts. At the same time, the currents in the parallel branches are the calculated from the zero iteration, according to (7).

The self and mutual resistivities R_{ii} and R_{ij} of the parts of cables, from (8), can easily be calculated by using the method of medium potentials. The mutual resistivities among electrodes of the grounding grid of the supply HV/MV station and every part of a cable can be calculated in the same way or according:

$$R_{0i} = \frac{\rho}{\pi \cdot D} \arcsin\left(1 + \frac{r}{D}\right)^{-1} \qquad (9)$$

where D is the diameter of an equivalent horizontal circular plate by which the grounding grid of HV/MV station is substituted and r is the distance from the edge of the grid to the center of the element. The distance r is greater, this approximation is more accurate.

The procedure continues so that the voltage generators from figure 2, can be transformed into currents ones, by means of the relation:

$$\underline{I}_{gk} = \underline{E}_k \cdot \underline{YL}_k \tag{10}$$

In this case, there are current injections in all nodes, so, according to the procedure of their fictive removing (relation (5)), they are taken into account while calculating the new corrected voltages in the nodes, according to the relation (6). With the help of the corrected voltages in the nodes and the relations (7), the corrected currents in the parallel branches are calculated. So, in the first iteration, as in all the rest of iterations, except in the zero one, only the second step is in process, (the step forward sweep to the calculation of the new voltages). The first step of summation the admittances is carried out only once, in the zero iteration.

With these new, corrected currents in the parallel branches, obtained from the first iteration, the new voltage generators in the nodes are calculated according to the system of equations (8), that will be used in the second iteration. The iterative process continues in the same way, until it convergates i.e until the absolute value of the maximal difference of all differences of voltages in all nodes of the network, in two iterations, one after another, f, f-1 becomes smaller from some in advance defined very small number ε:

$$max\left|\underline{U}_k{}^f - \underline{U}_k{}^{f-1}\right| < \varepsilon \;;\; k=1,2,\dots ns \tag{11}$$

After calculating the exact voltages in the nodes, which are potentials of certain grounding electrodes, and the exact currents in the parallel branches, further on, the potential of any point M on the surface of the earth can be calculated, and thus the distribution of the potentials in the environment of the grounding grid, can be determinated according:

$$\underline{U}_M = R_{0M} \cdot \underline{J}_0 + \sum_{i=1}^{n \cdot s} R_{iM} \cdot \underline{J}_i \tag{12}$$

where R_{0M} is the mutual resistance between the point M and the HV/MV supply TS grounding grid, and R_{iM} are mutual resistences between the point M and all other elements of the GS. Once the distribution of the potentials on the surface of the earth is known, the touch and step voltages can easily be determined.

On the basis of the proposed method, an appropriate software for calculation of the characteristic values of the grounding systems with an arbitrary complexity has been produced from the authors.

4. EXAMPLE

Let from HV/MV TS run out ten cables supplying MV/LV stations. Let the rectangular grounding grid of the HV/MV station be in form of square with side of 50m, with conductors diameter D=11mm buried on depth 0,80m. The location and the length of the cables, as a comparison, are as in fig. 8 from [3]. The touch voltage U_t is calculated in point T, and the step voltage U_s along the direction h-h is also calculated. Let the cables be with lead sheath and conductive jacket (type IP013 3x150) with a diameter over the sheath D = 50 mm, buried in depth of 0,80 m. The specific electric resistance of the earth can change, but in this example, it is adopted that the earth where the whole grounding system is placed, is homogenous with soil resistivity ρ=

100 Ωm. Let the injected current at HV/MV station be $\underline{I}_{g0}$ = 1000 A. The described example is taken from [3], where the results, i.e. main characteristics of the GS are obtained by means of a matrix model, described also in [3].

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

$$|\underline{Z}_0| = \frac{\underline{U}_0}{\underline{I}_{g0}} \qquad |\underline{\alpha}| = \frac{\underline{Z}_0}{r_0} \tag{13}$$

where is:

$\underline{Z}_0$ -apparent impedance to ground of the source HV/MV TS 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, PROPOSED HERE	MATRIX MODEL FROM [3]
$r_0 = 1{,}008\Omega$	$r_0 = 1{,}008\Omega$
$\|Z_0\| = 0{,}290\Omega$	$\|Z_0\| = 0{,}303\Omega$
$\|\alpha\| = 0{,}288$	$\|\alpha\| = 0{,}300$
$\|U_0\| = 290$ V	$\|U_0\| = 303$ V
$U_t = 57{,}7$ V = 22,3%	$U_t = 54{,}5V$ = 19,5%
$U_s = 8{,}1$ V = 2,7%	$U_s = 8{,}1$ V = 2,9%

The coordinates that the step voltage is calculated for, almost cover the point on the picture 125,4 i.e. 126,4 metres along the x-axis. The touch voltage (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. The total currents flowing through the shields of certain cables I_s, as well as the voltages at the end of the cables U_{ns} are given in the table 1.

TABLE 1.

s	$\|I_s\|(A)$	$\|Z_{cs}\|(\Omega)$	$\|U_{ns}\|(V)$
1	87,549	3,462	300,849
2	122,776	2,469	265,709
3	132,114	2,294	294,707
4	71,189	4,259	300,572
5	72,462	4,183	245,269
6	54,945	5,517	300,277
7	63,409	4,780	283,720
8	138,839	2,183	280,369
9	64,415	4,706	280.221
10	63,304	4,788	243,002

As a comparison, the total current dissipating from the cables is 84,5% from the injected fault current, while in the example [3] it is 86,9%. The rectangular grounding grid of the HV/MV TS dissipates only 15,5% of the total injected current. Generally, it can be concluded that all other results don't differ for more than 10%, and at the same time, the exposed method is much faster than the matrix method proposed in [3].

An analysis of the characteristics of the exposed example has been carried out for different lengths of the cables, different specific resistences on the earth, where the grounding system is put. By increasing the lengths of cables, percentage of the current flowing through the sheaths of the cables increases, while, by reducing their length, this percentage reduces, too. However, by increasing the length of the cables, the currents through the sheaths of the cables don't increase proportionally. The closer certain parts of the cables are to each other, the more expressed is the proximity effect. As a result, the currents don't increase so drastically by increasing the length.

5. 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 sheathed cables, outgoing from the source substation. The proposed model takes into account voltage drops along the cable sheaths and mutual interaction among cable sheaths and substation grounding electrode elements through the soil. 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 large and complex GS such as those in the MV distribution networks of large urban areas.

One of the advantages of this method in relation to the matrix ones, is its speed, because in this case operation with big matrices is avoided. If the grounding system consists of large number of elements, the difference in the speed becomes more expressed and more important.

The method is also applicable for a two-layer environment, where every grounding of TS, as well as every element (cable) can be placed into the earth with different specific resistivities of the soil on the upper layer and the bottom layer of the earth. That way, the presented method, approaches even more to the real models, because in the practice, the soil is not homogeneous, but multi-layer in a vertical and horizontal direction. The vertical unhomogenousness can best be approximated with a two-layer, and the horizontal by dividing the cables in a number of smaller parts, that have constant specific soil resistivities along their length.

6. References

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