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COMPUTER SIMULATION AND NEW RELATIONS FOR DIMENSIONING OF GROUNDING SYSTEMS OF TRANSFORMER STATION HIGH VOLTAGE/MEDIUM VOLTAGE (HV/MV)

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SUMMARY

Designing and dimensioning of grounding systems (GS) of transformer stations (TS) are often made approximately, using various empiric or semi-empiric formulas based on various assumptions and simplifications. Till the appearance of modern, fast and powerful computers, it was the only possible way for designing. As a result of that, as well as our unclear regulations and the lack of good national recommendations, designers are confronted with a series of problems. In this paper, an effort has been made to try to resolve such associated problems. For that purpose, in short form, a modern analytic procedure for designing of GS of HV/MV TS has been exposed, at the same time showing some more accurate models and practical relations. As it is well known, the most suitable way for dimensioning of grounding systems (GS) of HV/MV transformer stations (TS) is the computer simulation aided by some verification computer program, as it enables accurate dimensioning of the whole grounding systems (GS) of transformer stations (TS) and accurate calculation of all its performances.

In this paper, a correlation of results obtained on real-life example is made by using the proposed relations and those which are obtained by computer simulation. It is found that the results obtained in both ways coincide to a great extent.

Key words: high voltage/medium voltage transformer station, grid grounding, dimensioning, grounding system.

1. INTRODUCTION

In all new stations and HV/MV transformer stations, and in those that are either being rehabilitated or expanded, the designing of GS is carried out under previously established procedure:

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- the specific soil resistance and top-layer of the soil are determined,
- distribution and calculation of fault current through the grounding is made,
- dimensioning of the density of horizontal grid grounding and control of the selected solution is made,
- selection of material and cross-section of the ground links and the elements of the grounding is made,
- measures for equalizing of the potential in the inner side of the fence and protection measures outside the fence are taken,
- impedance and voltage of grounding system is calculated,
- control of designed station grounding is performed.

2. DESIGN PROCEDURE

2.1. Determining of the specific soil resistance and its improvement

As it is already known, the value of the specific soil resistance ρ in which the future grounding will be placed is determined by measuring, using some of the well-known methods, such as the Wenner method with four electrodes (1). For designing purposes, it is usually assumed that the soil is of homogenous structure, but if measuring shows vertical arrangement of layers and significant homogeneity of the ground, than, by performing a series of measurements, during which the distance between electrodes would be changed, this method gives the opportunity for measuring of the specific soil resistance of each layer as well.

Further, during the calculations, the multilayer soil is, for practical reasons, replaced with equivalent double layer. In order to prevent the risk of dangerous electric shock, on the surface of the ground, near the grounded buildings, a thin layer of gravel (cca 10 cm) or asphalt (cca 1cm) is placed, which have high specific resistance. In that case, an artificial double layer is formed, which reduces the current flow through human body exposed to electric shock, for the reducing factor C_p (2), which is calculated with this relation 1.

$$C_p = 1 - \frac{0{,}09 \cdot \left(1 - \rho_2 / \rho_1\right)}{2h + 0{,}09} \qquad 1$$

where h is the thickness of the surface layer soil, ρ_2 is specific soil resistance under the surface layer, and ρ_1 is the specific soil resistance of the surface layer.

2.2. Distribution and calculation of grounding fault current

The size of the fault current (fault to ground) through GS depends on the place of fault to ground, which could be in the station or on some of the towers of the overhead transmission lines (OHTL). Besides the currents coming from each connected OHTL, current comes from the power transformers as well, i.e. through the transformers from the neighboring networks with other voltage levels, (3) and (7). Because of the existence of inductive link between the phase conductor which is in connection with the ground and the protective rope (ropes), a part of the fault current from certain OHTL will return to its source through the protective rope and will not flow through the TS grounding. For this reason, during calculation of current which is injected in the TS grounding is operated with corrected currents which flow from each OHTL to the fault place. The correction is made using the so-called reduction factor of suppression, which is calculated with relation 2.

$$\underline{r} = \underline{Z}_m / \underline{Z}_s \qquad (2)$$

In the last relation, $\underline{Z}_s$ is the impedance of the protective rope itself from the OHTL, while $\underline{Z}_m$ is the mutual impedance between the phase conductor and the protective rope. These parameters are calculated in accordance with the well-known Carson relations, (6).

In case of a fault to ground on some of the OHTL, from all sources again flow currents to the fault place, but flowing through the OHTL grounding, they return to the sources through the ground and the protective rope. This is why from the station grid grounding will flow just the current of single-phase short circuit from the transformers and it could be appropriate for dimensioning. Procedure for distribution of currents along the GS of the OHTL in which the fault to ground has occurred is described detail in (10).

2.3. Dimensioning of the density of horizontal grid grounding of transformer stations and checking the selected solution

In the high voltage/high voltage HV/HV transformer stations i.e. HV/MV criteria in respect of grounding can be satisfied if grid grounding elements are used, made of more parallel and mutually normally positioned ropes, i.e. tapes, placed in the shape of rectangles/squares. The density of the horizontal grid grounding elements of HV/MV TS is dimensioned according to the size of the part of the corrected earth fault current which flows from the grounding elements of station and lead to the ground. Furthermore, the selected solution must be verified to satisfy the safety conditions for too high touch voltage (step) both inside and outside the fence. Previous practice in the Republic of Macedonia was calculation of dimension of openings to be made using the graph-analytical procedure described in (3), where grid grounding of any shape is approximated with an equivalent rectangle. Then, using the so-called “universal diagram”, the number of parallel conductors n is read using the same recommendation.

In this way regular grounding is obtained, which will consist of equal number of parallel conductors in length and width.

If the real shape of the grounding it o be taken into consideration when calculating the number of parallel conductors of the equivalent rectangle, the following relation is recommended (2):

$$n = n_a \cdot n_b \cdot n_c \cdot n_d \qquad (3)$$

where:

$$n_a = \frac{2 \cdot L_c}{L_p} \qquad (4)$$

$n_b = 1$ for grid grounding of quadrangular shape,

$n_c = 1$ for grid grounding in quadrangular and rectangular shape,

$n_d = 1$ for grid grounding in quadrangular, rectangular and L shape.

For any other shape is valid:

$$n_b = \sqrt{\frac{L_p}{4 \cdot \sqrt{A}}} \qquad (5)$$

$$n_c = \left[\frac{L_x \cdot L_y}{A}\right]^{\frac{0,7 \cdot A}{L_x \cdot L_y}} \qquad (6)$$

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} \qquad 7$$

where:

L_c - total length of all elements in the grid grounding,

L_p - perimeter of the grid grounding,

L_x - maximum length of the grid grounding in x- direction,

L_y - maximum length of the grid grounding in y- direction,

D_m - maximum distance between any two points of the grounding,

A - area embraced with the grid grounding.

Furthermore, the calculated dimensions of the openings according to relation 3 are examined to verify that they satisfy the safety criteria for too high potential differences on touch and step inside and outside the fence. The biggest touch potential difference could appear at the angles of the grid from inside, and according to (2), is valid:

$$E_d = \frac{\rho \cdot k_m \cdot k_i \cdot I_e}{L_m} \qquad 8$$

The geometry factor k_m is calculated according to the following relation:

$$k_m = \frac{1}{2\pi}\left[\ln\left[\frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d}\right] + \frac{k_{ii}}{k_h} \cdot \ln\left[\frac{8}{\pi \cdot (2 \cdot n - 1)}\right]\right] \qquad 9$$

where:

d - is the diameter of grid elements, in meters,

L_m - is the total length of all elements of grounding (including the vertical ones)

D - is the length of one opening,

h - is the depth of inserting of the grid grounding,

I_e - is the total current which is led out from grid grounding.

For grid groundings with vertical elements placed either on the grounding perimeter or only at its edges, then $k_{ii} = 1$. In case there are no vertical elements or there are just a few, but which are not placed on the edges of the grid grounding, the following is valid:

$$k_{ii} = \frac{1}{(2n)^{\frac{2}{n}}} \qquad 10$$

$$k_h = \sqrt{1 + \frac{h}{h_0}}, h_0 = 1m \qquad 11$$

The factor of unequal current distribution is given with relation 12.

$$k_i = 0{,}644 + 0{,}148 \cdot n \qquad 12$$

The potential step difference E_c is permanently very lower than the touch one, and is not appropriate for dimensioning of openings. It is calculated according to the relation 13.

$$E_c = \frac{\rho \cdot k_c \cdot k_i \cdot I_e}{L_m} \qquad 13$$

$$k_c = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}\left(1 - 0.5^{n-2}\right)\right] \qquad 14$$

2.4. Selection of material and cross-section of the grounding links and the grounding elements

Grounding ropes and horizontal elements of grounding are usually made of Cu ropes, while the vertical elements are made of FeZn tubes. Grounding links in the command building and the grounding links and the grounding on metal fences of the station are usually made of zinc-coated steel. In accordance with the recommendation (3), the cross-section of the grounding links conductors, collective grounding links and grounding of the station is determined for the total current of fault to earth in transient period at fault duration of 1s. This recommendation is in collision with the assumption from the same recommendation, according to which the danger of too high touch voltages and step voltages for short circuit current with duration of 0,25 s. Our technical regulations (6) do not specifically explain this, and our recommendation would be that calculations should be done with real times 0,25 s, which would lead to saving both material and price during execution of the groundings. If the values of the total fault to ground current are higher than those in table 4 (3), then cross-sections are selected according to the current density.

2.5. Measures for protection inside the station and outside the station fence

In order to control the touch voltage under the value of 230 V (which, in accordance with (3) corresponds to fault duration of 0,25 s), more measures are required, which are in more detail described in (3). We will here mention only a few. First, the grounding grid must correspond to the cubicle arrangement, device position, stands and equipment supports. All metal parts of the equipment, the metal cable protections/shields and cable armature, grounding ropes of the connecting overhead lines, lightning grounding, etc. should be connected to the station grounding grid. Metal parts of the station which do not belong to the current circles, but which may, in case of fault, come under voltage (such as the fences and grids around individual devices and stations, pipelines, reinforcements, etc.) should also be connected to the station grounding grid.

Around the building foundations in the station (command-operative, workshops, storehouses, etc) a ring positioned at 1-2 m from building foundation and at a depth of 0,5 m should be placed. It, too, should be connected to station grid grounding. The outside metal fences from the station grounding at a distance of more than 2 m must not be connected to the grid grounding in order not to be brought to its potential. A grounding is placed on the outside of the fence at a distance of 1m, at a depth of 0,5m, which is galvanically connected to the fence, which enables achieving better forming of potential. Besides these measures, it is a practice in the HV/MV TS to isolate the potentially dangerous points around the fence, by placing an insulation layer of asphalt with thickness of 1 cm, or 10 cm layer of gravel of at least 1, 25 m width. The metal protections/shields and armatures of the cables coming from the station are broken at the point at which they exit the building and are insulated with inserts in order to have touch voltage, outside the fence, smaller than 115 V.

2.6. Impedance and voltage calculation of grounding system

The impedance of GS R_z is obtained as a parallel connection of resistance to ground R_{mr} of the TS grid grounding and the incoming impedances of all additional horizontal grounding (strips, metal cable protective covers/shields, water pipes, etc.), the incoming impedances of the OHTL with the grounding ropes, as well as the resistance of the foundation groundings, included through an equivalent incoming impedance $Z_{vl.ekv}$.

There are a number of simple practical relations of semi-empirical character for evaluation of the grid grounding resistance, such as the known relations of Laurent, Schwartz and others. But they do not take into account some of the constructive parameters, such as: the depth of insertion, the shape and dimension of the grounding electrode cross-section, the shape of grid openings, etc. Two of the more recent relations which satisfy in many cases, are the relation of Sverak, relation 15, and the more recent relation of Thapar, Gerez relation 16 (2):

$$R_{mr} = \rho \cdot \left[\frac{1}{L_t} + \frac{1}{\sqrt{20S}}\left(1+\frac{1}{1+H\cdot\sqrt{20/S}}\right)\right] \qquad 15$$

$$R_{mr} = \rho \cdot \left[\frac{1}{L_t} + \frac{1}{\sqrt{20S}}\left(1+\frac{1}{1+H\cdot\sqrt{20/S}}\right)\right]\cdot 1{,}52\cdot\left[2ln\left(L_p\sqrt{2/S}\right)-1\right]\cdot\frac{\sqrt{S}}{L_p} \qquad 16$$

The last relation is applicable not only for grid groundings in rectangular or quadrangular shape, but for L, T and other shapes as well. However, in cases when contours have vertical elements, distributed along grid length, each with length of *l,* it become almost inapplicable. In such cases the relation 17 (2) may be used. In this relation with *N* , the number of openings of the grid grounding is marked, *H* showing the depth of laying, while *A* is the grounding area.

$$R_{mr} = 0{,}13\cdot\frac{\rho}{\sqrt{A}}\log_{10}\left(\frac{2400\cdot\sqrt{A}}{N}\right)\cdot\left(1-\frac{2}{3}\cdot\frac{l}{\sqrt{A}}\right), \frac{l}{\sqrt{A}}\le 0{,}2 \qquad 17$$

The voltage of the GS, U_z , is calculated according to relation 18, in which the impedance module of GS R_z is calculated in accordance with relation 19.

$$U_z = I_e \cdot R_z \qquad 18$$

$$R_z = \frac{R_{mr}\cdot Z_{vl.ekv}}{R_{mr}+Z_{vl.ekv}} \qquad 19$$

For calculating the input impedance of cables and OHTL are used relations from (5).

2.7. Control of designed station grounding

At the end, the impedance of GS (for HV/MV TS it ranges from 0,05 to 0,1 Ω) and touch voltage is measured and it is compared with the permitted one. If 20 is valid, the designed solution is satisfactory.

$$E_d \le E_{d.dozv.} = 230 + 0{,}34\cdot\rho_p \qquad 20$$

3. CALCULATION USING COMPUTER SIMULATION AND COMPARISON

The empiric relations are simple and practical for use. By using them, one can promptly come to an approximate, but sufficiently accurate solution. However, the computer simulation with some of the known methods has proven as most accurate (in this case we have used the ZAZEM program package which is based on applying the Maxwell method and medium potentials, (9).). As an illustration of the application of both procedures let us use a concrete example of the existing TS 220/110/35 kV Skopje 1, together with actual expansion with the new part TS 400/110 kV Skopje 5, (8). The grid grounding of the TS has a complex, irregular shape, (Figure 1).

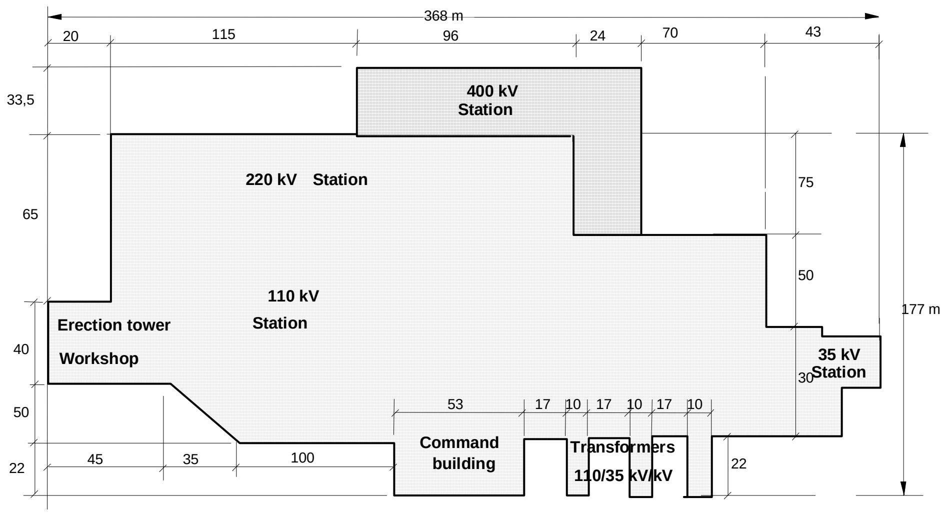

Figure 1. Grounding of TS 220/110/35 kV Skopje 1 after expansion with the 400 kV part, Skopje 5

It is made of Cu rope 70 mm^2, laid at depth of 0,8 m. The project estimates that the specific soil resistance in the area of TS is ρ=100 Ωm. The project anticipates that both peripheral ropes of the grid grounding, marked as potential ramps, be placed at greater depth, i.e. at 1 m, and 1,5 m respectively, in order to gain a small drop of potential at all entry points. The fence basically follows the overall dimensions of the grounding and is placed at a distance of at least 10 m from the peripheral ropes. It has its own grounding, placed at a distance of 1 m on the outside, which is not galvanically connected to the main grounding in order to prevent export of potentials outside the fence. The grid grounding is galvanically connected with the GS to all OHTL

Table 1 shows resistance to ground calculated in two ways, according to the empirical relations and computer simulation.

TABLE 1 - RESISTANCE TO GROUND OF THE GRID GROUNDING CALCULATED WITH:

Relation 16	Relation 17	Computer simulation
$R_{mr} = 0{,}192\Omega$	$R_{mr} = 0{,}189\Omega$	$R_{mr} = 0{,}19\Omega$

The input impedance of all HV, connected to the TS, is calculated in (8) and amount to 0,1+j0,05 Ω. In this case, for the input impedance module of GS the approximately achieved value is $R_z = 0{,}07$ Ω. If $R_{mr} = 0{,}187\Omega$, value adopted according to the project, for the grounding potential during a single-phase short circuit in 2020, $U_z = 3254$ V is achieved. The last value is received by determining that for the grid grounding itself the short circuit occurring in the station itself is not critical, which is most usually the case, but rather the case when the short circuit has occurred at the first tower of one of the 110 kV. It has thereof been calculated that from the grid grounding in 2020 will be lead out an earth fault current of $I_e = 17{,}4$ kA. In addition, the value of the grounding potential is necessary for selecting and dimensioning of the grid density. Table 2 shows the dimensions of the grid opening, calculated according to the two different procedures and the dimensions of the old 110 kV part.

TABLE 2 - GRID OPENING DIMENSIONS OF DIFFERENT GROUNDING PARTS EXPRESSED IN METERS

Universal diagram	Relation 3	On old 110 kV part
10 x 10 inside part	13,2 x 13,2 inside part	8 x 8 inside part
10 x 5,7 peripheral belt	13,2 x 7,3 peripheral belt	8 x 4,4 peripheral belt
5,7 x 5,7 at angles	7,3 x 7,3 at angles	4,4 x 4,4 at angles

Taking into account the present rigorous regulations ($E_{dd} = 264$ V, according to relation 20) this project has adopt the grid opening dimensions to be same as in the 110 kV part. Having such adopted dimensions, resistance to ground and potential difference on touch and step in TS have been calculated. Those are $U_{d\max} = 245$ V, i.e. $U_{c\max} = 29$ V, which means that the regulations have been satisfied since these values are below the permitted ones of $E_{dd} = 264$ V.

4. CONCLUSION

In this paper we have exposed procedures and new practical relations for selection and dimensioning of grounding of HV/MV TS. The suggested relations avoid the large number of simplifications which were present in the previously known and applied empirical relations. However, as the most reliable is the computer simulation, with has been used to control the element selection of GS of TS 220/110/35 kV Skopje 1, and the expansion with the new part TS 400/110 kV Skopje 5, (project in stage of realization, (8)). The results obtained through both procedures coincide to a great extent.

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