Practical analytical procedure for grounding grids design for HV/MV TS

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Abstract: **The HV/MV substation (TS) grounding design in the past was usually performed by using simple empiric and semi empiric formula based on some assumptions and simplifications. This fact, in combination with the problems relating the lack of good technical roles and national recommendations, makes the engineers designers meeting number of problems while projecting grounding devices of HV/MV TS. In this paper an effort to relief part of these problems is done. A practical analytical procedure for grounding grids design for HV/MV TS is presented.**

Keywords – **groundings, voltages of touch, step.**

I. Introduction

The usual practice in the world but also here [3], is to take as competent for dimensions of grounding system (GS) the transient current of mono-phase short circuit witch will appear after 5 (for the permanent facilities), or after 10 years (for the facilities witch are being built or reconstructed) in the moment of its building process. As a condition for safety it is taken the value of the touch voltage U_d (the step voltage is taken as lower, $U_c < U_d$). It must not be bigger than 230V in the area of the facility, and 150V out of it.

II. Designing procedure

In all new facilities and TS HV/MV, as well as in those which are being reconstructed or broadened, the designing of GS is executed in procedure which is planed in advice:
-The structure of the ground is determined and its specific resistance ρ.
-The entering impedances $\underline{Z}_k$ are calculated, and the reduction factors $\underline{r}_k$ of all the overhead lines and cables, and also it is calculated the equivalence (entering) impedance Z_{ek} of all the GS.
-The allocation of the currents of fault is calculated in the whole GS and the GS voltage U_{ek} at the time of fault.
-The material and cross-section of the elements of the grounding grid (GG) is chosen as well as the other additional elements of GS.
–The choice and dimensional measurement is made for the density of the horizontal grounding grid (GG) and the chosen solution is made.
-Steps are taken for equalization of the potential in the inner part of the fence and outside the fence of the facility.
-The chosen solution is checked and corrected.

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Needed parameters for designing the GG are**:**
- The characteristic of the ground.
- Information about the short circuit with ground.
- The characteristic of the connected overhead lines and cables, needed for calculation of the entering impedances $\underline{Z}_k$ and the reduction factors $\underline{r}_k$.
- Information about the area and the placement of the buildings, the important equipment and other objects.

2.1 Determination of the specific resistance of the ground

The value of the specific resistance of the ground ρ in witch the GS will be put is determined by measuring, using some of the known methods as the Wenner's method with four drills. For the necessity of the design it is presumed that the ground is homogenous in structure, but if there are vertical layers, than with measuring and changing the inter electrode distance *a,* the structure of those layers is determined. The number of points of measurement depends of the area A that takes the GS. Usually the measuring is made on 5 points if area is smaller than 10000 m^2, or on 10 or more for bigger areas.

2.2 Calculating the equivalent impedance and the voltage of the grounding system

The equivalent impedance of GS Z_{ek}, is derived as a parallel connection of the resistance of GG R_{mr}, and the entering resistance $\underline{Z}_k$, of all the additional groundings (bands, water pipes, foundation groundings of the objects in TS), the metal palls of the energetic cables, the entering impedance of the overhead lines with grounding ropes:

$$\underline{Z}_{ek} = \left(\frac{1}{R_{mr}} + \sum_k \frac{1}{\underline{Z}_k} \right)^{-1} \quad (1)$$

There are many simple practical relations of half-empirical character for calculating the resistance of the GG R_{mf} of which kind are the famous relations of Laurent, Schwartz and others, which are mentioned in the recommendation also [3]. But they haven't comprised some constructive parameters of the grounding system such as: the depth of burial $h_{mr/}$ the shape and dimension of the cross section of the electrodes of the grounding system, the dimensions of the eyelets of the network etc. Two of the newer relations, which in most of the cases give good results, are the relation of Sverak, and Thapar:

$$R_{mr} = \rho \cdot \left[\frac{1}{L_\Sigma} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h_{mr} \cdot \sqrt{20/A}} \right) \right] \quad (2)$$

$$R_{mr} = \rho \cdot \left[\frac{1}{L_\Sigma} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h_{mr} \cdot \sqrt{20/A}} \right) \right] \cdot 1{,}52 \cdot \left[2\ln\left(L_p \sqrt{2/A}\right) - 1 \right] \cdot \frac{\sqrt{A}}{L_p} \quad (3)$$

This last relation is usable not only for GG in shape of rectangle or square, but also for GG with L or T- forms. But in the cases when the contours have vertical elements arranged to the perimeter of GG, each with length of l_v, that becomes almost unusable. In that case the relation (4) can be used, In that relation N is the symbol for the eyelets in the GG, h_{mr} is the depth of installation, while A is the area which is enclosed by GG. It is general and can be used in the cases when GG has no vertical elements also.

$$R_{mr} = 0{,}13 \cdot \frac{\rho}{\sqrt{A}} \cdot \left(1 - \frac{2}{3} \cdot \frac{l_V}{\sqrt{A}} \right) \cdot \log_{10}\left(\frac{2400 \cdot \sqrt{A}}{N} \right); \quad \frac{l_V}{\sqrt{A}} \le 0{,}2 \quad (4)$$

The calculation of the grounding resistance R_{mr} for the case when GG is installed in double layer can be done with adequate computer programs or to be calculated with some empirical formula ([11],[12]).

2.3. Distribution and calculation of the current of ground connection in GS

The current I_{ek} which is taken to the ground in the time of short circuit with earth connection cannot be measured directly, but it is calculated. From [12] it is equal to the sum of the triple null components of the current which comes trough the connected overhead lines and cables:

$$\underline{I}_{ek} = \sum_k \underline{r}_k \cdot 3\underline{I}_k^0 = \sum_k (1 - \underline{Z}_{m,k} / \underline{Z}_{s,k}) \cdot 3\underline{I}_k^0 \quad (5)$$

The values of these currents are derived from the studies of short circuit which are made for cases in EES for some near future. Here with the index k are enclosed just those overhead lines and cables trough which the current of fault is brought to the place of short circuit with ground.
The voltage of GS U_{ek}, which will also be voltage of the GG U_{mr}, is calculated in accordance to the relation;

$$\underline{U}_{mr} \equiv \underline{U}_{ek} = \underline{Z}_{ek} \cdot \underline{I}_{ek} \quad (6)$$

The part from the current I_{mr}, which trough GG is taken to the earth will be:

$$\underline{I}_{mr} = \frac{\underline{U}_{mr}}{R_{mr}} = \frac{\underline{Z}_{ek}}{R_{mr}} \cdot \underline{I}_{ek} \quad (7)$$

The last relation gives the current took to the earth from GG when the fault happened in the facility itself. That current is competent for finding a dimension of GG. But sometimes, when the part of the local energetic transformers in the whole fault current is big, it may happen that the current of taking to earth from GG to be competent for giving dimension of GG, for the case of ground connection of some of the starting columns to some of the connecting overhead lines. In that case, from all the sources of EES the currents will flow again to the place of break down, but passing trough the grounding of the column, they will return back to earth trough the protecting ropes of overhead lines. In that case only the current of mono-phase short circuit from the transformers in the facility will be taken. Sometimes it can be competent for dimensions. The process of calculating of currents in GS in this case is described in detail in [10].

2.4. Choice of the denseness of the horizontal grounding grid (GG) of TS and checking of the chosen solution.

The groundings of TS HV/HV or HV/MV are made as grid, containing from many parallel and mutually normal ropes, put in shape of rectangle. The resistance of the extension R_{mr} as well as the potential differences on touch E_d and step E_s, depends on the denseness of the grid with which the grounding system is made.

In the designing practice until now, the calculation of the dimensions of the eyelets have been made with graphic-analytic action described in TP23 [3]. According to it GG with any shape is approximated to equal rectangle and then using universal diagram the number of parallel armatures is determined. In this way we get correct GS in which the number of parallel horizontal and vertical armatures will be equal. If we want to take into consideration the real shape of the GS in the calculation and the number of parallel armatures of the equivalent rectangle it is recommended the number of parallel armatures to be calculated with the following relation:

$$n = n_a \cdot n_b \cdot n_c \cdot n_d \quad (8)$$

$$n_a = \frac{2 \cdot L_{mr}}{L_p}; \quad n_b = \sqrt{\frac{L_p}{4 \cdot \sqrt{A}}} \quad n_c = \left[\frac{L_x \cdot L_y}{A} \right]^{\frac{0{,}7 \cdot A}{L_x \cdot L_y}}; \quad n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} \quad (9)$$

If GG is in shape of square it is taken $n_b = n_c = n_d = 1$, while GG in shape of rectangle is taken $n_c = n_d = 1$. In addition to that for GG in shape of the letter L, $n_d = 1$.
Then, for the denseness of GG calculated in this way, it is also calculated the maximal potential difference on touch and step E_m and E_s and it is investigated if the criteria for protection of too big potential differences of touch and step in and out of the fence. As it is [12] known, the potential difference of touch in the corner eyelets E_m is difference of the potentials on which, in the time of the short circuit with ground, come the grounding from the installation and the point in the middle of the eyelet, which is taken as point with lowest potential of the surface enclosed with GG. That is why the potential differences on touch Ed which can be bridged with touch in any other point of GG, surely will not be bigger than the value E_m, ($E_d \le E_m$). The biggest potential difference of touch at GG put on homogenous ground can be calculated with [12]:

$$E_d = \frac{\rho \cdot k_m \cdot k_{im} \cdot I_{mr}}{L_{em}} \quad (10)$$

In it there is the factor of irregular division of current k_{im} as well as the factor of geometry k_m. They are calculated with the following relations:

$$k_{im} = 0{,}656 + 0{,}172 \cdot n \quad (11)$$

$$k_m = \frac{1}{2\pi} \left[\ln\left[\frac{D^2}{16 \cdot h_{mr} \cdot d} + \frac{(D + 2 \cdot h_{mr})^2}{8 \cdot D \cdot d} - \frac{h_{mr}}{4 \cdot d} \right] + \frac{k_{ii}}{\sqrt{1 + h_{mr}}} \cdot \ln\left[\frac{8}{\pi \cdot (2 \cdot n - 1)} \right] \right] \quad (12)$$

Where: d- is diameter of the elements of the GS in meters

$$L_{em} = L_{mr} + 1{,}15 \cdot L_S;$$

For GG systems with vertical elements put in the parameter of the grounding or in its corner $k_u = 1$.
If there are no vertical elements or there are only some of them, but they are not installed in the corners of the GG:

$$k_{ii} = (2n)^{-2/n} \tag{13}$$

The potential difference of step is regularly much lower than that of touch and it is not valid for giving dimensions of the eyelets. The maximal potential difference of step E_c, which can appear in the armature, is calculated with:

$$E_c = \frac{\rho \cdot k_s \cdot k_{is} \cdot I_{mr}}{L_{es}} \tag{14}$$

$$k_{is} = 0,94 + 0,047 \cdot n \tag{15}$$

$$k_s = \frac{1}{\pi}\left[\frac{1}{2h_{mr}} + \frac{1}{D + h_{mr}} + \frac{W}{D}\right] \tag{16}$$

$$L_{es} = L_{mr} + 2 \cdot L_S \tag{17}$$

$$W = 0,5 + 0,9 \ln \frac{n-1}{2}; n > 2 \tag{18}$$

$$W = 0; n = 2$$

2.5. Choice of material for the elements of grounding system

The ropes of the earth canals and the horizontal elements of the GS, as a rule, are made from Cu rope, while the vertical elements from FeZn pipes. The groundings in the command building as well as the groundings of the metal fences of the armature, as a rule, are made from steal covered with Zink. In accordance with the recommendation [3] the cross section of the canals of the groundings, of the assembled earth connections and the grounding of the armature should be determined on the basis of the whole current of short circuit with ground in the transitory period and the time of fault *Is* taken as 1s. This is in collision with the part from the same recommendation where it is said that the dangers from too high voltages on touch and step are estimated under presumption that the fault lasts for 0,25s. Our technical regulations [6] do not say anything concrete about it, and that is why we can conclude that the thermal giving dimensions of the elements from GS should be made with real times of fault exclusion, with which we would save on material and price in making of GG.

After the choice of the denseness of the network and the over crossings of the elements from GS the conditions of safety are controlled, calculation of the maximal possible voltages on touch and step $U_{d,\max}$ and $U_{c,\max}$

$$U_{d,\max} = \frac{E_m}{1 + 1,5 \cdot 10^{-3} \cdot \rho_p}; \quad U_{c,\max} = \frac{E_s}{1 + 6 \cdot 10^{-3} \cdot \rho_p} \tag{19}$$

In the last relations with ρ_p is denoted the specific resistance of the surface of the ground. It can be different from the specific resistance of the ground if the case is that over the surface of GG Is put a layer of broken stone, big gravel or a thin layer of asphalt in order to reduce the voltages of touch and step. This measure is taken in the hard conditions of grounding (high specific resistance ρ, small area available A, big electricity of taking l_{mr}) for rationalization of the technical solution. If we use layer of broken stone or clean sprinkled gravel it should be at least 10 cm thick and in that case in the relations (19) is taken ρ_p = 5000 Ωm [3]. Similarly, if an asphalt layer is needed with thickness $h_p \geq 1$ cm, is taken ρ_p = 10.000 Ωm,

If the values of the voltages of touch and step calculated with (19) are not smaller than the permitted, correction is made on the denseness of GG.

2.6. Measures for protection in and out of the fence

In order to control the voltage on touch under the value 230 V many measures will be needed to be taken, which are described in detail in [3], and here we have only a few. At first the GG should be adapted to the place of the fields, the position of the machines, the bases and the bearers of the equipment. All the operating groundings, the metal palls and armatures of the cables, earth connected ropes from the connected overhead lines, lightning rod groundings should be connected to GG.

The metal parts of the operating appliances which are not part of the electrical circuits, and which in case of fault can come under voltage (as the fences around some machines and armatures, tubes etc also should be connected to the GG.

Around the foundation of each of the buildings in the installation (command-operation, workshops, stockrooms) a ring with distance of 1-2 m should be put and with depth of 0,5m, which will be connected, also to GG. The outdoors fences should be ad distance not less than 2m from GG and should not be connected to GG so then will not be brought under its potential.

On the outer side of the fence on depth of 0,5 m on a distance of 1m from the fence the grounding is installed. It is connected with the fence which brings to better shape of the potential from the outer side. Apart from these measures, in the TS HV/MV isolation of the potentially dangerous places is practiced, with putting an isolation layer of asphalt with thickness of 1cm, or 10 cm of gravel which will be at least 1,25 m wide. Sometimes it may be made enclosing with metal fence of the potentially dangerous places of the TS. The metal palls and the armatures of the cables which come out of the TS are disconnected at the places where they leave the object and are isolated with isolation in order to be achieved voltage on touch out of the fence lesser than 115 V.

III. Calculation with Computer Simulation

The empiric relations are simple and practical for usage and with their help we can come to the approximate solution fast. But, the best way to solve the problem is computer simulation, especially in cases when GG are taking a big area. In this paper we have analyzed GG of the permanent TS 220/110/35 kV Skopje 1, with the new enlarging with the new part TS 400/l10kV Skopje 5 [7].

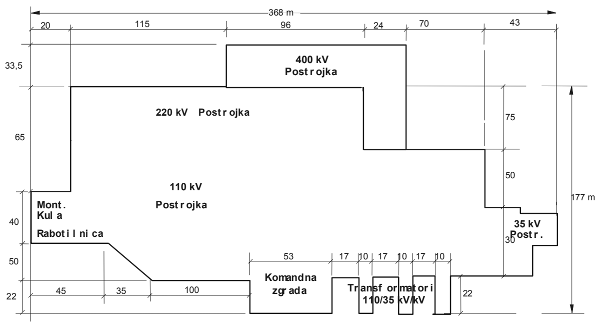

Fig.1.

The GG of this TS has irregular complicated form. It is made with Cu rope 70mm^2, installed in depth of h_{mr}=0,8 It is calculated that the resistance of the ground in the area of the TS is ρ=100 Ω. The two peripheral ropes from the GG, marked as potential gates, are installed in bigger depths, on 1m or 1,5 m respectively, in order to get small descent of the potential of all entries. The fence basically follows the gabardine of GG and is installed on distance of at least 10m from the peripheral ropes. It has its own grounding, put on distance of 1m from the outer side, which is not galvanic connection with the main grounding, in order to hinder the exit of potentials out of the fence.

The GG is connected in galvanic way with the protective ropes of all the connected overhead lines.

In the table we have shown the values of resistance R_{mr} of this grounding, in two ways: with the empirical relations (3) and (4) and with computer simulation. In the concrete situation we need a program package ZAZEM [9] which is based on the usage of the Maxwell's relations and the method of middle potentials.

TABLE I. GROUNDING RESISTANCE

Relation (3)	Relation (4)	Computer sim.
R_{mr} = 0,192Ω	R_{mr} = 0,189Ω	R_{mr} = 0,190Ω

The entering impedance of all overhead lines, connected to TS is calculated in [8] and is 0,l±j0,05Ω. In that case for the module of the entering impedance of GS we get the value $|\underline{Z}_{ek}| = 0,07\ \Omega$, while for the potential of the grounding in the time of the fault (mono-phase short circuit in 2020) we get the value U_{mr}=3254V. The last value is derived with from the fact that it is determined that for the network grounding it is not critical the case of short connection happened in the installation itself, but in the case when the fault happened in the first column from one of 110KV overhead lines. It is calculated that from GG to the earth will be taken current of fault I_{mr}=17,4 kA.

This current, together with the potential U_{mr} are valid for the choice and giving dimensions of the denseness of the GG. In the next table we have shown the calculated dimensions of the eyelets of the network, according to the two different procedures. ln the project [7] is accepted, as a final solution, in the newly designed part of the installation the dimensions of the eyelets to be same as in the old part, which leads to bigger safety. With dimensions accepted in this way, the resistance of spreading of GG is calculated; the distribution of fault current in GS, as well as the potential differences of touch and step in TS. They are E_m=245V and E_S=29V. Under presumption that $\rho_p = \rho = 100\ \Omega$, for the biggest voltages of touch and step in the installation we get: $U_{d,\max} = 213$ V and $U_{c,\max} = 25$ V, which means that the conditions for safety, are taken into consideration because the voltages of touch and step are in the borders of the allowed 230V.

TABLE II

Universal dia. [3]	Procedure 2.4	old 110 kV part
10 x 10 inside	13,2 x 13,2 inside	8 x 8 inside
10 x 5,7 perifer. belt	13,2 x 7,3 perifer. belt	8 x 4,4 perifer. belt
5,7 x 5,7 corners	7,3 x 7,3 corners	4,4 x 4,4 corners

IV. CONCLUSION

In this paper, in short is described the procedure and are recommended new, practical, relations for choice and dimensions of the GG of TS HV/MV. In the recommended relations it is avoided the big number of simplifications which were present until now in the known and used empiric relations. However, as a most credible is proved the computer simulation , with which in the frames of [8] the choice of the elements of GS is checked in TS 220/110/35 kV Skopje 1, and the enlarging of the new part TS 400/110 kV Skopje *5,* (project [7]). The results from the two procedures are same in great extent.

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