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Effect of Fault-Clearing Time on the Sizing of the Ground Mesh in A 220kv Station According IEEE-80 Standard And Its Profitability

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Abstract: The present article aims to analyze and demonstrate that it is technically and economically feasible to optimize the design of the ground mesh in an electric station, considering as a parameter the fault-clearing time, according to the IEEE-80 standard, field experience and scientific literature, regardless if the event is internal or external. In this case the fault-clearing time is reduced from 0.5 seconds to shorter times, so that no fibrillation occurs in the human body and the values of the permissible touch and step voltages of the 220 kV station's ground mesh won't be compromised. For this purpose are considered the surface dimensions of a conventional 220 kV station according to the technical specifications of the national company ANDE. The rules listed in the IEEE-80 Standard and the introduction to the mathematical method for calculating the distribution of the potential gradient is the focus of this research. For the economic evaluation are analyzed the material and installation savings and the measurements of a ground mesh system using copper conductors.

Keywords: step voltage, touch voltage, fence voltage, ground mesh, short circuit

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I. INTRODUCTION

The design of Grounding Systems, specifically concerning the sizing of the ground mesh, is part of the activities related to the design of all electric stations, regardless of their voltage level. It is an essential activity in both project engineering and the safety of people. This article bases its methodology on the mathematical development stated in the ANSI / IEEE 80 Standard "Guide for Safety in AC Substation Grounding" and mathematical models extracted from scientific literature to be applied to practical cases, so that design engineers of electric stations and electrical and electromechanical engineering students know the standards to be able to solve practical problems they will face during their professional lives. The calculations begin with the assessment of the values of short-circuit currents for the different types of scenarios of events that may occur within a standard 220kV station. Then a fixed value of apparent soil resistivity, usually calculated by the Werner method, is adopted. Follows the calculation of the parameters obtained by the mathematical model under the IEEE 80 Standard, in which are applied options in the variation of the fault-clearing time. In all cases the size of the ground mesh perimeter is rectangular, but it's also possible to choose a square shape.

Regarding the calculation of allowable stress values of touch and step voltage it is adopted as fault-clearing time interval 0.5 s to 0.12 s, considering that the human body has a permissible current fibrillation of up to 3 s (Kindermann, 1991). The step, touch and fence voltages of the project will be calculated on a rectangular mesh for a person weighing 70kg. As the inertial reference frame are taken rectangular coordinates (x, y) at one end of the mesh. Then, the behavior of the project voltages along the rectangular axes is assessed to be compared with the allowable values. The sizing of the conductor is part of this article, according to those available on the market, made of tinned copper. The earth electrodes are of the copperweld and the connectors of the compression type (ANSI/IEEE 80, 2000; ANDE, 2008; ANDE, 2013).

The mathematical model described by Kindermann (1991) is used to calculate the fence voltage near the endpoints of the station. This value is compared with the permissible touch voltage. Then, the optimum location of the earth electrodes inside the station is evaluated, taking into account the variation of the volage gradient. Comparative tables are drawn up for each of the proposed cases to find out the most optimal cases to

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be presented. The concepts developed here will allow to the designer of grounding systems of electric stations, in particular regarding the sizing of the ground mesh, to have available a fairly practical methodology, starting with obtaining the field data, continuing with the design itself and finishing with the resistance measurement of the already built grounding system.

Evaluation Of The Short Circuit Current For A 220 Kv Station

Table 1 shows the values of the effective short-circuit current (kA) for the different scenarios based on studies made by ANDE for a standard station with voltage levels 220/23 kV. The single-phase short circuit current on the 23kV side of the bar has the highest phase-to-ground amperage (I_{CC} = 9.60 kA). For the sizing of the ground mesh is considered only 70% of this maximum current (ANSI/IEEE-80-2000 Standard).

Table 1: Values of short-circuit currents for different failure scenarios in kA.
Source: ANDE, 2013

Voltage level	kV	220	23
Single-phase	F	5.76	9.60
	N	5.72	15.51
Three-phase	Ia	4.939	6.494
Phase-ground	Ia	5.35	9.154
Phase-phase	Ib = Ic	4.278	5.624
Phase-phase-ground	Ib	4.442	9.556
	Ic	5.761	9.602
	In	5.72	15.51

Resistance of the grounding mesh and soil resistivity

To calculate the resistance of the grounding mesh is required the soil resistivity as an input. As a reference for the apparent soil resistivity is employed a value of 200 Ohm-m, given that the methodology of calculating soil resistivity is not part of the present article (ANDE, 2013). Furthermore, to evaluate the allowable voltage in the mesh is required the resistivity of the surface layer of the station covered by crushed stone, whose resistivity is 3000 Ohm-m (ANSI/IEEE-80-2000 Standard).

Maximum Permissible Voltages

The permissible maximum volages are defined as indicated in the ANSI / IEEE 80 Standard. Step and maximum allowable touch voltages depend on soil resistivity. In the station you have 2 layers, the ground and crushed stone. Therefore should evaluate the reduction due to reflection (Kindermann, 1991). The reflection factor is given by equation (1), where ρ is the resistivity of the crushed stone and ρ_s the apparent resistivity of the soil.

$$k = \frac{\rho - \rho_s}{\rho + \rho_s} \tag{1}$$

$$C_s = \frac{1}{0.96}\left[1 + 2\sum_{j=1}^{1000} \frac{k^j}{\sqrt{1 + \left(2j\frac{h_s}{0.08}\right)^2}}\right] \tag{2}$$

With this value and a thickness of the crushed stone layer of 0.10 m equation (2) is used to calculate the reduction coefficient of the surface layer C_s used to calculate the effective resistance of a person's foot in presence of surface material of finite thickness (Ramírez, 2010).

II. DURATION OF SHORT CIRCUITS

To determine the permissible touch and step voltages is considered that the duration of the short circuit will be in seconds. The durations of failure t_f and of shock t_s are typically assumed as equal, unless the duration of failure is the sum of successive impacts as those produced by the automatic reclosing of the SF6 type switches of 220 kV, which have an opening time of 0.06 s and a closing time 0.16 s (IEC Nº 62271-100 Standard). The selection of failure duration t_f, may reflect times of rapid clearance of the transmission station and slow clearance times for distribution and industrial substations. The selection of t_f and t_s can result in the most pessimistic combination of factors of decreased fault currents and allowed currents by the human body (Ramírez, 2010).

Typical values for t_f and t_s are in the range 0.25 to 1 s (Ramírez, 2010). According to Kindermann (1991) 99.5% of people weighing 50 kg or more can endure without an occurrence of ventricular fibrillation within a range of 0.03 to 3 s. This time interval is a permissible and acceptable limit, so that no fibrillation will occur during the time the person is under touch or step voltage. The crash time is limited by the performance of the protection systems, according to the curve of the relay (Kindermann, 2005). Thus, for a greater fault current in the system passing through the grounding, the relay curve provides the time for action of the protection systems, bearing in mind that the general principle of the protection systems is to eliminate the quickest possible fault, so to have the smallest number of customers without power. For digital relays there is no need to have time curves printed on paper, because it operates associating the curve to a function that reproduces the normalized curve (IEEE Standard C37.112-1996). For a deeper and more realistic technical analysis as set out in the preceding paragraphs we shall take as reference of the fault clearing time of the switch the value of t_s = 0.12 s (ANDE, 2013).

Maximum Permissible Voltages

The safety of a person depends on the amount of energy that it can be absorb during a certain period of time, which in this case is the duration of the fault. Consequently, the maximum allowable voltages depend on the weight of the person and on the duration of the short circuit. According to the ANSI / IEEE 80 Standard can be considered people weighing 50 kg and 70 kg respectively. For a more realistic analysis is applied the mathematical model of the maximum permissible step and touch voltages to achieve security for the personnel weighing 70 kg, as shown in equations (3) and (4) obtained from Kindermann (1991).

$$V_{p_{70}} = \left(1000 + 6C_s\rho_s\right)\frac{0.157}{\sqrt{t_s}} \tag{3}$$

$$V_{t_{70}} = \left(1000 + 1.5C_s\rho_s\right)\frac{0.157}{\sqrt{t_s}} \tag{4}$$

Sizing Of Ground Mesh Conductor

Table (II) shows the constants of different types of conductors used for the selection and sizing of grounding systems of stations. For a more simplified technical analysis are considered the constants of tinned bare soft type copper wire with 100% conductivity (ANSI/IEEE 80-2000 Standard).

The thermal limit of the conductors is determined by the used splice. In this case is considered the compression type having the following values:

Operating temperature of the conductor: T_a = 40°C

Maximum temperature inside the conductor (with compression splicing): T_m = 250°C

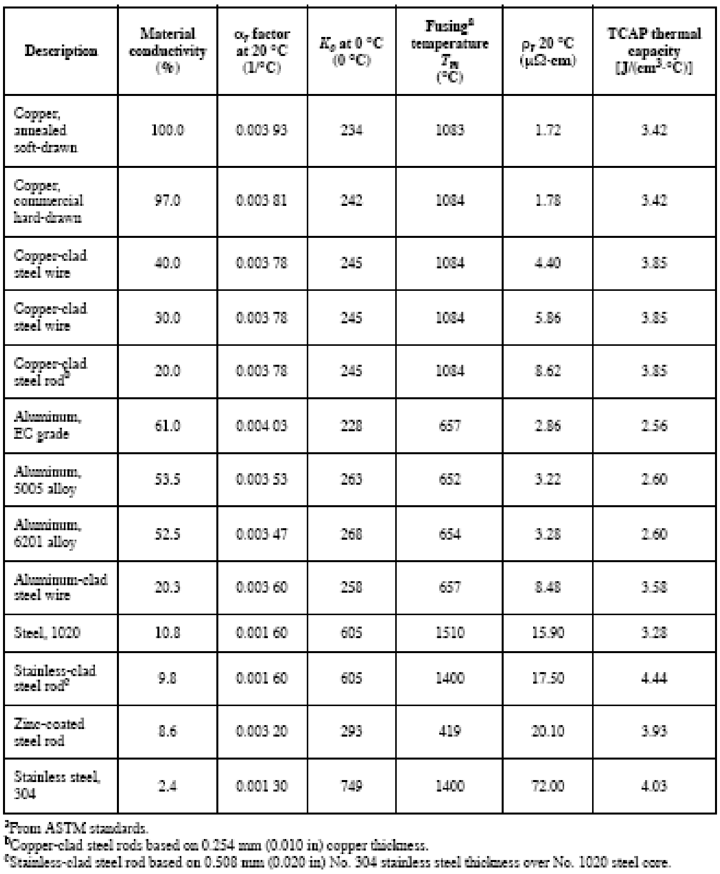
Thermal coefficient of resistivity (reference temperature: 20°C): α_r = 0.00393 1/°C

Inverse of the thermal coefficient of resistivity at 0°C: K_0 = 234°C

Resistivity of the conductor of the mesh (reference temperature: 20°C): ρ_r = 1.7241 μΩ cm

Thermal Capacity Factor: T_{CAP} = 3.422 J/(cm^3 °C).

Table II: Material Constants Of Conductors For Ground Mesh. Source: ANSI/IEEE 80-2000 Standard



Description	Material conductivity (%)	α_r factor at 20 °C (1/°C)	K_0 at 0 °C (0 °C)	Fusing[a] temperature T_m (°C)	ρ_r 20 °C (μΩ·cm)	TCAP thermal capacity [J/(cm³·°C)]
Copper, annealed soft-drawn	100.0	0.003 93	234	1083	1.72	3.42
Copper, commercial hard-drawn	97.0	0.003 81	242	1084	1.78	3.42
Copper-clad steel wire	40.0	0.003 78	245	1084	4.40	3.85
Copper-clad steel wire	30.0	0.003 78	245	1084	5.86	3.85
Copper-clad steel rod[b]	20.0	0.003 78	245	1084	8.62	3.85
Aluminum, EC grade	61.0	0.004 03	228	657	2.86	2.56
Aluminum, 5005 alloy	53.5	0.003 53	263	652	3.22	2.60
Aluminum, 6201 alloy	52.5	0.003 47	268	654	3.28	2.60
Aluminum-clad steel wire	20.3	0.003 60	258	657	8.48	3.58
Steel, 1020	10.8	0.001 60	605	1510	15.90	3.28
Stainless-clad steel rod[c]	9.8	0.001 60	605	1400	17.50	4.44
Zinc-coated steel rod	8.6	0.003 20	293	419	20.10	3.93
Stainless steel, 304	2.4	0.001 30	749	1400	72.00	4.03

[a] From ASTM standards.
[b] Copper-clad steel rods based on 0.254 mm (0.010 in) copper thickness.
[c] Stainless-clad steel rod based on 0.508 mm (0.020 in) No. 304 stainless steel thickness over No. 1020 steel core.

The minimum conductor section in mm2 is expressed by equation (5) proposed by Kindermann (1991).

$$A = I_{cc}\sqrt{t_c \alpha_r \rho_r \frac{10^4}{T_{CAP} Ln\left(1 + \frac{T_m - T_a}{K_0 + T_a}\right)}} \tag{5}$$

Using the above constants in this equation the minimum section is: A = 20 mm^2.

However, the smallest size of tinned copper conductor commonly used for grounding in electrical stations is AWG code 2/0 (= 67.46 mm^2), which has an area equivalent to 133.1 MCM and a diameter d = 0.01 m. This oversizing allows future expansions and a better safety of persons (ANSI/IEEE 80-2000 Standard).

Earth Mesh Geometry

The ground mesh, which is the subject of the technical and economic analysis in the present article, is located in a 100 m long and 100 m wide plot at a depth h = 0.6 m from the surface. It will be designed to maintain the safety of a person with a minimum weight of 70 kg (ANDE, 2008). As the potential is a vector quantity, is taken as inertial reference frame one of the corners of the mesh, considering that the potential gradient distribution exhibits higher values in the corners.

Table (III) shows 5 cases of clearing time t_s with its respective mesh geometry and conductor cost for the mesh considering a specific cost of US$25/m (ANDE, 2015). For all 5 cases the length of the conductors in the rectangular axes (L_x; L_y) will remain constant. The mesh is divided into squares with a variable separation (D_x; D_y) generating a variable number of parallel conductors (n_x; n_y).

Table III: Correlation between Geometry Of Earth Mesh And Fault Clearing Time. Source: ANDE, 2015

t_s (s)	L_x (m)	L_y (m)	D_x (m)	D_y (m)	n_x (un)	n_y (un)	L_t (m)	Cost (US$)	Relat. cost (%)
0.12	95	85	10	10	10	9	1768	44,200	100
0.2	95	85	7	7	14	13	2488	62,200	141
0.3	95	85	5	5	20	18	3473	86,825	196
0.4	95	85	4.5	4.5	22	20	3833	95,825	217
0.5	95	85	4	4	25	22	4278	106,950	242

The total conductor length is given by Lt increased by 63 m due to the total length of the 21 earth electrodes having each a length of 3 m, so to help to reduce the resistance of ground mesh. The earth electrodes with a diameter of ¾ " are of the Cooperweld type. They will be distributed on the mesh in places of greater sensitivity concerning failure events, such as the star center of the power transformer, transmission line arresters and perimeter fence, so to reduce touch and step voltages of the planned ground mesh (ANDE, 2013).

Table III shows clearly that the selection of the fault clearing time has a significant impact on the cost of the ground mesh. For longer durations the costs are much higher, due to a larger quantity of copper conductors used for the mesh. For instance, a time of 0.5 s generate 242% higher costs compared to duration of 0.12 s.

Ground Mesh Parameters

To calculate the resistance of the ground mesh R_g the following formula given by equation (6) is used (Kindermann, 1991).

$$R_g = \rho\left[\frac{1}{L_t} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}}\right)\right]$$

(6)

Constants For Project Voltage Calculations

Prior to the calculation of the project mesh potential, have to be determined the constants K_m (geometric factor), K_i (current dispersion factor) and K_s (geometric factor for step voltage) on both axes (x; y). For each of these constants is used the highest value to calculate the project voltages (ANSI/IEEE-80-2000 Standard).

The K_i constant helps to correct the effect of the distribution non-uniformity of the current to the ground. The highest current dispersion is verified on the periphery of the mesh and mainly in its vertices. K_i is calculated by equation (7) proposed by Kindermann (1991).

$$K_i = 0.656 + 0.172\,n \qquad (7)$$

K_m is calculated by equation (8) below (Kindermann, 1991).

$$K_m = \frac{1}{2\pi}\left[\ln\left(\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right) + \frac{1}{\sqrt{1+h}}\ln\frac{8}{\pi(2n-1)}\right] \qquad (8)$$

The constant K_s is given by equation (9) indicated below. This factor introduces to the calculation the effect of depth of the mesh, as well as the separation and the number of conductors (Kindermann, 1991).

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}\left(1 - 0.5^{(n-2)}\right)\right] \qquad (9)$$

Touch And Step Voltages Of The Project

For the calculation of both the touch and the step volages of the project short circuit current I_{cc} can be reduced by 70%. They are function of soil resistivity, the current through the mesh and the lengths of the used cables L_t and electrodes L_j. Touch voltage is given by equation (10) and step voltage by equation (11) (Kindermann, 1991).

$$V_t = \rho I_{cc}\left(\frac{K_m K_i}{L_t + 1.15L_j}\right)10^3 \qquad (10)$$

$$V_p = \rho I_{cc}\left(\frac{K_s K_i}{L_t + 1.15 L_j}\right)10^3 \quad (11)$$

Fence Voltage Of The Project

Depending on the degree of risk, the location of the plot and the characteristics of the mesh it has to be decided how to fence the area properly. Usually, it is used a metallic fence for being economic, but also conductive. It is subject to native voltage currents shorts station that the physical principle of magnetic induction energized metal fences. So, any person in contact with the metallic fence will be subject to a potential difference.

It has to be verified that the value of the fence potential V_c is below the limit of the allowable touch potential. The parameter K_c is a coefficient, which relates all the parameters of the mesh with the position of the person, who is in contact with the metallic fence. Its value is given by equation (12) proposed by Kindermann (1991). The parameter x represents the distance between a person weighing 70 kg touching the fence and the fence itself. K_c has to be calculated for both cases, x being 0 and 1 m. It has to be stressed, that the verification of the fence voltage is critical for the sizing of the ground mesh, considering that potential gradients are highest at the borders of the station.

$$K_c = \frac{1}{2\pi}\left\{\ln\left[\frac{\left(h^2 + x^2\right)\left[h^2 + \left(D + x\right)^2\right]}{hd\left(h^2 + D^2\right)}\right] + 2\ln\left\{\left[\frac{2D + x}{2D}\right]\left[\frac{3D + x}{3D}\right]\left[\frac{\left(n-1\right)D + x}{\left(n-1\right)D}\right]\right\}\right\} \quad (12)$$

The fence potential V_c is given by equation (13) proposed by Kindermann (1991).

$$V_c = \rho I_{cc}\left(\frac{K_c K_i}{L_t + 1.15 L_j}\right)10^3 \quad (13)$$

Table IV. Parameters And Earth Potential Of The Projected Mesh, Source: ANSI/IEEE-80-2000 Standard, Kindermann (1991).

t_s(s)	K_i	K_s	K_m	K_c	V_p	V_t	V_c	V_{p*}	V_{t*}(V)	R_g
0.12	2.37	0.32	0.88	0.27	562	1514	463	5000	1600	1.09
0.2	3.00	0.35	0.73	0.29	569	1186	468	3921	1244	1.06
0.3	4.09	0.38	0.59	0.32	611	944	507	3302	1015	1.04
0.4	4.44	0.39	0.55	0.34	620	865	529	2773	879	1.03
0.5	4.78	0.41	0.51	0.35	622	772	545	2480	787	1.03

* Admissible values.

The results in Table IV show clearly how the selection of the fault clearing time t_s affects the elaboration of a ground mesh project, concerning the parameters, as well as the touch, step and fence voltages and their distribution inside the mesh. Considering that the duration of failure or clearance has an inverse behavior to the allowable values of the potential gradient, with a minimum duration of 0.12 s there will be a clearance of a 100% of allowable voltage values, without being exceeded compared to the project voltages to maintain the security of the people for the analyzed scenario. Another point to take into account is that the allowable step voltage values are limited to 5000 V for the minimum value of failure time, considering that safety boots are made for this allowable value (ANDE, 2013).

III. CONCLUSIONS

It can be concluded, that the projected ground mesh for a 220/23kV station with the proposed fault time interval reaches levels of touch, step and fence voltages, which are within safe limits required by the IEEE 80 Standard. Also the value of the ground mesh resistance is within the allowable value of this same standard. The mathematical model and the methodology proposed in the present article was designed for a rectangular mesh, however is also valid for a square mesh without committing the allowable values of the potentials. Regarding the economic evaluation it can be observed, that the reduction of the time of failure will lower considerably the investment costs. Besides, it would be advisable to reengineer the protection settings, specifically concerning the protection scheme and their synchronization in case of events, considering that it’s a key factor in the power system scheme of any electrical station. As a final point it has to be stressed, that the calculation of the fence voltage represents a new concept for the sizing of ground meshes. However, this calculation is very important to guarantee safety of any person being inside the station plot or touching the fence.

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