GROUNDING GRIDS ANALYSIS OF ENERGIZED SUBSTATIONS

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Abstract: Techniques of analysis and diagnosis of problems with grounding grids in energized substations are presented. Among the known techniques are the calculus of step and touch voltage, while among the new techniques which are presented are ground resistance measuring in energized substations, surface potential measurement and graphic analysis of surface potentials by using software that was developed to diagnose grounding grids in energized substations.

1 INTRODUCTION

Grounding systems have performed an important role in the protection of power systems. The main objective of these systems is to ensure personal safety, prevent harm to installed equipment, establish a point of voltage reference for all the interconnected power system, as well as providing a low impedance path for currents originating from lightning, short circuits and static caused on equipment housings, aside from electrical currents due to imbalance of electric charges fed by voltage source, [1] and [2].

Many times, in setting up installations, poor contact between electrodes results in an increase in resistance, and this hampers the flow of the currents. Another factor related to the poor performance of a grounding system is the process of corrosion of the rods and cables, due to chemical action of the soil, which can reach advanced levels which can provoke the infeasibility of the grounding system. In both of these cases, the potentials of the grid and their surroundings can reach values which are not within safety Standards, causing situations of risk both to the electrical system and to people.

For these reasons, it is essential to analyze the behavior of grounding grids in substations over time, to detect possible faults or alterations. In light of this, this research presents an analysis and diagnosis technique for problems in grounding grids in substations, without the need to de-energize them.

2 METHODOLOGY

With the objective of evaluating the operational conditions of the grounding grids in substations, the traditional measurements of touch and step voltage, energized grid resistance measurement, and surface potential measurement were used, along with analysis software which permits the evaluation of grounding grid conditions without the need of de-energizing.

2.1 Touch voltage measurement

By definition, touch voltage is the difference of an existent potential between a determined point on a metallic structure, situated within reach of a person's hand, and a point on the ground situated one meter from the base of the structure in question, as described in [3].

In taking the measurement of the touch voltage, two interconnected metallic masses are used, each weighing 25 kg, thus simulating a 50 kg person. The masses have the purpose of increasing contact with the soil, and, with this in mind and intending to facilitate the flow of the electrical current from the metallic structure to the soil, wet rags are used on the bases of the metallic masses.

The metallic masses must be positioned at a distance of 1 m from the base of the metallic structure (tower, transformer, etc.). This distance corresponds to a person with his/her arm extended toward the structure.

The connection between the metallic masses and the structure is made on a resistance of 1 kΩ, which simulates the human body resistance, and parallel to the resistance a high sensitivity voltmeter is connected, as described in [3] and [4].

The values measured correspond to the touch voltage of the imbalance of the transformer at the measuring instant. The approximate touch voltage, at the instant of the short circuit, may be obtained by a linear extrapolation between the measured current and the short circuit current [4]. This extrapolation is valid supposing that the ground maintain invariant resistive features for high currents. For safety reasons, the extrapolated values should remain below the specified safety limit values.

2.2 Step voltage measurement

The classic definition of step voltage for safety analysis is the difference of potential that appears between two points situated on the ground at 1 m from each other, due to the passing of short circuit current through the ground as described in [3]. The flow of the current through the soil, which could come from a short circuit, provokes the onset of different potentials on the surface of the soil. Thus, the step voltages occur when a person steps on different potentials.

The procedure for the performance of step voltage measurement is similar to the touch voltage measurement. The metallic masses must be positioned at a distance of 1 m from each other. With the aid of a high sensitivity voltmeter, the values for step voltage are measured in the normal functioning conditions of the substation. The approximate step voltage, at the instant of the short circuit, may be obtained by a linear extrapolation. For safety reasons, the extrapolated values should remain below the specified safety limit values, as described in [3] and [4].

2.3 Grounding grid resistance measurement in energized substation

The resistance measuring of the grounding grid in energized substations can be made by using a digital ground resistance tester and clamp.

The digital ground resistance tester used has a "*SWEEP*" option where several measurements in several different frequencies are performed automatically, in a range from 41 to 5,078 Hz, so as to verify how the results vary according to the frequency. This option is possible on the automatic mode and the measuring process is ended only when all the frequencies are injected.

The clamp model used in the measuring is very precise and is capable of performing measurements of up to 40 A rms.

Figure 1 illustrates the configuration of the procedure that was adopted to measure the resistance of grounding grid in energized substations. The measuring procedure consists of: fix the electrodes **H(Z)** and **S(Y)**, spaced at least 30 meters from each other, avoiding interference between them; connect the terminal **ES(Xv)** onto the clamp and its terminal to the grounding point to be measured; connect the terminal **E(X)** to another point on the same grounding wished to be measured.

By using this measurement procedure more precise values are found than those found when using the traditional method for ground resistance measuring, aside from not needing great distances between the measuring electrodes used.

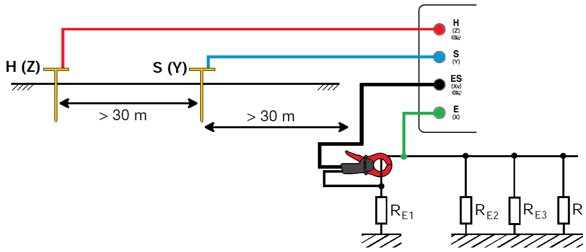

Figure 1: Configuration of the grounding grid resistance measurement procedure

2.4 Surface Potential Measurement

In practice, the levels of potentials in the interior of a substation may not be presented totally within the calculated limits, due to seasonal climatic variations, grid wear, modifications in the system's configuration, etc., and this can compromise the safety and protection of the electrical system and of the people.

Thus, it is necessary to monitor the levels of potential on the surface of the soil, within and out of the grounding grid limits. The measurements can be performed with the simple use of a voltmeter and two copper rods driven into the ground. However, to facilitate the surface potential measuring process, an electronic instrument was developed to measure potentials in grounding grids in energized substations. This instrument has the capacity to measure and store peak values of potential of up to 127 points of measuring, one at a time. The measuring points are chosen and distributed along the ground encompassing the grounding grid and its surroundings. The potential meter that was developed has the capacity to communicate with the microcomputer in order to transfer data. The values of the potentials transferred are treated and analyzed on software specifically developed for this. Figure 2 illustrates the measuring scheme and presents a photograph of the developed potential meter.

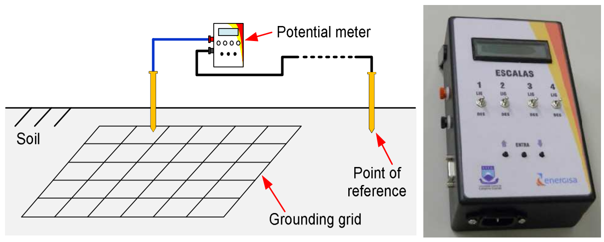

Figure 2: Measuring scheme and photograph of the surface potential meter

2.5 Software for diagnosis of grounding grids in energized substations

Diagnosis software for grounding grid was developed with the objective of revealing the operational conditions of the grounding grids in energized substations. This software is capable of mapping the potentials on the surface of the grid and in its surroundings, indicating the possible concentrations of the field or the difficulties of the grid in draining the electrical current, externalizing the probable zones of high resistivity, zones of wearing or of discontinuity in the grid, both in steady state and in the occurrence of a short circuit.

The Finite Difference Method (FDM) was used in developing the software. This is a method of mapping that can solve the Laplace equation iteratively, as described in [5] and [6]. The software has as input and boundary condition the values measured and stored in the memory of the developed potential meter.

The current imbalance of the transformer, the short circuit current furnished by the project, the soil resistivity, the dimensions of the ground area wished to map for the surface potential, the dimensions of the grounding grid, aside from the coordinates of the points where the surface potentials were measured, were also part of the input data on the software.

The software generates graphs in two and three dimensions that present the behavior of the potentials on the surface of the soil, both in steady state and in the occurrence of a short circuit, referring to the same point of reference.

Aside from the generated graphs, the software is also capable of calculating and externalizing in the form of a report the step voltages at the moment of a short circuit, presenting the locations and the respective values of the potentials that pass a maximum pre-established limit. To be conservative, the safety limit was fixed at 75% of the maximum limit calculated from the recommendations established in [3].

3 RESULTS AND DISCUSSION

3.1 Results obtained from the touch voltage measurement

Measurements of the touch voltage were performed at a substation ***I***, so as to verify if the levels of potential found were in accordance with the maximum values calculated and presented in Table 1.

Table 1: Limits of safety potentials for substation ***I***

Safety potentials	Average mass of a person	
	50 kg	70 kg
Touch	1,401.80 V	1,897.30 V
Step	4,971.80 V	6,729.10 V

The measurements of potential were performed taking as reference the imbalance current of 17.15 A, the measurement of the neutral of the transformer, and the short circuit current of 1.745 kA, furnished by the utility. The resistance of the grounding grid measured at 2.5 Ω, for the physical, climatic and geological conditions involving the grid.

Measurements of the touch voltage between the transformer and the ground were performed as described in item 2.1 of the Methodology. The measurement schemes for the touch voltage on the transformer, for two distinct configurations, are shown in Figure 3 and the values of approximate touch voltage for a short circuit current of 1.745 kA are presented in Table 2.

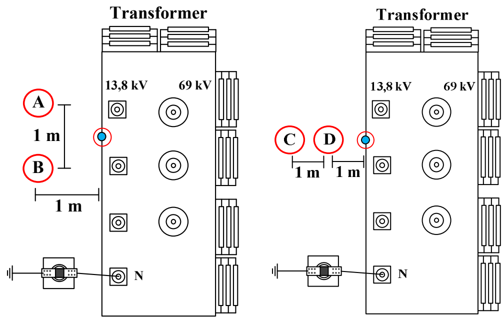

Figure 3: Measurement scheme of the touch voltage on the transformer housing

Table 2: Touch voltages on the transformer of the substation at the moment of the short circuit

Touch voltage at the moment of the short circuit	
Masses in A and B	2.44 V
Masses in C and D	2.04 V

As shown on Table 2, the levels of touch voltages for the transformer housing at the moment of the short circuit were way under the values established in Table 1. One of the explanations for the low values of the measured touch voltages is in the implantation of the area expansion of the grounding grid and the high humidity of the soil on the day of the measuring, due to the occurrence of rains five days before measurements were taken.

3.2 Results obtained from the step voltage measurement

The measurements of step voltage were performed at the same substation ***I*** used for touch voltage, and submitted to the same testing conditions, since they were performed on the same day as the measurements for touch voltage.

As presented in [3], the measurements of step voltages were performed in a region near the transformer and the grid (inside and out). The measurements were taken as described in item 2.2 of the Methodology. The measurement schemes for the step voltage are shown in Figure 4 and the values of approximate step voltage for a short circuit current of 1.745 kA are presented in Table 3.

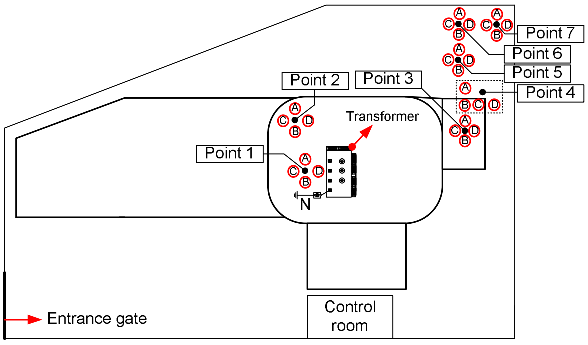

Figure 4: Step voltage measurement scheme

Table 3: Step voltages at the moment of short circuit

Points	Positions	Step voltages
1	A and B C and D	101.75 mV 508.75 mV
2	A and B C and D	2.44 V 2.95 V
3	A and B C and D	2.34 V 3.97 V
4	A and B C and D	2.95 V 8.04 V
5	A and B C and D	67.77 V 13.53 V
6	A and B C and D	68.58 V 14.96 V
7	A and B C and D	40.09 V 16.48 V

As shown in Table 3, the levels of the step voltages at the moment of the short circuit were much below the values presented in Table 1. One of the explanations for the low values of the measured step voltages is in the implantation of the expansion in the area of the grounding grid, and the high humidity of the soil on the day of the measuring, due to the occurrence of rains five days before the measurements.

3.3 Measuring the resistance of grounding grid in energized substation

The measuring of resistance of grounding grid was performed at a recently built substation ***II***, first de-energized. The measuring of resistance of the grounding grid was performed by the traditional method of potential drop, as described in [4] and [7]. The traditional measurement consists in measuring the grounding resistance according to the potential drop by using an auxiliary ground electrode, constituting a structure composed by a current rod (***B***), a measuring rod for potential (***P***) and the grounding grid to be measured (***A***), according to the scheme in Figure 5.

From the values obtained from measuring, the curve of ground resistance in relation to the distance can be designed. The resistance of the grounding grid of the system is found in the region of the plateau of the curve obtained.

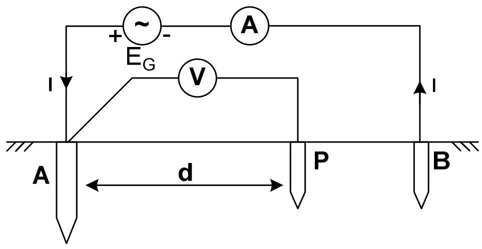

Figure 5: Scheme for measuring ground resistance with the grid de-energized

The values obtained in the measuring of resistance of grounding grid for the substation when de-energized are shown in Table 4, and from the values of resistance, the curve of ground resistance in relation to the distance was designed, as shown in Figure 6. From the graph, it can be concluded that the resistance in the plateau region was 2.12 Ω, characterizing a situation of low resistance of the grounding grid.

Table 4: Measuring of the resistance of the grounding grid with the substation de-energized

Distance (m)	Measurement (Ω)
10	1.29
20	1.57
30	1.74
40	1.88
50	2.03
60	2.19
70	2.39
80	2.65
90	2.97
100	28.90

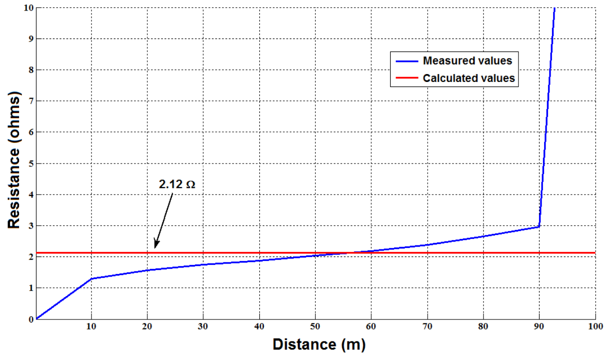

Figure 6: Curve of ground resistance versus distance

After the energizing of the substation, measurements of ground resistance were performed by using the method of grounding grid resistance measurement for energized substations, as described in item 2.3 of the Methodology.

The measurements remained restricted to the manholes of the grid and to the grounding of the potential transformer (PT). The imbalance current of the transformer, at the moment of the measurement, was 12.8 A. The sketch of the measuring scheme for the resistance of the grounding grid is illustrated in Figure 7. Table 5 shows the results obtained from measurements of ground resistance by using the manhole and the grounding cable of the PT.

The values of the measurements of resistance of the grounding grid are low, confirming the efficiency of the project and its implantation. The simulation of the Project foresaw a resistance of the grid equal to 2.5 Ω.

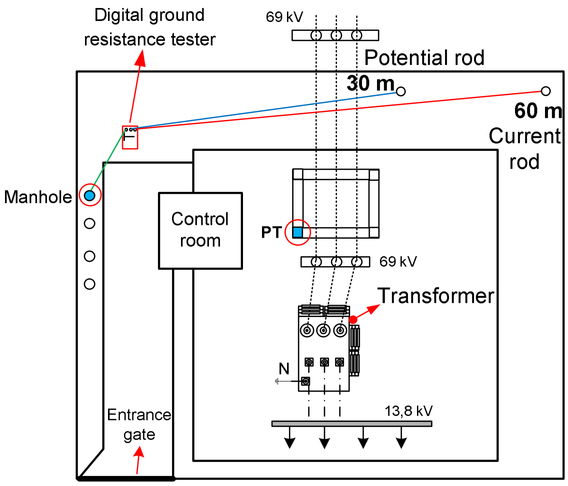

Figure 7: Sketch of the scheme for measuring the grounding grid resistance at the energized substation

Table 5: Measuring of the resistance of the grounding grid with the substation energized

Measuring points	Resistance (Ω)
Manhole	1,23 Ω
PT	1,38 Ω

The approximate values also validate the measuring technique with the grid energized. The measurements were performed with total safety for the technical personnel in charge, as shown in [8].

3.4 Results obtained on measuring the surface potential

Figure 8 illustrates a sketch of an area where substation ***III,*** used for the surface potential measurements, is located. Inside the substation, the land area was gridded and divided into 70 distinct points, encompassing the effective area of the substation and its surroundings. In this figure, the location of the reference point can also be seen. The point of reference is used with the infinite and was positioned at 40 m from where the substation's grounding grid is found.

The measuring of the surface potentials were performed by using the potential meter that was developed, which was capable of performing the measurements, storing the peak values of the potentials, and successfully transferring these values to a microcomputer. The values of the surface potentials are treated and analyzed, via software.

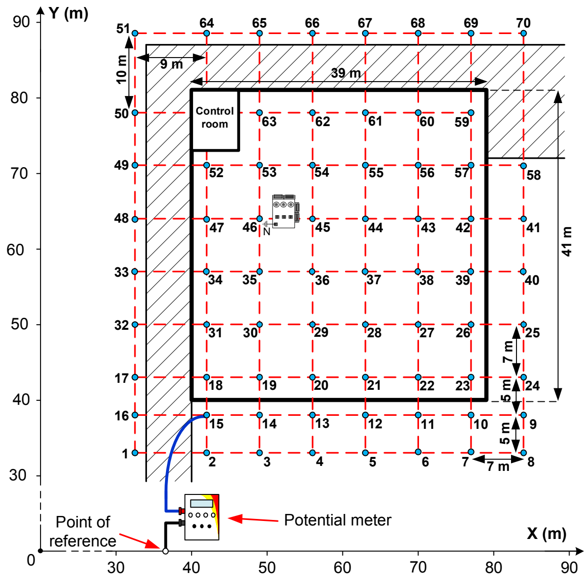

Figure 8: Sketch of the land area of the substation which was used to measure the surface potential

3.5 Analysis via software for grounding grid diagnosis in energized substations

The mapping of the levels of surface potential is performed via an analysis software which uses the values of potential obtained on measuring the surface potential in the previous topic as input data of the computational routine, aside from other variables, as described in item 2.5 of the Methodology. The dimensions of the land area and the grounding grid, along with the coordinates of the measured surface potentials are found in Figure 8. The measured imbalance current of the transformer was 4.24 A and the short circuit current calculated for the original grid project was 4.866 kA.

For substation ***III***, the software calculated a value of 3,049.90 V for the maximum step voltage permitted for a person of 50 kg. Thus, a safety limit of 2,287.43 V was attributed, corresponding to 75% of the value calculated, as mentioned in item 2.5 of the Methodology.

The software was capable of mapping the potentials on the surface of the soil, indicating the probable field concentrations, both in steady state and in the occurrence of short circuit, generating graphs in two and three dimensions for both situations, referring to the same point of reference. However, in this paper only the graphs referring to the occurrence of a short circuit are shown, since for both cases the graphs differ mostly only in amplitude.

Figure 9 shows the behavior of the levels of superficial potential in the occurrence of a short circuit for substation ***III***, which was used in measuring the superficial potential cited in the previous topic.

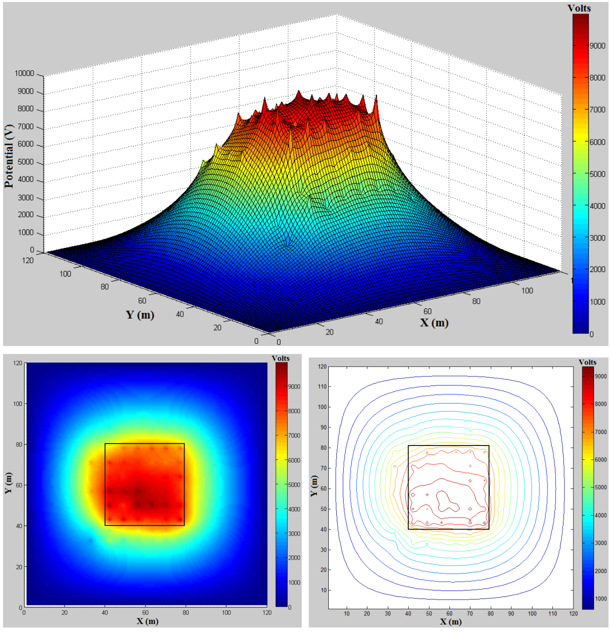

Figure 9: Behavior of the levels of superficial potential in the occurrence of a short circuit

Aside from the graphs with were generated, the software was also capable of calculating and externalizing in a report the step voltages for the occurrence of a short circuit. For the case analyzed, the software showed that all of the step voltages calculated were below the safety limit calculated, as mentioned in item 2.5 of the Methodology. However, in a more refined analysis, it was observed that five of the step voltages calculated were above 1 kV, and the highest one was 1,35 kV. The highest potentials were found near the end of the grid, near points 18 and 23 of Figure 8.

From the analysis of the surface potentials via software it can be concluded that the grounding grid was in good condition, since the graphs showed a distribution of the field lines in a relatively uniform pattern, in the substation, as well as the step voltages below the maximum limits calculated. For more accuracy in mapping surface potentials, measurement lattices no larger than 7 m x 7 m are suggested.

4 CONCLUSIONS

This research presented techniques for analysis and diagnosis of grounding grids in energized substations.

The measuring of touch and step voltages in substation ***I*** showed that the safety limits calculated were not exceeded for the physical, climatic, and geological conditions on the day of measurement; thus, concluding that the substation was in good operational conditions, after remodeling.

Ground resistance measurements were performed in substation ***II***. First, the measuring was performed with the substation de-energized, and by the traditional measuring method for ground resistance. After the energizing of the substation, ground resistance was performed by an innovative method, with the aid of a digital ground resistance tester and clamp. The results obtained were satisfactory and approximate when compared to those obtained through the traditional procedure, legitimating the measuring technique presented. Furthermore, the measurements were taken with total safety for the technical personnel and with much practicality.

Measurements of superficial potential were performed at substation ***III***, with the aid of the surface potential meter which was developed. With the data obtained in the measurements treated via software it was possible to map the behavior of the levels of surface potential of the substation, both in steady state and in the occurrence of a short circuit. The step voltages in the occurrence of a short circuit are also calculated and their values are externalized in the form of a report if they go over the calculated safety limit.

Studies are being performed in order to substitute the traditional step voltage measuring procedure for the analysis of the results obtained from measuring the surface potential.

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