VALIDATION OF AN INTEGRATED METHODOLOGY FOR DESIGN OF GROUNDING SYSTEMS THROUGH FIELD MEASUREMENTS

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ABSTRACT

EDP Labelec is responsible for the safety analysis of the grounding system of every new substation in the Portuguese distribution grid, and over the past 14 years has developed and perfected an integrated methodology for designing grounding systems, which was described in a previous publication. The company has also 30+ years of experience in earthing field measurements, and is responsible for performing almost all earthing measurements in substations from Portugal's electrical grid. The key goal of this paper is to validate the integrated methodology used by EDP Labelec, while identifying the main strengths and weaknesses of each soil resistivity measurement method (2D/3D geoelectrical surveys vs. traditional 1D Wenner/Schlumberger), and their impact on the measured results vs. simulated results, for different soil types and substation layouts.

To accomplish this, it is described the results and statistical data for six selected substations, which had their grounding grid recently designed and measured by EDP Labelec, before and after their construction, respectively. In sum, the results obtained are very encouraging, and the integrated methodology is considered validated, with results that largely exceeded expectations. Despite this, some significant questions emerged during the analysis of the results. These issues will be addressed in future work.

INTRODUCTION

EDP Labelec is an EDP Group company created with human and material resources from the former EDP Central Laboratory, having as part of its mission to provide specialized technical support to the EDP Group.

The company is responsible for the safety analysis of the grounding system of every new substation in the Portuguese distribution grid and, since 2004, has developed and perfected an integrated methodology for designing grounding systems. EDP Labelec has also 30+ years of experience in earthing field measurements, and is responsible for performing almost all earthing measurements in substations from Portugal's electrical grid.

The main objective of the integrated methodology is to ensure the safety of people near the facility in analysis against HV short-circuits, while providing the best optimization of material and economical investments in the grounding system. This methodology was described in a previous publication [1].

One of the most usual issues with methodologies of this kind is the possibility of discrepancies between simulated and measured grounding grid impedances and potential gradients, creating some uncertainty in the level of safety of the designed grids. Also, the latest and more elaborate 2D and 3D soil resistivity measurement methods (which are used by EDP Labelec) have placed challenges in the ways that the complex measured resistivity data is used in earthing design software. This is possibly limiting the widespread use of this method.

The key goal of this paper is to validate the integrated methodology used by EDP Labelec, while identifying the main strengths and weaknesses of each soil resistivity measurement method (2D/3D geoelectrical surveys vs. traditional 1D Wenner/Schlumberger), and their impact on the measured results vs. simulated results, for different soil types and substation layouts.

BACKGROUND

The main objective of an earthing grid evaluation and design work is to ensure the safety of people in a substation and its surroundings against electrocution in non-live areas. This is the focus of the methodology which led to this work, and is ensured through the application of the touch and step voltages criteria.

Potential gradients and Touch and Step voltages

When a current circulates to earth through an earthing electrode, the soil behaves like a distributed resistance. This way, each point in the soil, near the electrodes, takes a different potential value. The distribution of potential values is called potential gradient (or voltage gradient). The values are usually expressed in a percentage of GPR – Ground Potential Rise, or the voltage of the earthing grid in relation to a distant point (zero potential):

$$GPR = R_G \times I_{SC} \quad (1)$$

Where:

- R_G is the earthing resistance of the grid;
- I_{SC} is the short-circuit current.

When a person is present in this scenario, he can be subjected mainly to two types of voltages:

- Touch voltages: voltages between metallic parts bonded or not to the earthing grid and the point in the soil where the person is standing;
- Step voltages: voltages between two points in the soil separated by the length of a stride.

This way, potential gradients in the soil of a substation and its earthing resistance are a direct measurement of the possible touch and step voltages that may be present in a short-circuit scenario.

It is easy to conclude that, the higher the short-circuit currents and/or earthing impedances are, the more difficult it is to get reduced touch and step voltages. To have small step voltages, the voltage gradient should not have sharp slopes. On the other hand, to have reduced touch voltages, the voltage gradient should be very close to 100% near substation equipment.

Computer simulations

The simulations are conducted in CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis) software package.
To calculate the maximum expected touch and step voltages, specialized software firstly calculates the earthing grid resistance and the potential distribution, or gradient, in every point of the surface, inside and outside the substation. For that, it uses mainly two inputs: an earthing grid model and a soil resistivity model.
The first one is possible to accurately model, because it is composed of a finite set of electrodes.
The second one is much more difficult to model accurately, because the soil is composed of almost infinite and continuous resistivity variations. Therefore, the soil has to be modelled approximately by a number of layers or volumes of uniform resistivity. To determine these models, EDP Labelec uses the following two methods.

- **1D Wenner/Schlumberger**

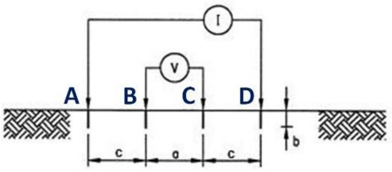

Figure 1 – Wenner/Schlumberger method diagram

In this case, the soil resistivity measurement is similar to a 4 point resistance measurement. With an array of four electrodes, positioned in a straight line and separated by a distance "a", and using and external current source, a dc current is generated between the electrodes (A) and (D). By measuring the current flowing through (A) and (D) and the voltage potential difference between electrodes (B) and (C) this method allows us to compute the resistance of the soil (for a particular distance "a"). The final result – an 1D array of apparent resistivity values for different values of soil depth – is achieved with several measurements for multiple values of "a".
For a new substation earthing grid design several of these arrays are constructed (reaching depths of 20 meters) in order to achieve the most accurate modeling of the soil possible.

- **2D/3D Geoelectrical surveys [1]**

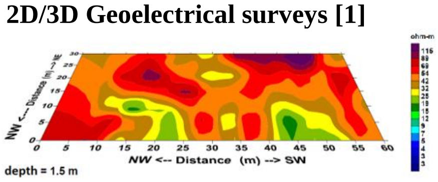

Figure 2 – Example of a 2D resistivity map

This soil characterization is produced using several parallel arrays of electrodes, which are arranged to take many apparent resistivity readings using Pole-Dipole and Schlumberger methods. A specialized software uses those readings to compute a detailed 2D/3D soil model, which is then rounded and inputted in CDEGS.
Finally, with the computed potential distribution, CDEGS determines the maximum expected touch and step voltage values. While the results of the simulation studies are usually presented in 3D charts, this time 2D profiles were simulated for direct comparison with measured profiles.

Field measurements

The potential gradients are, in this case, induced in the soil through the flowing of a current between the substation's earthing grid and a distant electrode. This current is applied by a high power voltage source and is usually in the range of 1 to 10 Amps, depending on the earthing impedance and the soil resistivity. Then, using 2 voltmeters and 2 electrodes, the voltage potential – with reference to a distant electrode – of a point in the soil of the substation can be measured, and the % of GPR calculated, through division of the values by the GPR induced by the test source. The points are usually measured in multiple linear profiles. Measured values will have in account every tiny soil resistivity change.
Touch and step voltages are then determined by the same rules as the computer simulated values (by using the short-circuit current and the earth resistance of the substation).

Comparison

This way, one can conclude that, if the measured and simulated potential gradients and the grounding resistance are equal, then the expected maximum touch and step voltages will also be equal.
One can also easily conclude that this will hardly be the case, because simulation software, as advanced as it can be, uses soil models with volumes or layers of uniform soil resistivity, which is inherently a significant simplification.
Nevertheless, in this paper, the authors will try to compare simulated and measured potential gradient and earthing resistance values and identify factors that may prevent a match between both sets of values.

METHODOLOGY

Eight new HV/MV substations (about two year's work), that had their earthing grid evaluated and designed by EDP Labelec, were selected to participate in the work which led to this study.
From those eight, two were excluded due to problems with measuring equipment during the measurements, or different grounding grid configuration than designed.
Consequently, the work presented in this paper is based on the results of six substations, which are presented in the following table.

Table 1 – Selected substations

	A	B	C	D	E	F
Type	Ext.	Ext.	Int.	Ext.	Int.	Ext.
Resistivity measurement method	1D	1D	2D/3D	2D/3D	2D/3D	1D
Resistivity model	HoL	LoH	HoL	Low	HoL	LoH

Legend:
Ext./Int.: Exterior (open air) or Interior(building).
HoL: High resistivity layer over low resistivity layer.
LoW: Low resistivity layer over high resistivity layer.

Comparison between measured and simulated values

In the statistical analysis chapter, it will be presented a statistical comparison between measured and simulated grounding impedances and potential gradients of all six substations.
To accomplish this, for every measured potential gradient point in the six selected substations, the difference between the measured and simulated potential gradient value was calculated.
Points that were located more than 1 m outside the substation perimeter were excluded. Points influenced positively by metallic structures on the ground were also excluded from the analysis, to avoid unfair results. The comparison between the values will be relatively simple, because they are already expressed in a percentage.
In the case studies chapter, it will be presented and discussed the graphical comparison between measured and simulated potential gradients of selected case studies.
Possible factors that influence discrepancies will be analyzed and discussed in both chapters.

Considerations about conversion to touch and step voltages

This is the first time that EDP Labelec is measuring potential gradients in substations designed using the integrated methodology. As all those substations are being currently designed to 25 kA solid short-circuit current and 2 second fault clearing time, the touch voltages, for example, are being designed to a very small percentage of GPR, roughly in the range of 0.5 to 3% in these six substations.
This means that the uncertainty value in the field measurements – which varies slightly from case to case, but was calculated to be approximately ±2% – is in the same order of magnitude (or even bigger) than the touch values to which the substation is designed, as discussed previously. This means that it will only be possible to compare accurately and directly potential gradients and not touch and/or step voltages.

STATISTICAL ANALISYS

Grounding impedances

In the following table, it is presented, for each one of the six substations, the measured and simulated grounding impedance values.

Table 2 - Measured and Simulated Grounding Impedances

	A	B	C	D	E	F
Type	Ext.	Ext.	Int.	Ext.	Int.	Ext.
Resistivity measurement method	1D	1D	2D/3D	2D/3D	2D/3D	1D
Resistivity model	HoL	LoH	HoL	Low	HoL	LoH
Measured grounding impedance (Ω)	0.23	0.50	1.50	0.14	1.00	0.79
Simulated grounding impedance (Ω)	0.24 (+4%)	0.50	1.49 (-0.7%)	0.23 (+64%)	0.93 (-7%)	0.72 (-9%)

Note that the measured and simulated grounding impedances include the circuits formed by high voltage lines' shield wires and tower footing impedances.
One can see that two of the results were excellent (less than 1% error) and three of them were good to very good (less than 10% error). Substation D had a significant difference that could not be explained (possible changes in high voltage shield wires configurations, or soil moisture content). In spite of this, its potential gradients results were among the best, as it will be seen in the next chapter.

Potential gradients

In the next figure it is presented the results of the comparison between measured and simulated grounding impedance and potential gradient values for each of the six substations. For reference, the area corresponding to the order of magnitude of the uncertainty in the measured values is shaded. Positive % difference means that the potential gradient values measured in the field are higher than those obtained by simulation. Negative % difference means they are lower.

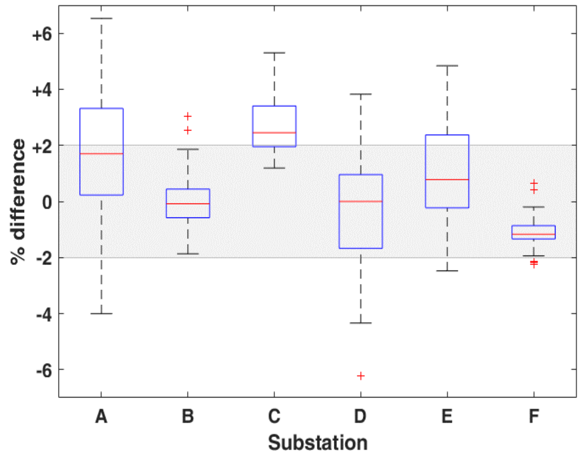

Figure 3 - Statistical results for all six selected substations

It is possible to see that the results are very good. Most values are inside the measurement uncertainty area. There are very few negative values outside that area. The median values are very close to 0 (simulated=measured), except for subs. C and A (despite this, they are positively shifted, which increases safety levels from designed). Virtually all values are contained in the range [-4%,+6%].
It is also possible to conclude that there is not a clear

relationship between potential gradient results and grounding impedance results, nor between their differences to simulated values.
To identify other possible patterns, in the next charts, the substations will be grouped by resistivity measuring technique and soil type.
Firstly, in Figure 4, it is presented the results grouped by resistivity measuring technique. It is possible to see that there is not a significant difference between the results for the substations that had their soil model designed using multiple 1D Wenner profiles or the ones with the more complex 2D/3D geoelectrical survey, which is a surprising observation. Both of them yield very good results, with similar median and extreme values.

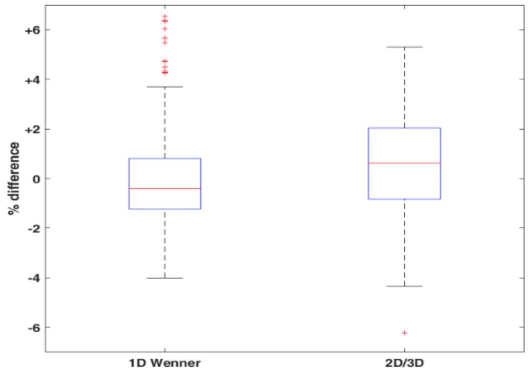

Figure 4 - Statistical results grouped by resistivity measurement method

In Figure 5, results are grouped by soil type.

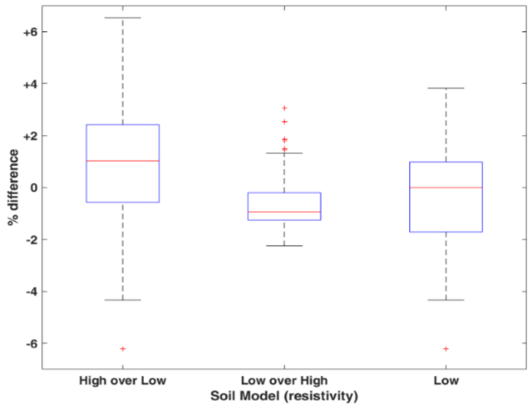

Figure 5 - Statistical results grouped by soil type

In the previous figure, it is presented the results grouped by soil type. Unlike the previous case, in this case it is possible to identify some patterns. High over Low resistivity soils produce much more dispersion in measured values than Low over High resistivity soils. Uniform low resistivity soil produces results somewhere in-between. Low over High soils also present a negative shift over simulated values, although virtually all values are contained in the measurement uncertainty area.

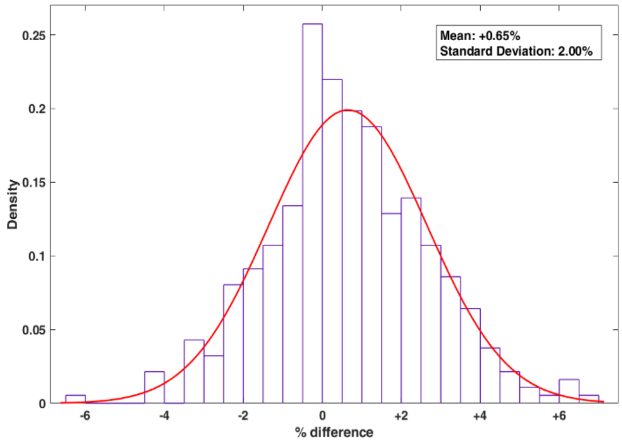

Figure 6 - Statistical results fitted by a Gaussian distribution

In Figure 6, it is represented a density chart of the statistical results for all substations. One can see clearly the random nature of the differences between simulated and measured values, which can be satisfactorily fitted by a Gaussian distribution almost centered in zero, with a mean value of +0.65% and a standard deviation value of 2.00%. These results are very encouraging to the methodology currently used by EDP Labelec.
On the other hand, these findings arise some other issues. As all new substations are being currently designed to a very small percentage of GPR, roughly in the range of 0.5 to 5% in these six substations. This means that the uncertainty value in the field measurements – roughly ±2% – is in the same order of magnitude (or even bigger) than the touch values to which the substation is designed, as discussed previously.
Also, the random nature of the differences, seen above, although it is centered in almost zero, has a standard deviation of 2.00% and extreme values of almost ±6%, which can be many times the designed touch voltage values.
This means that future work is needed to:

- Improve measuring methodology so that uncertainty values are reduced from roughly 2% to something more like 0.1%, for example;
- After that, analyze the possibility of the natural Gaussian dispersion of measured values is, in fact, real and conclude about the physical possibility or not of designing touch and step voltages to such small percent values of GPR.

CASE STUDIES

In this chapter, it will be presented three selected case studies of gradient profiles, for visual comparison between simulated and measured values. In this comparison, all measured values will be presented. In the following figure, it is possible to see a profile from sub.E.

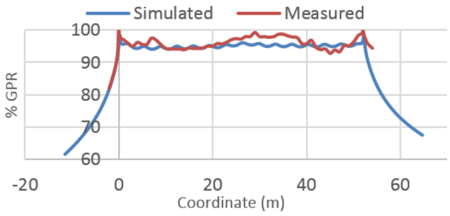

Figure 7 - Case study 1: Substation E

One can see a very good match between simulated and measured values. Even the drop on the left (outside the sub.) is a perfect match. Between coordinates 20 and 40 m there are some metallic structures in the ground (cable ducts), which are apparently positively influencing the gradient. A copper cable was installed around the fence, which means that the potential in the soil is near 100% GPR in the limits of the sub. This is seen both in simulated and measured values. In the following figure, it is possible to see a profile from sub. D.

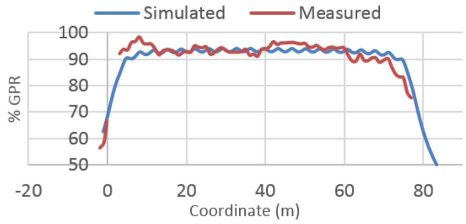

Figure 8 - Case study 2: Substation D

In this case, there are also some metallic items between coordinates 40 and 60 m, having the same effect than in the last sub. Between 60 and 80 m, there is a slope in the soil, meaning it is thicker towards the fence. This was not considered in the simulation and has the expected effect of reducing the potential gradient values. This situation has no practical impacts, because there is not any substation equipment in that area. Finally, the difference between 5 and 15 m could not be explained. In the following figure, it is possible to see a profile from sub.B.

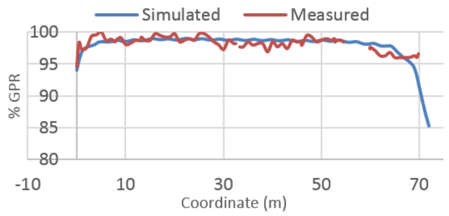

Figure 9 - Case study 3: Substation B

This is the sub. with the closest match between the simulated and measured values (remember that the median deviation was practically 0%). Even though, it is possible to see an apparently random deviation around simulated values, which can be partially justified by the measuring accuracy. This can have great impact in the measured values of mainly the touch voltages, because they are calculated as the difference between 100% GPR and the gradient profile (see conclusions of last chapter).

CONCLUSIONS AND FUTURE WORK

As seen previously, the results obtained are very encouraging. From the six selected substations, only one substation presented a significant error (>10%) in the simulated grounding impedance.

Regarding the difference between measured and simulated potential gradients, most values are inside the measurement uncertainty area. The median values are very close to zero (simulated=measured). After fitting a Gaussian distribution, one can see clearly the random nature of the differences between simulated and measured values, with a mean value of +0.65% and a standard deviation value of 2.00%.

As a surprising observation, the results shown that there is not a significant difference between the results for the substations that had their soil model designed using multiple 1D Wenner profiles or the ones with the more complex 2D/3D geoelectrical survey.

On the opposite, some difference in the dispersion of values could be observed between soils composed by high over low/low over high resistivity layers.

In sum, the integrated methodology is considered validated, with results that largely exceeded expectations. Despite this, some significant questions emerged during the analysis of the results. These issues will be addressed in future work and are:

- Having in account, in the design phase, factors that may lead to worse results than simulated, like soil thickness, layers and constitution, and conductors/metallic structures at different depths.
- Give special attention to substations where the potential gradients run above 95% GPR, in average, case where the observed dispersion of measured values is in the same order of magnitude as the possible touch and step voltage values.
- Improve measuring methodology so that uncertainty values are reduced from roughly 2% to something more like 0.1%, for example, so that small (in percentage) touch and step voltage values can be accurately measured;
- After that, analyze the possibility of the natural Gaussian dispersion of measured values is, in fact, real and conclude about the physical possibility, or not, of designing touch and step voltages to such small percent values of GPR.

With the result of the work that resulted in this paper, it will be possible to improve and fine-tune the methodology used by EDP Labelec.

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[2] CENELEC, 1999, HD 637 S1 – Power installations exceeding 1 kV