AN INTEGRATED METHODOLOGY FOR DESIGN OF GROUNDING SYSTEMS

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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 years has developed and perfected an integrated methodology for design of grounding systems, mainly for those new substations but also for the upgrade of existing ones, and for other type of installations.

This integrated methodology uses the expertise gathered by EDP Labelec in the field of grounding systems, with the main goal to ensure the safety of people in the vicinity of the facility in analysis against HV short-circuits, while providing the best optimization of material and economical investments in the grounding system, having also in account the technical constraints of every specific case.

The methodology, which is described in this paper, has several steps, and integrates both field tests and computer simulations, using several equipment and software. A case study has been selected as an example of the methodology application to a new substation. In this case, a base standard grounding grid which did not guarantee the safety of people in the vicinity of the substation was made safe, by the application of the integrated methodology. After its construction, EDP Labelec measured the real grounding impedance, which validated the study.

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.

Since its creation, EDP Labelec provides several services dedicated to grounding systems, namely grounding impedance measurements, electrical continuity verifications, touch and step voltages measurements and soil resistivity measurements.

These services have been requested intensively over the years, mainly by EDP Distribuição (Portuguese distribution system operator), REN (Portuguese transmission system operator) and EDP Produção (biggest electrical power generation company in Portugal), among others. These activities developed by EDP Labelec contributed for a great know-how in this area.

Since 2004, motivated by the increasing personnel safety concerns and technical and economic challenges, and taking advantage of the recognized expertise in the area, EDP Labelec started developing a methodology for design of grounding systems to be applied on Portuguese distribution grid new substations and for the upgrade of existing ones. The purpose of this methodology is to guarantee the safety of people in the vicinity of the facility against HV short-circuits, through the touch and step voltages criteria, while providing the best optimization of material and economical investments in the grounding system, taking also into account the technical constraints of every specific case.

The methodology has been developed and improved over the years, being nowadays applied to every new distribution substation in Portugal and to other types of facilities, like power generation facilities and communication installations. The methodology, which is described in this paper, has several steps, and integrates both field tests and computer simulations, using several equipment and software. A case study has been selected for this paper, as an example of the application of this methodology to a new substation.

METHODOLOGY

Preliminary analysis

The analysis of a new substation grounding system starts with the collection and analysis of all relevant data for the study provided by EDP Distribuição, namely:

- Location coordinates;
- Substation plans and layouts;
- Standard base grounding grid plans and data;
- HV network data between the transmission grid feeder and the new substation, including lines/cables and shield wires parameters;
- Maximum single-phase short-circuit current, specified on the feeder or on the new substation;
- Maximum fault clearing time;
- Type of fence/wall for the substation perimeter;
- Types of surface material layers inside the substation.

After this preliminary analysis, EDP Labelec starts the field works and modelling phases.

Ground resistivity measurement and modelling

The first step is the ground resistivity measurement on site and development of a soil model for the study. To accomplish this task, EDP Labelec has a partnership with Instituto de Ciências da Terra e do Espaço (ICTE) of the University of Lisbon.

After the new substation terrain is bulldozed, ICTE begins the resistivity measurements, which are very complex and take normally two to three days. ICTE uses state of the art equipment and software to create 2D and 3D soil resistivity models, providing a very precise characterization. The measurements are based on the

Pole-Dipole and Schlumberger methods.
Usually, during the measurements, the specialists working on the study also visit the terrain of the future substation, with the purpose of clarifying terrain or substation characteristics and identifying possible constraints that may arise during the building phase.
The results are processed and reported by ICTE to EDP Labelec. A soil model is then developed using the results. This soil model is normally comprised of horizontal layers with different thickness and mean resistivity, because the soil resistivity usually varies much more in depth than horizontally. If significant pockets of lower or higher resistivity soil are identified (for example, respectively: an aquifer or a rock), they are also included in the soil model.
In the case of a substation upgrade, the method used by ICTE can't be applied, because there are usually already buried electrodes in the soil, which influence the measurements. In this particular case, it is a team from EDP Labelec which measures the soil resistivity in several profiles near the substation using the Wenner method.

HV network modelling

The next step is the modelling of the HV network between the transmission grid feeder and the new substation, using the software EMTP-RV and the data supplied by EDP Distribuição.
The model includes accurate line/cable configurations and lengths, as well as conductor and shield wire parameters. Every power line span and tower is modeled, with its grounding impedance values according to EDP Distribuição standards.
Because EDP Labelec regularly measures every existing Portuguese distribution substation's grounding impedance, the last values measured are also included in the model.
With this model, using EMTP-RV, various things can be determined. Inputting the maximum single-phase short-circuit current forecasted by the transmission network operator on the transmission grid feeder, it is possible to determine not only the expected maximum short-circuit current on the new substation, but also (once the new substation's grounding impedance is determined) the current distribution between the substation grounding grid and the power lines shield wires or cables sheaths that connect to it.
However, EDP Distribuição usually opts to specify a design maximum single-phase short circuit on its substations. In this case, the EMTP-RV model is only used to determine short-circuit current division, i.e. the splitting factor.

Substation grounding grid modelling and safety analysis

The third step is the modelling of the substation grounding grid, using the CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis) software package, one of the most powerful tools available in this area.
Usually, the analysis of a new substation starts with a standard grounding grid specified by EDP Distribuição, adapted to the substation area and perimeter. EDP Distribuição provides the base grounding grid, which is then imported by CDEGS. There is also the possibility to manually draw the grounding grid in CDEGS own CAD module. The conductors' thicknesses and other parameters are also inputted.
Then, the soil model determined in the first step using ICTE data is also entered, or alternatively, if soil resistivity measurements were taken by EDP Labelec using the Wenner method, CDEGS automatically determines the best soil model.
With these data, CDEGS calculates the expected grounding impedance for the base grounding grid. This value is then applied to the EMTP-RV HV network model, from which the short-circuit current division is calculated.
The short-circuit current value dissipated by the substation grounding grid is then used by CDEGS to determine ground potential rise (GPR) and thus, the expected touch and step voltages in the vicinity of the new installation.
The safety limits for these voltages are also determined using the CDEGS package. This calculation is based on IEC 60479-1 technical specification and follows the recommendations of CENELEC HD637 S1 harmonization document. The maximum fault clearing time, which has great influence in the calculated safety limits, is supplied by EDP Distribuição.
Normally, there are different types of surface material layers inside the substation, for example: asphalt or gravel. In this case, different safety limits are calculated for every type of surface material layer.
The touch and step voltages results are then exported to an in-house developed application (in MATLAB). The application generates touch and step voltages charts based on a color scale. The higher the values, the hotter are the corresponding colors. Values over the safety limit are represented by shades of red. The resulting charts are very easy to understand, as the red areas are intuitively associated with danger.
If the standard base grounding grid supplied by EDP Distribuição is considered safe, the study is concluded. However, this situation is very rare, due to various reasons, the most important being the high design single-phase short-circuit current, the high soil resistivity on most of the Portuguese territory, the high maximum fault clearing time and the limited substation grounding grid dimensions. So, in most cases, it is necessary to develop safety enhancement proposals.

Safety enhancement proposals

If the base standard grid is considered not safe, one or more enhancement proposals to make it safe are developed using CDEGS, taking into account both the technical and economic constraints specified by EDP Distribuição.

This is the most time-consuming step of the study, because for every tested modification of the base grounding grid, new CDEGS and EMTP-RV simulations have to be run each time. This means that the best optimization of additional material investments in the grounding grid may need many simulations to attain.

Usually, the most troublesome areas of the substation in terms of touch and step voltages are the ones next to the limits of the grounding grid, i.e. the areas near the facility fence, either inside or outside the substation.

After the simulations, for each enhancement proposal, a set of improvement measures is defined. These measures may or may not include direct modifications of the base grounding grid. Improvements by modification of the base grounding grid are essentially the addition of vertical or horizontal electrodes. On the other hand, examples of improvement measures that do not involve modifications of the grounding grid are: changing of the surface material layer inside the substation to one with higher resistivity, changing the substation fence to an insulated one or a non-conducting wall, and relocation of metallic equipment (for example HV towers).

The improvement measures needed in every proposal and their respective results are then reported for EDP Distribuição to analyze and choose the most technical and economically suitable one to be fulfilled.

Validation measurements

Finally, after the substation construction, EDP Labelec can provide the service of measuring the grounding impedance and touch and step voltages, to validate the results of the study.

These measurements are also useful as feedback for EDP Labelec to continue improving and perfecting this integrated methodology.

CASE STUDY

A case study has been selected as an example of the methodology application to a new substation.

In this case, a base standard grounding grid of a new substation which did not ensure the safety of people in the vicinity of the substation was made safe by the application of the integrated methodology.

Firstly, EDP Labelec made a preliminary analysis of the project, as described before, to identify its main constraints. The standard grounding grid was, in this case, 44 m by 35 m wide, with 3 m by 3 m divisions, and buried at a depth of 1 m. There were also 6 vertical electrodes 6 m in length, each one, distributed along the substation area. The most of the substation surface was planned to be covered with asphalt, except for the building, which was built in concrete containing a steel mesh. The substation fence was metallic and considered non-insulated, and had nearly the same dimensions of the grounding grid.

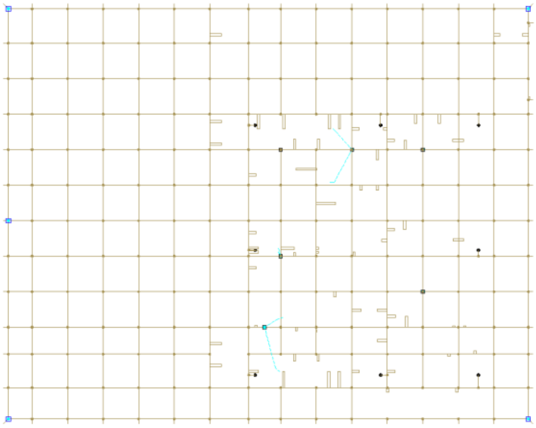

Figure 1 - Base grounding grid project

The maximum single-phase short-circuit current, specified for the new substation, was 25 kA, and the specified maximum fault clearing time was 2 s. These are demanding specifications, which means that it is very difficult to guarantee the safety of a substation with these parameters, in terms of touch and step voltages, without this specialized analysis.

After the preliminary analysis, a team of ICTE performed the soil resistivity analysis, as described before. The team of EDP Labelec working on the safety analysis also visited the new substation area.

The soil resistivity results can be seen in Figure 2. The charts represent the horizontal variation of soil resistivity at different depths.

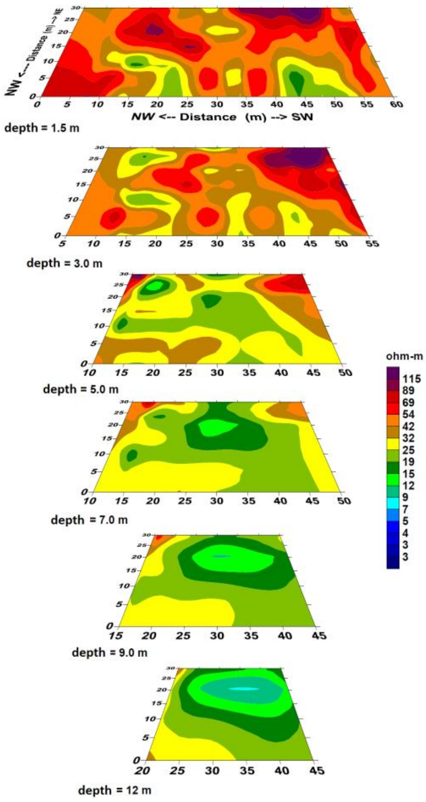

Figure 2 - 3D soil resistivity measurements

With all the data, EDP Labelec built a soil model for the substation area, to be used in CDEGS, which can be seen in the following figure.

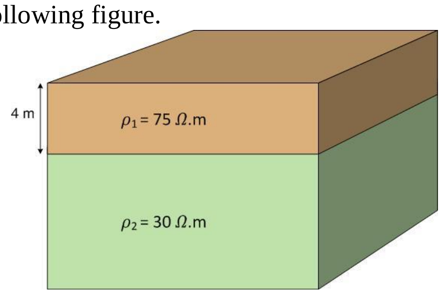

Figure 3 - Soil model

At this point, the safety limits for the touch and step voltages in the substation vicinity could already be computed using CDEGS. The touch voltage limit was 134 V and the step voltage limit was 312 V.

In parallel, the grounding grid model was prepared using the CDEGS package, and the HV network model was created using EMTP-RV.

The CDEGS model of the grounding grid can be seen in Figure 4 (the fence is drawn in red colour).

Using this grid model and the soil model determined above, CDEGS computed a grounding impedance value of 0.4 Ω.

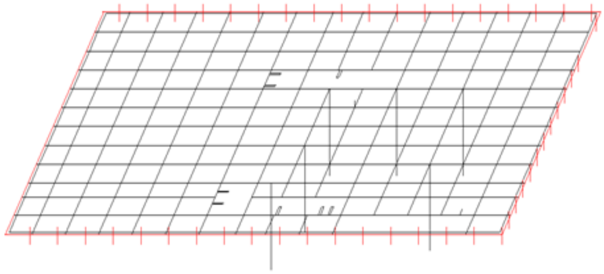

Figure 4 - CDEGS base grounding grid model

In this particular case, the substation was connected to the transmission network feeder through two branches in parallel, both made of relatively short underground insulated cables. This means that the single phase short-circuit current distribution was mainly to the cables' sheaths, which were solidly connected to ground on both ends.

The EMTP-RV model of the HV network can be seen in Figure 5.

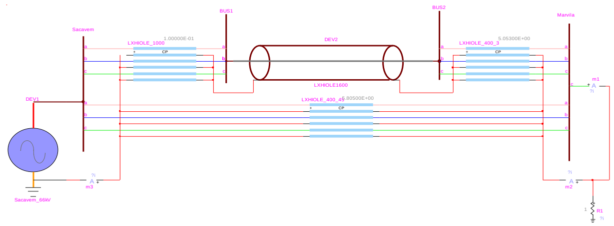

Figure 5 - EMTP-RV HV network model

Using this model, the computed grounding impedance value of 0.4 Ω and the specified maximum single-phase short-circuit current of 25 kA, EMTP-RV determined that a current of 2750 A was dissipated in the substation grounding grid.

This value was then applied to CDEGS, to compute the expected touch and step voltages in the vicinity of the new substation. The values were then exported to the in-house developed application to be processed into colour charts.

In the following chart, it is possible to see the expected touch voltages inside the substation, for the base scenario.

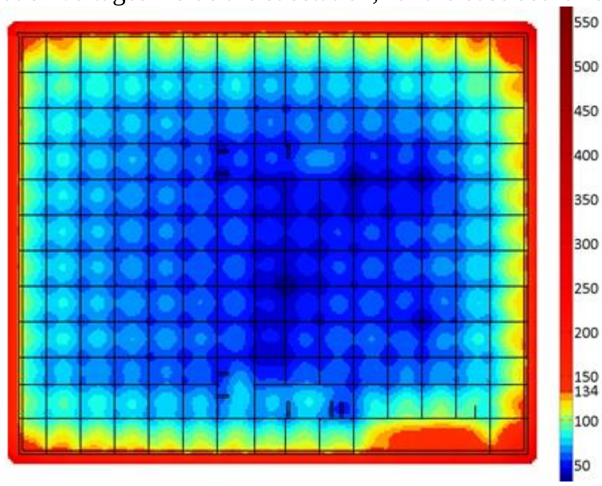

Figure 6 - Computed touch voltages for the base scenario

The expected touch voltages were over the safety limit on the outside of the substation fence, in its entire perimeter. The touch voltages also reached values over the limit inside the substation, at the corners, and in a zone without grounding grid (bottom right corner of the chart).

In the following chart, it is possible to see the expected step voltages inside the substation, for the base scenario.

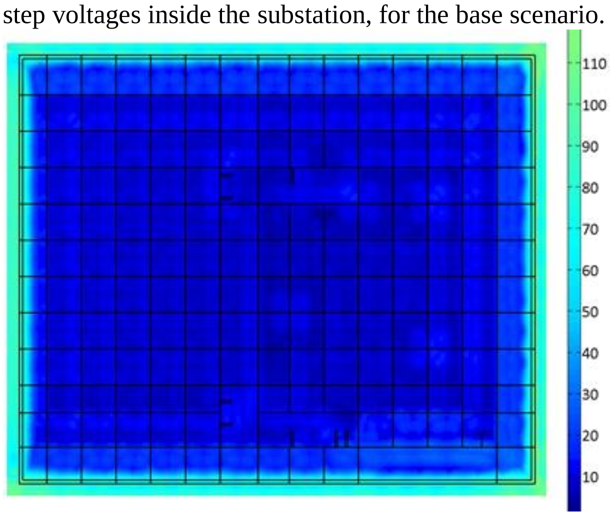

Figure 7 - Computed step voltages for the base scenario

The expected step voltages were well below the safety limit.

It was possible to conclude that enhancement measures for the grounding grid must be created, to guarantee the safety of personnel in the vicinity of the substation.

The easiest, less demanding option to reduce the touch voltage values outside the substation fence was to add one or two extra copper rings connected to the grounding grid, around the substation, approximately 1 to 2 m outside the fence. But the installation of copper electrodes outside the substation fence is considered unreliable because these electrodes are left exposed to third party modifications. This means that a solution which ensured the safety of people in the area of the substation had to be found, without installing any grounding electrode outside the substation fence.

One option was to build an electrically insulated fence. The disadvantage of this option is that the fence is exposed to environmental agents, like solar light and rain, which degrade its insulation over time. So this solution implies that the fence must be regularly inspected and maintained.

So, EDP Labelec designed a proposal without an insulated fence and without grounding electrodes outside the substation fence. After several simulations, the team working on the safety analysis concluded that the addition of five 50 m electrodes in the outermost ring of the grounding grid should reduce the touch voltages to acceptable levels.

The computed grounding impedance for this proposal was 0.2 Ω. The CDEGS model of this proposal can be seen in Figure 8.

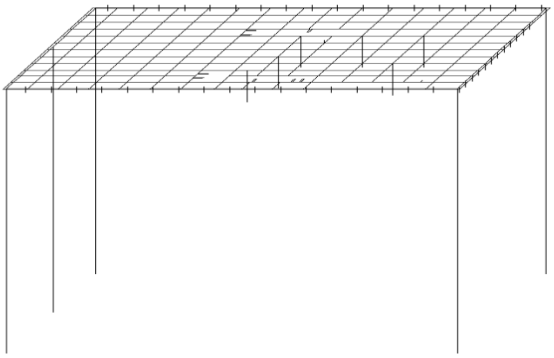

Figure 8 – Grounding grid safety enhancement proposal CDEGS model

In Figure 9, it is possible to see the expected touch voltages inside the substation, for this proposal.

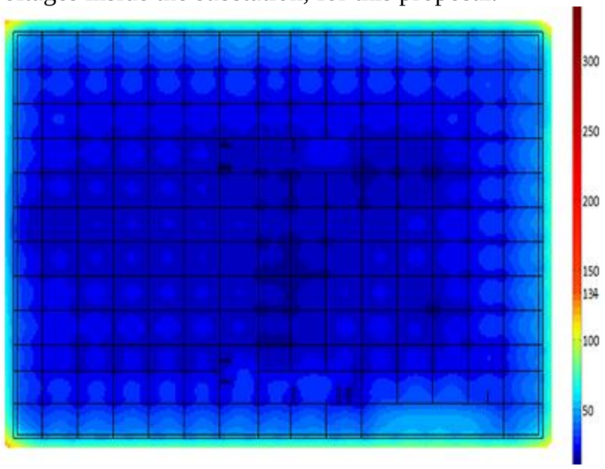

Figure 9 - Computed touch voltages for the grounding grid safety enhancement proposal

The expected touch voltages for this proposal were well below the safety limit in the vicinity of the substation, including a 1 m radius outside the fence.

EDP Distribuição implemented this enhancement proposal on the new substation. After its construction, EDP Labelec measured the real grounding impedance. The measured value was 0.17 Ω, which validated the study.

CONCLUSIONS

This paper described the integrated methodology for design of grounding systems developed by EDP Labelec over the last years, mainly for new substations but also for the upgrade of existing ones, and for other type of installations.

The steps of the methodology were presented and described, including both the field tests (soil resistivity and grounding impedance measurements) and computer simulations (grounding grid modelling using CDEGS and HV network modelling using EMTP-RV).

After this, the presentation of results and their analysis was also described, followed by the steps usually taken to conceive safety enhancement proposals, with the purpose of making the substation safe in terms of touch and step voltages, in case of a single-phase short-circuit in the substation.

Finally, a case study has been presented, as a typical case of a base grounding grid of a new substation which did not guarantee the safety of personnel. The steps to create enhancements to the base grid were described, as well as their results. The real measured grounding impedance of the improved grounding grid was also presented.

EDP Labelec continues to conduct the safety analysis of the grounding system of every new substation in the Portuguese distribution grid. Thanks to the data collected through the field measurements of grounding impedance and touch and step voltages of the substations after their construction, EDP Labelec presently continues to improve the integrated methodology presented in this paper.

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