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Design of grounding systems in substations using a mixed-integer linear programming formulation

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ABSTRACT

The main purpose of this paper is the development of an optimization model to design grounding grids in electrical substations. The design of a grounding grid in a substation is formulated as a mixed-integer linear programming problem. The developed optimization model incorporates the constructive characteristics, as well as the technical and security requirements inherent to the construction, installation and operation of these grids.

The model includes variables defining the grid characteristics according to the configurations admitted by the designer, which are selected amongst a set of pre-selected grounding designs. The definition of these configurations includes the geometry of the grid, the depth at which the conductors will be installed and the radius of the conductor. A finite number of configurations can be generated before running the optimization process by considering all the variables in accordance with the IEEE Std 80-2000. The optimization problem also includes safety constraints related with the maximum allowed touching and step voltages, which are defined according to the fibrillation discharge limits. These fibrillation discharge limits are defined by IEEE Std 80-2000 for low frequencies (for high frequencies, the limits are not the same as in 50 Hz). The model also includes the equivalent impedance of the transmission line supplying the substation where it will be located the grounding grid to be designed. As a result, the problem outputs define the most adequate grounding grid among the possible pre-selected configurations. This selection is driven by the total investment and installation costs, corresponding to the objective of the optimization model. To illustrate the interest of this research, the paper includes a case study based on a real situation, as an example of a potential application of this approach for engineering grounding design.

Finally, it should also be referred that the scope of application of this methodology is potentially very wide given that it is in accordance with the specifications defined by the IEEE Std 80-2000.

1. Introduction

Grounding systems are one of the most important elements of power transmission and distribution system design. The main purpose of grounding grids of power system substations is to maintain reliable operation and to provide protection for personnel and apparatus during fault conditions. Grounding systems also allow controlling harmonics as well as draining fault currents to earth.

A good grounding grid design should be able to maintain the touch and step voltages and the ground potential rise inside the substation within permissible limits, which are defined based on the fibrillation discharge limit. In this paper, the limits considered are taken from IEEE Std 80-2000 for 50 Hz faults. Designing grounding systems, building them and putting them in operation is a difficult task. In fact, the soil where the grounding system will be installed will generally be non-uniform. There are usually measuring errors associated with the soil resistivity, and, furthermore, several data and factors that have impact on the performance of the grounding systems are frequently difficult to be considered in simulation models.

These problems impose that the designed value of the grounding system impedance is checked against the measured one as soon as the grounding system is installed. This design problem usually includes variables that are established by the designer in many cases. It is also important to recognize that several design methods using approximated models can lead to high construction costs, and they do not completely ensure safe operation conditions. However, the literature includes appropriate design methods that are able to

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offer adequate reliability in terms of the results that one can obtain as, for instance [1–3]. On the other hand, ref. [4] details a model that minimizes the cost of building substation grounding grids.

The problem associated with the grounding system construction in substations has been studied by many researchers that investigated how to optimize the grid design while addressing the related technical problems [5–10]. Other researchers studied the grounding system design problem in terms of searching the most efficient grounding grid, taking into account bi-stratified and multi-stratified soils [8], induced voltages [11], and fault currents [12,13] among others, while considering some cost-benefit approaches.

In this work, we describe a mathematical model to design substation grounding systems based on the approach presented in ref. [1] and on the grounding transmission line model detailed in ref. [14]. This paper outlines the adopted formulation and details the optimization problem that allows selecting a grounding grid configuration including the geometry, the depth and the conductor radius among a large number of possible combinations. Additionally, the model allows the designer to select a complementary electrode system for the transmission line that supplies the substation. This selection is determined by the minimization of the investment cost while fulfilling system technical and safety constraints, namely the maximum allowed touch and step voltages and the ground potential rise.

The developed application requires that the designer prepares a database including all the relevant parameters of the system, all the possible grid configurations and the complementary electrodes that the designer admits to install. The optimization problem includes a linear objective function and linear constraints but the decision variables are binary thus leading to a mixed-integer linear formulation. This mixed-integer linear problem is solved using an application of the Branch and Bound technique available in the commercial platform LINDO [15]. Within the developed model, the touch and step voltages are computed in accordance with the recommended methodology detailed in the IEEE Std 80-2000 [1].

Apart from this introductory section, Section 2 addresses the field of application envisaged for the developed approach; Section 3 details the proposed methodology, describes the developed mathematical model and the adopted solution approach. Finally, Section 4 presents a case study to illustrate the developed methodology and Section 5 draws the most relevant conclusions.

2. Field of application

The proposed methodology can be used for all grid geometries considered in the Standard IEEE Std 80-2000, obviously taking into account the premises indicated in this standard. Apart from the conformity and coherency with these specifications, it is also important to refer that the adopted optimization technique, LINDO [15], is widely known and well established, thus contributing to ensure the robustness of the whole methodology. In any case, it should be referred that the developed formulation can be easily adapted to other commercial packages available in the market. In any case, it is important to stress that the results do not depend on the modelling language (LINDO) and in fact they would be the same using other optimization platform.

The calculation of the cost coefficients for different grid configurations and for the complementary electrodes indicated in the outlined methodology turns out to be very simple and can be carried out with the help of an Excel calculation sheet. For a new design project it is then necessary to consider the cost of all the new materials for all the possible solutions.

Given the aforementioned indications, the methodology outlined in the next sections of this paper has the same application field as the one referred in the Standard IEEE Std 80-2000.

It is also important to note that this paper opens up a route to other researches in this topic. Although the developed model uses a linear objective function and linear constraints, non-linear optimization models could also be used to take into account more accurately the behavior of several variables included in the design as, for instance, the soil resistivity. In this case, one should have used other optimization packages available in the market. However, non-linear formulations were not considered as necessary since the developed approach provides good results, as it will be inferred clearly from analyzing the case study presented in Section 4. Therefore, the adoption of non-linear models would certainly lead to an unnecessary higher level of complexity and larger computation time.

Finally, as referred in Section 1, the design of a substation grounding system is very complex due to the number of involved phenomena. One of them comes from the fact that lightning influences the local resistivity of the soil given that, when lightning occurs, non-linear phenomena appear in the soil [18]. Nevertheless, this is not the only difference regarding the low frequency case. Indeed, the high frequency response of both grounding grids [19,20] and human body [21] are not the same for fast transients and power frequency. This very complex phenomenon was not considered in the research reported in this paper.

3. Proposed methodology

3.1. General description

In order to properly establish the optimization model associated with the design of the grounding grid of a substation it is important to recognize two important aspects:

- in the first place, in a given area one can build different grid configurations characterized by different distances between conductors, by different geometries and also by different excavation depths;
- in the second place, the design of the grounding system should take into account the part of the fault current that returns to the transmission line that supplies the substation. In fact, when a fault occurs in the substation, this fault current is drained to earth by the grounding grid and part of the fault current returns to the transmission line through the grounding line.

According to the preceding ideas, the objective function of the problem has two components. One of them is associated with the cost of the grounding grid whereas the second one reflects the cost of the complementary electrodes that protect the adjacent transmission lines. These costs include the installation cost as well as the purchasing cost of the required materials.

The formulation uses a number of elements that aim at characterizing electrical and physical environment of the grounding grid to be defined. These elements include the soil equivalent resistivity, the crashed rock superficial resistivity, the crashed rock superficial thickness, the grid area, the clearing time of the fault current, the ambient temperature and the line equivalent grounding impedance given that a line is simulated with its equivalent electrical circuit including its grounding system. Moreover, the problem has a number of decision variables that are selected so that each grounding grid to be analyzed gets completely defined. These variables include the conductor radius, the geometry of the grid, the number of rods and the depth at which the conductors will be installed.