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Development of a new methodology for measurements of earth resistance, touch and step voltages within urban substations

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ABSTRACT

This paper discusses the development of a new methodology for measurements of earth resistance and touch and step voltages in ground mesh of urban power substations. The main challenge of the work is to find a feasible solution for performing earth resistance measurements from short distances, given that this is the condition actually found in the majority of urban substations. A test field with four ground mesh units of different geometric configurations was implemented and used for performing numerous measurement tests. Based on all the data collected and analysis of the measurement results, a mathematical model was developed to estimate and predict the correct distance in order to obtain earth resistance measurements from short distances, the PRED Method – Polynomial Regression from Database Method. A discussion of the proposed method, as well as analysis of its accuracy and susceptibility to external interference is performed, in addition to its validation in real substations, so as to prove the efficiency and applicability of the proposed method.

1. Introduction

Obtaining grounding resistance values is a major factor in the analysis of electrical safety in electrical substations. This information is considered essential, not only to maintain a low impedance path for the protection of the electrical system in any outbreak, but also to ensure that the potential increase on the ground does not reach levels above the limits set for touch and step voltages in substations.

In view of its fundamental importance, it is possible to historically observe a major concern of the scientific community and engineers in obtaining measurements that are able to set the correct value of the grounding system resistance with a high degree of accuracy [1–9]. These methods are often the subject of work for the establishment of technical safety standards, with well-established protocols and measurement methods [11–13]. The ANSI/IEEE Std 81 [11] is the main *Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System.*

There are several methods for measuring resistance of the ground electrode system. Among them, as verified in many field tests, the fall-of-potential method is widely applied for almost all types of grounding systems [1–6]. However, the fall-of-potential method and its regulatory procedures require certain conditions that are often difficult to obtain for substations in operation in the electric power system, especially in urban environments. As a rule, it is necessary a distance of approximately 4–10 time the greater diagonal (D) of the mesh for the proper positioning of the current electrode (dA) and 2–6 time D for the placement of the potential electrode (dP) (sometimes referred as 62% rule). This measurement procedure is often infeasible, either for operational reasons or for practical reasons in urban substations, given the extent of cables and physical obstacles at measuring points. In an attempt to overcome the above-mentioned aspects, some alternative methods have been adapted, using other electric power system structures as auxiliary electrode, for example, grounded transmission line towers and other substations grounding meshes. In these cases, the distances can be very long and measurements may suffer from the influence of external factors (e.g. electromagnetic interference due to coupling with transmission lines). So either the assessments are made providing incorrect values, which contradicts safety, or the measurements end up not being performed.

In this paper, we propose an effective method for the evaluation of earth resistance, and touch and step voltages within urban substations in order to contribute with this area of research and development (R&D). It employs a mathematical model based on

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linear regression of a parametric analysis to compute the error estimate and evaluate the best electrode position to perform the test. In this sense, we addressed the aforementioned problem employing a method that can be easily applied to short distances and not as susceptible to outside interference, when compared to the traditional methods [11].

2. Literature review

2.1. General fall-of-potential method (FoP)

Several papers presented in the technical literature contribute to solving some of the aforementioned problems. In Ref. [5] an extended analysis is presented for the ground impedance measurement using the fall-of-potential method. It introduces a set of curves to represent the exact placement locations for the potential probe when the potential and current probes are in different directions. Also, curves representing measurement error are presented in the case when the potential probe is placed in locations where ground impedance cannot be measured correctly. A similar analysis for ground impedance measurements in multilayer soils is also discussed. In Ref. [10] is described a method and instrumentation for measuring touch and step voltages near the grounding system. The method injects the transient electric current between the ground under testing and an auxiliary ground electrode, allowing measurements of ground potential differences at different locations. The touch or step voltages are related with the system short circuit capability. The paper Ref. [9] proposes a technique for measuring ground resistance without using auxiliary electrodes. The measurement technique and a measurement tool are introduced and discussed. In Ref. [4], an alternative fall-of-potential method is presented. The method is a voltmeter and ammeter method, and does not require any auxiliary electrodes. Using the ground electrodes of a nearby substation, the method allows determining ground electrode resistance of one of the premises and of the effective ground electrode resistance of the substation. The method yields accurate results and is practically contributive for electrode resistance measurements in sites where the use of auxiliary electrodes is difficult. Also, numerical simulation analysis was presented in [14] in order to evaluate the fall-of-potential method and to assess the influence of auxiliary electrodes at near distances, providing an overview about the voltage distribution phenomena and grounding resistance.

2.2. Tagg Method

Tagg's Method, also recommended by IEEE Std. 81-2012 [11], is based on the work developed by Tagg [1] since 1970, and also known as the "slope" method. In this method, uniform resistivity assumptions of the soil and representation of the ground electrode system as an equivalent hemispheric electrode are used. Additionally, this method allows performing the measurement at near distances, by introducing the correction factor to the fall-of-potential procedure.

In general, Dr. Tagg's slope method [1] can be applied from the following protocol measures [11]:

a Choosing of a convenient starting point for linear measurements and the selection of a suitable distance for the positioning of the current electrode (d_A).
b Measurement of three resistance values *R1*, *R2*, *R3* inserting the potential electrodes (d_P) on the distance of *0.2* d_A, *0.4* d_A, and *0.6* d_A, respectively.
c Calculation of the inclination variation coefficient (μ) using the equation: $\mu = (R3 - R2)/(R2 - R1)$.

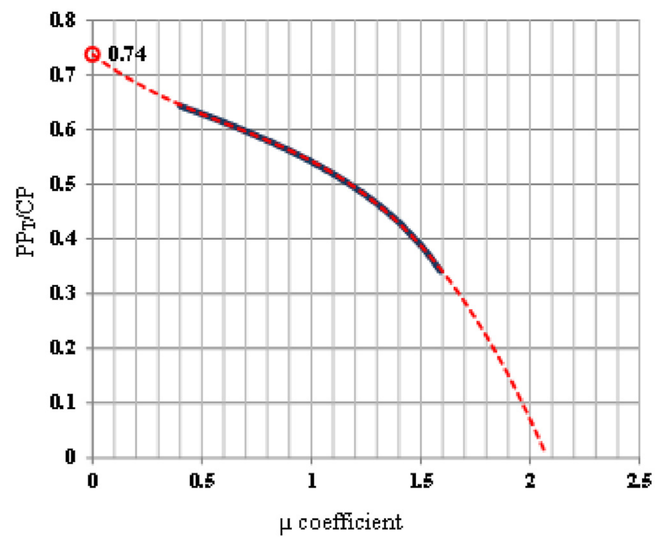

Fig. 1. Tagg Method (solid line) and Extended Tagg Method (ETM) (dashed line)[2].

d Selection of the d_{PT}/d_A value corresponding to the "μ" value in a correction table proposed by Tagg [11] (for μ ranging from 0.4 to 1.59).
e Measurement of the true grounding resistance by placing the potential probe at the distance d_{PT} established by the Tagg's table.

2.3. Extended Tagg Method

In a number of measurement tests performed in practical situations, it was noticed that Tagg's method showed a certain amount of points in which the μ coefficient could not be obtained in the interval of the correction table proposed by Tagg [1]. Taggs's table presented in the IEEE guide shows values for the relation d_{PT}/d_A due to the tilt variation coefficient (μ) in a range from 0.4 to 1.59 and the rate d_{PT}/d_A from 0.643 to 0.341 (referred as PP_T/CP at Ref. [11]). When the tilt coefficient obtained by the 3 consecutive resistance measurements of Tagg's method (i.e. 20%, 40%, 60%) is outside this range, the result of this method could not be defined.

Thus, in order to establish boundary conditions for measuring points with undefined values by Tagg's original method, Ref. [2] proposes the use of the Extended-Tagg Method (ETM), which extrapolates the table of the original method, from a mathematical approximation presented in Eq. (1):

$$PP_T/CP = -0.1242u^3 + 0.2339u^2 - 0.3049u + 0.738 \quad (1)$$

From this mathematical approximation, it is possible to perform the extrapolation of Tagg's method for applications in near distance situations, and frequently encountered in practical evaluations. In Fig. 1, original Tagg's method [1] is shown by the solid line, while the Extended-Tagg Method is shown by the dashed red line. This allows the use of Tagg's method for analysis of more near distance measurements, which is the main goal of this paper.

3. Formulation of the proposed method (PRED)

The proposed method, denominated PRED method (Polynomial Regression from Database), was developed from a series of experimental results considering the parametric assessment of d_A and d_P and subsequent analysis of the measurement database. This method presented a different approach from the other works found in the technical literature, but can also be employed in order to predict the correct probe placement for resistance measurement at