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An alternative approach for touch and step voltages measurement in high-voltage substations

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ABSTRACT

This paper presents the study of a measurement technique for touch and step voltages. In essence, we elaborate an approach which is very similar to the measurement of the grounding system impedance. In addition, the main focus is on the measurements at energized substation where different types of coupling between the test leads, grounding grids, sheats of underground cables and overhead ground wires affect the precise measurement. In order to avoid the measurement difficulties, we use low magnitude variable frequency AC test current (so called Frequency Shift Method – FSM). We compare FSM measurement results with the corresponding results obtained by well-known *Test Current Reversal Method.* The field tests were conducted in two quite different substations. Experimental results demonstrate the validity and usability of this approach.

1. Introduction

Safety and reliability are the two major concerns in the operation and design of an electrical supply system. Proper grounding system is the cheapest and most reliable way of providing safe conditions for personnel and equipment in the substation. Generally, a substation grounding system is designed to limit touch and step voltages within the tolerable limits in and around the yard of the substation [1]. Depending on the presumptions made in the designing, the actual touch and step voltages during the ground-fault might differ from the calculated values. For the purposes of performance analysis of the grounding system, many mathematical tools have been developed, among the others [2,3]. On the other hand, it is an accepted fact that field measurements will generally give more reliable results than the ones obtained by calculation alone. The main reason is that the grounding system is exposed to the influence of many factors – predictable and unpredictable (variable soil characteristics [4–6]; the impact of other underground metallic structures). Therefore, the step and touch voltage (safety-critical metrics) has to be precisely measured. Usually, the measurement should be performed when the substation is in-service. Consequently, the power system frequency interference and harmonic frequencies may adversely affect the measurement. In order to suppress power frequency interference, the field tests are often performed by using test current at a frequency slightly different from the power system frequency [7–10].

An appropriate design of grounding system limits the step and touch voltages to be within the values permitted by national or international standards. Substation grounding systems need to be inspected periodically to test and verify their original protective functionality and characteristics. When a significant difference appears between the calculated and measured value of Ground Potential Rise (GPR),[1] more extensive measurements should be made for grounding systems safety assessment. The IEEE Std 80-2000 provides limits and useful procedures for grounding systems safety assessment [1].

The list of references related to measurement of touch and step voltage cited here is not complete, but demonstrates the range of different approaches. In [11], detailed discussion of low-voltage and high-voltage measurement method for touch and step voltage was given. In the low-voltage method, in order to obtain high signal-to-interference ratio, a test current ~100 A is recommended.

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[1] During earth fault conditions, the flow of current via the grid to earth will therefore result in the grid rising in potential relative to remote earth to which other system neutrals are also connected. This produces potential gradient within and around the substation. This is defined as GPR.

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However, this is not a practical option, since a significant power of source is required, especially in situations where the remote substation cannot be used as an auxiliary grounding system. On the other hand, high-voltage current injection method is made with a full phase-to-ground fault current ranges from a few kA to more than 10 kA, so that interference seldom has any significance. Nevertheless, this method is rarely performed due to system operational constraints [12]. A computer-based ground multimeter for touch and step voltage measurement was introduced in [13]. Simplified conservative measurement of touch and step voltage, adopting current auxiliary electrodes at reduced distance, was described in [14]. In reference [15] an interesting method for eliminating interference, which is based on recording the transient state caused by switching-on the test circuit, was presented. Recently, in [16] an online monitoring scheme based on sensor technologies has been proposed. Namely, the measuring system continuously injects current into a grounding grid and then measures the corresponding touch and step voltages with a wireless sensors.

In this paper, we describe a measurement experiment for touch and step voltage. The measurements were conducted in two substations using simultaneously two measurement methods – *Frequency Shift Method* (FSM) and *Test Current Reversal Method* (TCRM). The first subtation is 110/6 kV (Steel Plant Smederevo, Serbia). The grounding system of this substation is very complex. Namely, the substation's grounding grid is placed together with various underground metal installations that are connected effectively to the earth. The second one is a typical 110/35 kV substation (Mislodjin, Serbia). This substation is placed in a rural area.

In this paper, we also describe in detail the FSM. We compare FSM results with the corresponding results obtained by widely accepted TCRM. For purposes of our experiment, the TCRM is reference method.

The remainder of this paper is organized as follows. Section 2 briefly presents the measurement techniques, hardware and procedures. Section 3 describes the experiments, conducted inside two substations, including comments the results obtained. Concluding remarks are given in Section 4.

2. Principles of measurement

2.1. Preliminaries

Here, as in the case of grounding system impedance measurement, the test current is circulated between the substation ground and an auxiliary grounding system (remote earth) to simulate a fault condition.

The touch voltage is defined as the potential difference between a person's outstretched hand, touching an earthed structure, and his foot. A person's maximum reach is assumed to be 1 m.

The step voltage is defined as a potential difference between a person's outstretched feet, 1 m apart, without the person touching any earthed structure.

For the purpose of safety, the resistance of a human body was assumed to be taken as 1000 Ohms [17].

The touch voltages are measured beside grounded metal objects in areas with high potential deviations from GPR level, while step voltages are inspected on positions suspected for high gradient values on earth surface.

All measurements will be performed with the grounding system in its normal operative configuration, that is, keeping all external connections in place.

Relatively thin rod (6 mm diameter), with a penetration depth ≈200 mm into the moist subsoil, was used as a fixed voltage probe.

2.2. TCRM (reference method)

The TCRM measurement setup is depicted in Fig. 1. In this case, the current injection system consists of a separate transformer with polarity reversal and regulation capabilities [18]. According to TCRM principle described in [12,18], the measured parameters are defined as follows:

$$I_{test} = \sqrt{\frac{{I_{test1}}^2 + {I_{test2}}^2}{2} - {I_i}^2} \tag{1}$$

where I_{test1} and I_{test2} are direct (first polarity) and reversed (second polarity – current is reversed 180° electrically in the phase angle after a dead interval) test current, respectively; I_i is the short-circuit current, i.e., the current in the test leads when the current source is short-circuited; the voltage (touch or step, depending on which voltage is measured) across $R = 1000\,\Omega$ is

$$U_{t,s} = \sqrt{\frac{{U_{t,s1}}^2 + {U_{t,s2}}^2}{2} - {U_{t,si}}^2} \tag{2}$$

where $U_{t,s1}$ and $U_{t,s2}$ are the voltages across R due to current I_{test1} and I_{test2}, respectively; $U_{t,si}$ is the corresponding touch or step voltage due to short-circuit current I_i. Finally, the touch voltage[2] $U \triangleq U_t$ or the step voltage $U \triangleq U_s$ is

$$U = U_{t,s} \cdot \frac{I_{fc}}{I_{test}} = Z_t \cdot I_{fc} \tag{3}$$

where $Z_t \triangleq Z_{tt}$, is the transimpedance for touch voltage or $Z_t \triangleq Z_{ts}$ is the transimpedance for the step voltage, and I_{fc} is the maximum projected fault current. Formally, the ratio $U_{t,s}/I_{test}$ is a resistance. Strictly speaking, $U_{t,s}/I_{test}$ is not resistance since I_{test} does not flow through R. However, we observe that the current, I_R, flows through R and is proportional to the test current, I_{test}. Therefore the ratio $U_{t,s}/I_{test}$ is proportional to the grounding resistance. Usually, the grounding system impedance is dominantly resistive. Hence, for the ratio $U_{t,s}/I_{test} \triangleq Z_t$, it is convenient to use the term transimpedance.[3]

The TCRM is sensitive to time-varying interference [12]. The interference is usually non-stationary and can vary in frequency, amplitude and phase. The frequency variations are usually small. However, the amplitude and phase variations can be large. In order to overcome this problem, in our experiment, we perform several successive TCRM measurements. As a valid TCRM measurement result, we choose the result that is the same at least at three of several measurements.

2.3. FSM

Over the years the principle of a shift frequency has been used in different contexts. Here, we use this principle for measurement of touch and step voltage. For the measurement method based on this principle we use term FSM. The FSM measurement setup is depicted in Fig. 2. A key part of the measurement setup is the variable frequency current source (California Instruments, type 15001iM).

In order to avoid power system frequency interference (50 Hz), the injected test current frequency has to be slightly different from the power system frequency. This approach, based on two frequencies (48 Hz and 52 Hz), for grounding system impedance measurement has been used in [10]. In this paper, in order to improve measurement accuracy, we performed experiment at three frequencies (40 Hz, 60 Hz and 75 Hz) using the appropriate

[2] ≙ refers to "is defined as".

[3] This term has been proposed an anonymous reviewer. Thanks for this suggestion.