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A study on high-voltage substation ground grid integrity measurement

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ABSTRACT

The condition of the substation grounding grid is vital for the safety of the people. Inadequate grounding may cause failures in major substation's equipment, as well as in control, metering and telecommunication equipment. Therefore, it is necessary to clearly identify damaged elements on grounding grid. This paper presents an approach to test the integrity of the grounding grid in a general framework of IEEE Std. 81-2012. More precisely, in order to locate damaged grounding riser(s) and/or grounding grid conductor(s), this paper is focused on novel unambiguous criteria for post-processing of raw-data collected from the measurements. In order to avoid the effect of power frequency interference on the measurement, we use DC test current of 100 A. The field test is described and discussed in details. The outcome of field test clearly shows the validity and feasibility of the proposed approach.

1. Introduction

The grounding grid provides a common ground for the electrical equipment as well as all the metallic structures in the substation. Effective grounding system design is important as it deals with personnel safety and protection of electrical equipment. A grounding grid arrangement system is commonly used in substations. It contains many interconnected bare copper or steel conductors buried about 0.8–1 m deep under the ground. Utility companies are constantly searching for techniques that can effectively and accurately evaluate the grounding grid conditions to ensure safety of the people and prevent equipment damage.

There are many reasons for damage to the grounding grid, e.g., bad construction welding, soil erosion, corrosion of conductors, direct lightning and power system fault currents into the ground network. In extreme cases, corrosion leads to disruption of the grounding conductor. The break of the grounding grid conductor affects grounding resistance. Consequently, the fault affects safety parameters: touch and step voltage. Thus, detection of the fault location on grounding grid is particularly important. Since grounding grids are buried in the ground, their characteristics are influenced by surroundings [1,2] and it is hard to find damaged elements in them.

Over the years there has been a growing concern about the issue of grounding grid integrity and corrosion diagnosis [3–7]. There is a consensus that substation's grounding grid integrity field measurements will generally give more reliable results than the analytically based estimation. The list of practical references cited here is not complete, but demonstrates the range of different approaches. In Refs. [8–10] diagnosis has been based on the measurement of port resistance. According to [11], the high frequency current (up to 1 MHz) has been used for testing the integrity of the grounding grid. By analyzing the distribution of the voltage patterns on the surface of the ground the broken conductors have been identified. In [12], the model is based on electric circuit theory and solved by applying a conventional nodal analysis technique. In [13], the square-wave current injection method has been proposed. Application of this approach depends on many uncertain changeable factors such as soil resistivity, moisture content and seasonal changes. A computer-based ground multimeter for the grounding grid integrity test was proposed in [14]. The methods proposed in [15–18] are based on the measurement of the magnetic field generated by the current flowing through the grid conductors. Conclusion about the integrity of the grid's element is directly related to the intensity of the magnetic field captured above the buried conductor. Recently, in [19] a sophisticated approach to the magnetic field based method is proposed. This method uses 400 Hz test pulse current. However, its drawback is that it has thus far only

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been verified through simulation and lab tests. Generally, application of the magnetic field measurement based test method prefers the de-energized substation. In many cases it is a serious practical limitation.

In [20–22] and [23,Sec. 11.7], the *high-current method* for testing the integrity of the ground grid has been considered. These references provide background information for high-current method. The high-current method is rather straightforward, but there are various pitfalls associated with the implementation. Namely, as far as we know, there is no simple, concise and practical guide available for the use of high-current method.

This paper is primarily concerned with the practical feasibility of the method recommended in IEEE Std. 81-2012 [20]. Ref. [20] recommends nominal test current of 300 A. In this paper, we will document our measurements that are based on the DC test current of 100 A. The measurements were conducted in a substation 110/10.5 kV (Uvac, Serbia). During the measurement the substation was in normal operating condition.

The remainder of this paper is organized as follows. Section 2 describes the measurement setup, as well as the methodology that we propose in order to test the integrity of the grounding grid. In Section 3, detailed discussion of the field test is presented. Finally, some conclusions are drawn in Section 4.

2. Measurement method

2.1. Overview

This section describes the measurement approach used to test the integrity of the grounding grid. Our goals are: (1) to perform the test when the substation is in-service[1], (2) to describe the raw-data acquisition method (field measurements), and (3) to automate post-processing of the collected raw-data from the measurement.

In order to fulfill the first objective, we use the DC test current. On the other hand, to ensure a sufficiently high signal-to-interference ratio needed for reliable measurement, a high test current is required. Such an approach is already proposed in IEEE Std. 81-2012 [20]. The test involves an injection of substantial current, 300 A, from a reference ground to the test ground riser. This test method is known as the high-current method (HCM). In many instances high test current may be impractical because of the high price for both the voltage source and the test cables. Ref. [22] described a measurement system based on the DC test current of 200 A and 300 A, respectively. We present an approach which uses the DC test current of 100 A. Selection of relatively low test current is based on many of our experiments previously conducted at different substations where grounding risers are very closely spaced. In this context, we have experimented with grounding grid conductors which were made of the different materials and/or had different cross sectional areas. So, we have found the minimum amount of the test current which would cause the voltage drop readable by a typical voltmeter (i.e., a voltage of the order of 100 mV). Accordingly, we suggest the DC test current of 100 A as suitable choice.

To fulfill the second and the third objective, we remain in a general framework of IEEE Std. 81-2012 [20]. However, experience has shown that significant improvements of the conventional HCM are needed. The reasons for this are as follows.

Testing continuity of the grounding grid, in particular in a large-size high-voltage substation, based on the general guidelines for HCM [20], is a challenging task. Namely, testing process takes place in two phases: measuring and evaluation of the measurement results. Unfortunately, the second phase has not been automated up till now. A lot of human intervention is still needed, which will inevitably introduce errors. Strange enough, it is hard to find literature that provides clear and complete treatment related to application of HCM. Hence, in most cases, HCM based testing could be very subjective, test environment-depended and time-consuming. In order to avoid these weaknesses and to reduce uncertainty of the HCM test, some changes are necessary in the measuring as well as in the post-processing of the raw-data. Of course, such an approach requires unified and precisely defined criteria that are based on field test results for a variety of scenarios. This motivated us to analyze the behavior of the eighteen available HCM tests results (out of these, 10 are missed test results) conducted in past by Institute Nikola Tesla, Belgrade, Serbia. In this way, we noticed certain regularity in terms of: (a) the test voltage at the neighboring non damaged grounding risers and/or grounding grid conductor, and (b) the current in the case of damaged grounding riser and/or grounding grid conductor. Based on this property, we will propose the corresponding steps for post-processing of the raw-data collected from the measurements.

2.2. Measurements procedure and post-processing

We propose the general setup for testing the integrity of the grounding grid in a high-voltage substation as shown in Fig. 1. Unless otherwise specified, we chose transformer neutral point as a reference ground. The current and voltage test circuits are configured separately (see circuits plotted by the red and blue lines, respectively). As a consequence, the measured values of voltage drop do not include voltage drops on the current test leads. Also, temperature and resistance of the current test leads do not affect the voltage drop measurement. In its turn, the occurrence of DC interference (or DC bias) from cathodic protection systems of pipelines, DC railroad tracks, and/or DC transmission lines can affect our low current measurement system. Generally, this fact should be taken into account. However, we have not seen DC interference as a severe problem in our measurement campaigns. Hence, an in depth analysis of the effects of DC interference is beyond the scope of this paper.

As already suggested in [20], we also use the maximum allowable voltage drop between the reference point and the grounding riser under test. Thus, if the test current is 300 A (as recommended in [20]), for a copper ground conductor (annealed soft-drawn, cross sectional area 53.4 mm^2–1/0 AWG) the maximum allowable voltage drop is 1.5 V for straight-line distance of 15.24 m (50 ft) between the reference ground and the grounding riser under test[2]. We use the DC test current of 100 A and copper conductor (annealed soft-drawn) having a cross sectional area 50 mm^2. Therefore, we use the voltage drop 525 mV per 15.24 m, i.e., **34.4 mV** *per meter length*[3]. This calculation is based on the fact that the voltage drop is $U = R \cdot I$, where $I = 100$ A, $R = \rho \cdot l/S$, ρ is the resistivity of the conductor at reference temperature 20 °C (1.72 μΩ cm for annealed soft-drawn copper conductor [21]), l is the length of the conductor, and S is the cross-sectional area of the conductor. We henceforth refer to

[1] Testing methods currently used to test grounding systems require a de-energized substation, which are only practical before it becomes energized (to avoid interruption of service and costly downtime).

[2] In fact, the resistance (say $R1$) between the two points of the ground grid is approximately substituted by the resistance (say $R2$), where $R2$ is the resistance of the conductor which has the length as the straight-line distance between points under consideration. Accordingly, $R1 \leq R2$ and $U_{R1} \leq U_{R2}$, where U_{Ri} is the voltage across a resistor of value R_i ($i = 1,2$). This reasoning is the same as in [20]. Hence, this approximation will be used later on.

[3] Copper is the most commonly used material for grounding. It is resistant to most underground corrosion. Steel can be also used for ground grid conductors, but corrosion is an issue. For ground grid based on steel conductors (e.g., steel-1020, cross-sectional area: 30 × 4) the voltage drop per 15.24 m is 2.02 V, i.e., **0.138** V/m.