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Special Attention to Impedance of Conductivity Enhancing Backfill Materials

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***Abstract*—Use of earthing enhancing compound (EEC) in electrical earthing system is a common practice in many countries. Naturally available materials and commercially modified materials are used as EEC. This research will enlighten further the phenomenon of using EEC to improve the performance of an electrical earthing system. The EEC used for this experiment was a commercially available product which the exact chemical composition is unknown. Both high impulse current generator and a modular impulse generator with suitable data acquisition systems were used to study the impedance characteristics of the product specifically under fast transients. Both 1.2/50 µs lighting impulses and 8/20 µs wave shapes were applied to the sample and analyzed the responsive V-I and impedance curves. Both experiments provide convincing evidence for healthy conductive character of the selected material under impulse conditions. However, some of the evidence suggests dissimilarities in the behavior of the test sample when compared to characteristics of soil under similar impulse conditions. The minimum impedance reached by the material during the experiment shows a diminishing pattern, which could be attributed to increasing ionized region inside the material. EEC was able to conduct currents as high as 20kA to 30kA with the impulse current generator experiments and rough estimations of the impedance lies around 500 mΩ range.**

Keywords-earthing, impulse characteristic, impulse impedance, conductivity enhancing backfill material

I. INTRODUCTION

The medium surrounding any earthing system; mainly soil, plays one of the most important factors in providing an effective earthing system. An extended number of research studies and publications can be found on the behavior of homogeneous and non-homogeneous soil types under fast impulse [1], [2]. Soil ionization, thermal effects, impact on moisture content due to large transient currents have been studied and are well experimented. Recently, this early researches has shifted its evolution from natural soil to more modified soil types which are gaining more popularity among the engineering community.

Almost all lightning protection systems whether structural or surge are designed to divert the devastating impulse to the earth mass and serve its purpose of protecting the intended lives, buildings or equipment. Thus it is imperative to have a solid and low impedance path for all fault current to pass to the earth. Experiments on the soil characteristics under such impulse conditions have been performed extensively. Soil types such as sand [3] gravel [4], clay [5], and humus [6] have been subjected to impulse voltages and different earthing configurations can also be found in these publications.

To create a low impedance earth system, it is common practice to use low resistive materials surrounding the earthing system such as bentonite [7]. However, the response of such material on lightning impulses is not fully understood. Previously published field experiments and laboratory experiments on such conductivity enhancing compounds can be found on [8], [9], [10] focusing on low-frequency resistance measurements and at the same time some work on the response of the earthing system to impulse currents [11], [12]. This research is more on learning the details of the characteristics of such commercially available EEC to high impulse current configurations. Requirements for use of EEC is given in IEC 62561-7.

II. THE EXPERIMENT

The experiment was in two stages; first, one using a modular impulse generator for low voltage impulses and the second one using a High impulse current generator with charging voltage of 20 kV and 40 kV. Both experiments were carried out at the Angstrom Laboratory Uppsala University – Sweden

A. *Experiment 1: Test with low voltage impulse generator*

EMC-Partner Modular Impulse Generator 1206 - Combination Tester was used to generate up to 9KV impulses to be introduced to the experiment setup. Further to that the output signal was captured with YOKOGAWA DL850 ScopeCorders. Industrial standard high voltage probe (Tektronix P6015A), with 3.0pF, 100 MΩ input impedance and 75 MHz bandwidth was used with 1:100 attenuation for voltage measurement. See Fig. 1 for the test setup.

The impulse current was measured with Rogowsky coil which a 1:10 attenuator was added at the connection to the oscilloscope.

The primary data analysis was done using the Xviewer software provided by YOKOGAWA Company while further analysis of data was carried out using MATLAB software.

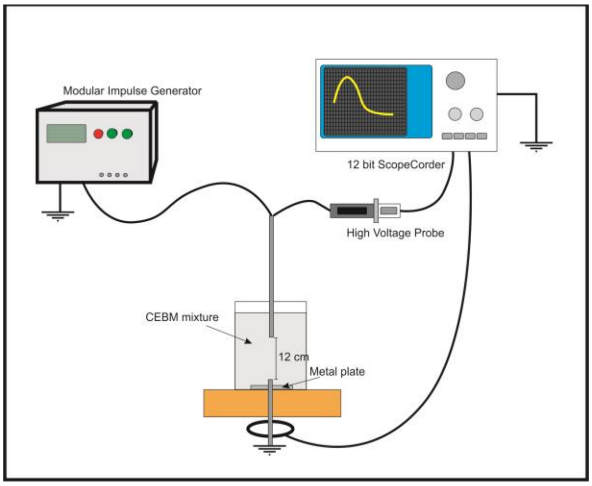

Figure 1. Schematic diagram of the experimental test setup for Experiment 1

B. Experiment 2: Test with high current impulse generator

An electrical discharge of 8/20 µs was created by high impulse current generator (Haefely). The gap between the spheres was maintained around 8mm and data was collected for 20kV charging voltage. Similar to the previous experiment the setup was connected to the generator and Rogowski coil with 10mV/A, 2 kA, and 10ns time response sensitivity was used to measure the current signals. The data were recorded using a computer with a data acquisition card (Dias 733 from Haefely) which is placed inside a separate screened room.

III. TEST SAMPLE

To prepare the sample setup, the selected conductive material was mixed with cement in 3:1 ratio and water was added to form the mixture and allowed to dry as per manufacturer's specification. A non-conductive plastic container was selected so as to direct the discharge path directly to the bottom rod and for both top and bottom rods 10mm galvanized mild steel rods were used. During this process, the rod arrangement was placed inside the mixture as shown in the Fig. 1. The gap inside the material and between the rods was maintained to be exactly at 12cm.

Once the sample is dried for seven days it was connected to the impulse generator and to the data acquisition system as depicted in the Fig. 2.

Figure 2. Experimental setup for Experiment 1

IV. DATA ANALYSIS WITH MODULER IMPULSE GENERATOR

Before each test, the dried test sample was tested for steady state resistance and it continuously demonstrate large DC resistance values.

The test sample was connected to the system as shown in the Fig. 1. Starting from 1kV up to 9kV, nine voltage impulses with 1kV voltage gaps were applied to the test sample while the results were recorded through the 12-bit oscilloscope. Comparatively, large currents were observed during all these impulses.

V. DISCUSSION ON THE IMPEDANCE OF THE TEST SAMPLE: EVIDENCE FROM EXPERIMENT 1

Since all the V-I values are time dependent, the resulting impedance values are also functions of time. Thus there are number of ways one can define impedance relevant to a time dependent function. Most effective and practical ways is to analyze the whole dynamic impedance curve of the impulse during the entire discharge duration. This provides evidence of the minimum and maximum impedance values reached by the sample during the discharge. Further to that impulse impedance (Z) can be defined based on a predefined point in time; such as at the peak of Current or Voltage, or simply as the ratio between peak of the voltage and peak value of the current passing through the sample. In each way, the results reveal important characteristic behaviors of the selected grounding material.

The dynamic impedance with respect to time of the sample for the charging voltage of 7kV is shown in the Fig. 3 along with the relevant V-I curves.

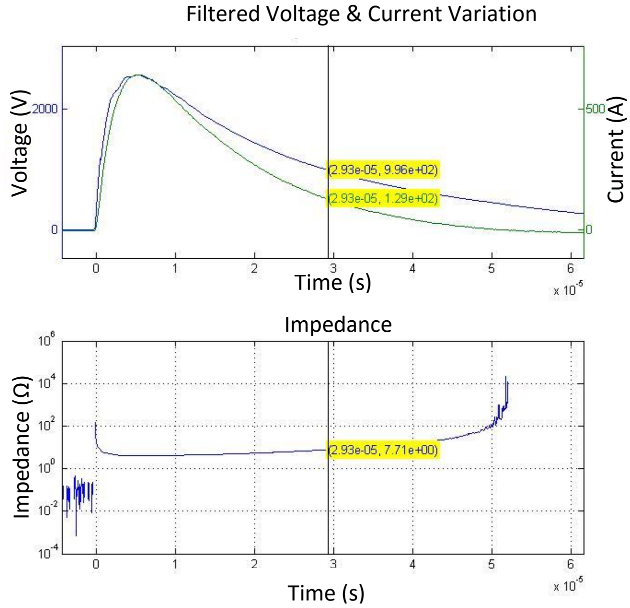

Figure 3. Impedance values on a log scale calculated from the experiment 2 (positive dischargers)

The impedance behavior shows similarities as well as dissimilarities to a typical high impulse impedance curve for soil [5]. The rise and drop in the current at the breakdown point as it is seen with soil experiments were not apparent with this test. Consequently, the distinctive vertical drop in impedance at the breakdown point is not apparent with the impedance curves observed with this experiment. However prominent non-linear change in impedance was observed which indicates the presence of conducting mechanism within the material between the gaps.

The material was able to conduct comparatively large currents even at low voltage values. Table 1 provides the peak currents obtained for each charging voltages for positive polarity test. Almost identical characteristics were observed for negative impulses.

TABLE I. PEAK CURRENT READINGS FOR POSITIVE POLARITY TEST

Test Number	Charging voltage (V)	Peak Current (A)
TEST0000	1000	146.80
TEST0001	2000	384.00
TEST0002	3000	643.62
TEST0003	4000	908.52
TEST0004	5000	1248.23
TEST0005	6000	1559.04
TEST0006	7000	1913.23
TEST0007	8000	2259.23
TEST0008	9000	2651.54

Behavior of the impulse impedance linking to each peak impulse voltage can be retrieved from finding the minimum value of figure 3 plots for all tests. This is done selecting an appropriate time starting from the beginning of the voltage until impedance becomes very high and the material become non-conducting. For both polarities, the test results show decreasing impedance values against increasing peak impulse voltages. This saturation phenomenon implies that further increasing the voltage will have a diminishing effect on reduction of the system impedance. See Figures 4.

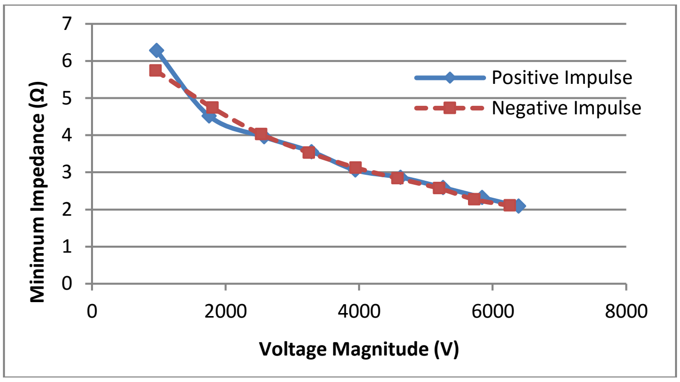

Figure 4. Minimum Impedance vs. Peak Voltage Magnitude

The diminishing impedance of the test sample could be attributed to the electric field created between the electrodes inside the bucket. The electric field will increase comparatively to the generated peak impulse voltage between the electrode ends. Rising of the e-field above a certain threshold will create an ionized region which starts conducting a current within the material. Consequently, higher peak voltages will result in increased ionized volume inside the already ionized region. The outcome of this increased volume could be contributed in further lowering impedance values within the discharge. Thus the impedance curve shows decreasing trend with regard to increased peak voltages. A similar behavior can be seen in experiments conducted on soil samples [2], [13] but with different electrode configurations.

However, as noted above the plot provides a saturation trend with increased peak voltages which needs further extension and analysis of the research.

VI. DATA ANALYSIS WITH IMPULSE CURRENT GENERATOR

Test sample was connected to the high impulse system and a typical current curve obtained for 20 kV charging voltage is shown in the Fig. 5. Compared to the previous experiment done using the modular impulse generator, the current curves display no ‘two peaks” as seen in most laboratory experiments relating to high impulse soil discharges [13], [14], [15]. These two peaks are generally attributed to the thermal effects due to reducing resistance during the pre-ionization period and the ionization process itself and the expanding ionization region [16].

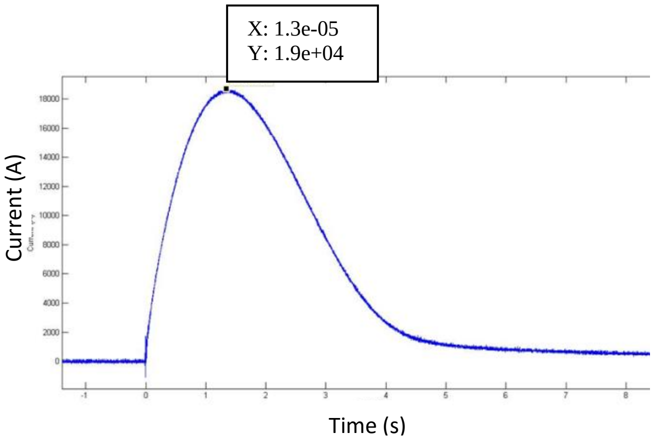

Figure 5. Minimum Impedance vs. Peak Voltage (positive) - 2kV charging voltage

VII. DISCUSSION ON THE IMPEDANCE OF THE TEST SAMPLE:EVIDENCE FROM EXPERIMENT 2

A charging voltage of 20kV produced a short circuit current of 40 kA by the impulse generator system. Thus the rough estimation of the system impedance can be calculated to be around 500mΩ.The average current reading was reduced to about 20 kA once the EEC was introduced to the setup. For example, In the case of Figure 5 plot, the peak current was 18.7 kA. Thus the impedance value of the EEC basket should also be around 500mΩ, which is quite a low value compared to the behavior of natural soil under impulse conditions.

VIII. CONCLUSION

Two experiments carried out using the prepared mixture reveal a high conductive nature of the selected EEC specifically for impulse voltages. On the other hand, the steady state resistance of the sample was in the MΩ range. Compared to soil the selected material demonstrates different characteristics when exposed to lightning impulses. From experiment 1 or from 2, V-I curves does not show any distinctive point of electrical breakdown as normally seen in soil breakdown curves. However, a sudden drop in the impedance; change of state from non-conducting to highly conducting material characteristics are evident both at the beginning of the discharge and to the end of it.

Calculated minimum impedance of the test sample shows a decreasing trend of increasing peak voltage. However, this diminishing trend seems to saturate at higher peak voltages. Further increase of the charging voltage will have a smaller impact on reducing the impedance of the prepared basket. This phenomenon was evident for both positive and negative polarities.

From the second experiment, it was clearly observed that large currents such as 20 kA are being conducted through the test basket. A rough estimation of the impedance of the sample tested was calculated to be around 500 MΩ. A field experiments with comparatively larger quantities of EEC will provide additional information about EEC response for the conducting of fast transients in a natural setting.

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