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Comparative Performance of Impulsive Grounding Systems Embedded in Concrete: an Experiment in Reduced Scale

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***Abstract*—This paper presents a comparative study of impulsive grounding systems encased in concrete (namely UFER grounding). Several topologies used in transmission and distribution networks as well as in industrial plants were evaluated considering soils with different properties. Scale measurements (in an electrolytic tank with soil) were carried out in order to quantify the performance of this grounding system. The study discusses the performance of different grounding configurations: 1 rod; 2 rods; counterweight; cross and grid embedded in concrete. The results show that the use of UFER grounding can reduce significantly the value of the grounding impulsive impedance both in soils with low and high resistivity for the different evaluated configurations.**

Keywords-Grounding systems embedded in concrete, Measurement experiments, UFER.

I. INTRODUCTION

The main purpose of a grounding system is to provide means for dissipation of lightning generated electrical currents. Power systems reliability and the physical integrity are obtained with grounding systems proper design, thus grounding systems works as an important component for society protection and safety.

Over the past years various methods and techniques have been developed to improve the performance of lightning protection systems (LPS). One of these methods is to encase the grounding system in concrete (UFER grounding). This method was initially proposed and used by a Military Consultant, Herbert George Ufer, in World War II, aiming to reduce the grounding resistance in bomb storage vaults in high resistivity soils in the Arizona desert. Thus, the use of concrete-encased electrodes is a technique that has been used for over 70 years. H. G. Ufer concluded that metal encased in concrete performs as an effective grounding electrode, which constituted in a major breakthrough in grounding technology [1]. Practical experiments have demonstrated that concrete-encased metal rods have very important ground current capability, and that the corrosion rate of such rods is lower than that of rods directly in earth [2]. Initially, the aim of using grounding embedded in concrete was to reduce the value of grounding resistance in arid areas where traditional grounding methods were not capable of achieving values low enough to ensure safety and acceptable performance of the involved system. UFER was also applied in residential buildings in the early 60s [3].

Since then, different authors have explored the use of foundations as grounding systems, considering their advantages and disadvantages as part of the lightning protection system. The state-of-the-art in this field shows that this technique leads to an efficient and reliable performance for grounding systems, both in low frequency (short-circuit and steady state analysis) and in high frequency (impulsive and transient analysis) [4]-[7].

The low resistance obtained from the UFER, its ability to absorb moisture and the presence of charged carriers in the form of ions in the slightly alkaline concrete are some of the characteristics of this kind of grounding system which enables its application to withstand lightning impulses [8].

One of the shortcomings regarding the use of UFER is the lack of knowledge about the actual performance and behavior of this grounding system type related to the reduction of voltages and impedance on the electrode.

In this context, the goal of the paper is to present a study based on measurements in reduced scale grounding electrodes, which considers the main topologies used in the transmission and distribution networks as well as in industrial plants. The study take into consideration soil with into account soil with different properties, providing qualitative knowledge about the efficiency of different structures subjected to a representative impulse of lightning surge, with and without concrete.

II. GROUNDING ENCASED IN CONCRETE AND MODELS

The effectiveness of concrete as a uniform resistivity soil is due to its inherent alkaline composition and hygroscopic nature. This combination meets the two requirements of electrolyte conductivity: moisture and ion mobility. The concrete in the ground tends to absorb moisture from the soil and maintain high water content, a condition which explains the consistent low resistivity, even under desert soil conditions [1].

Still, an environment with the pH of cement provides corrosion protection. A good grounding electrode provides a permanent low resistance, which means it can resist corrosion, withstand electrical surges and resist breaking or disintegration, increasing the grounding system reliability.

Concrete is hygroscopic and when buried in soil, a concrete block behaves as a semiconducting medium with a resistivity of 30 Ωm to 200 Ωm depending on the moisture level [9]. Some further concrete characteristics include: the low resistance resulting from the concrete electrode's large area; its ability to absorb moisture; the presence of charge carriers in the form of ions in the slightly alkaline concrete and the pressure on the electrode developed by a building's weight. Experience with encapsulated electrode shows that it can withstand lightning impulses, and last indefinitely [8]-[10].

In this study, the performance of the UFER grounding systems is evaluated based on models in reduced scale. These models are made of welded bare copper conductors (solid profile BWF-B 4 (mm^2) / AWG 11). Fig. 1 shows the different grounding types in reduced scale: one grounding rod (1gr); two grounding rods (2gr), counterweight (ctw), cross and grid. The grounding models dimensions are presented in Table I.

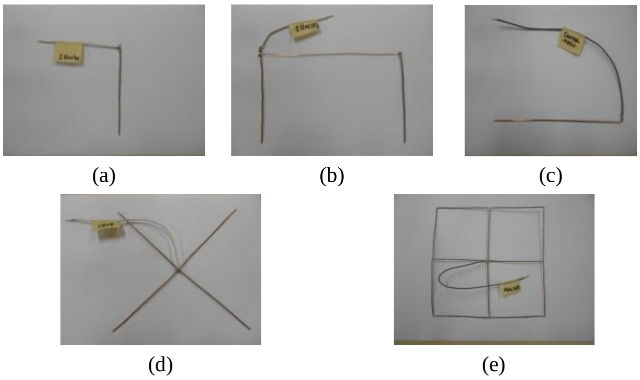

Figure 1. Different types of grounding in reduced scale: (a) 1gr, (b) 2gr, (c) ctw, (d) cross and (e) grid.

TABLE I. DIMENSIONS OF THE GROUNDINGS IN REDUCED SCALE.

Grounding Type	**1gr**	**2gr**	**ctw**	**cross**	**grid**
Length (m)	0.12	0.12	0.20	0.12	0.20
Span (m)	-	0.20	-	-	0.10

III. MEASUREMENTS PROCEDURES

The aim of this section is to present a methodology for evaluation of different types of grounding systems considered in the tests. In the measurements, an arbitrary function generator (model AFG3051), an oscilloscope (model DPO2014B), a current probe (model TCP0150) and a voltage passive probe (model TPP0200) are used to perform the tests. All the devices are Tektronix instruments.

Fig. 2 shows the metal tank filled with earth used in the tests. The tank is made of a steel sheet of approximately 4 mm thick and whose measures are: 1.5 m x 1.5 m x 0.2 m. Fig. 3 illustrates the measuring circuit and the involved devices.

The instruments (generator and oscilloscope) are connected to the different types of grounding, with the positive voltage probe tip (+) connected to the electrode and with the negative probe tip (-) connected to the metal tank (remote earth).

Figure 2. Metal tank with natural earth used in reduced-scale tests.

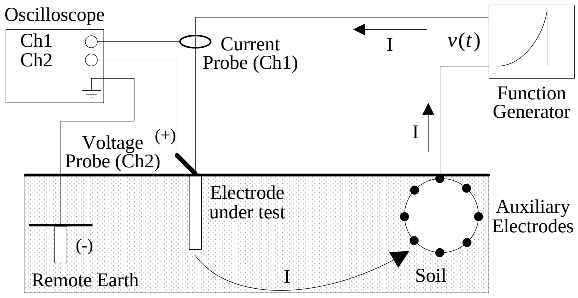

Figure 3. Measuring circuit and the equipment. Adapted from [11].

In order to establish the soil resistivity, measurements using the *Wenner's Four Electrode Method* [12] were carried out in accordance with Fig. 4.

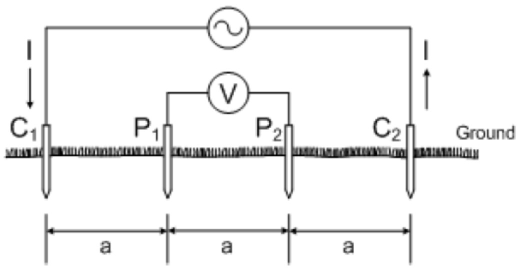

Figure 4. Wenner's Four Electrode Method.

A *MEGGER Earth Tester tool* (*Null Balance*) was used for this purpose. The rods used with the equipment ($4mm^2$) are made of copper and a span of a = 80 mm was considered. Eq. (1) can be used to calculate the soil resistivity,

$$\rho_{soil} = 2 \cdot \pi \cdot a \cdot R \tag{1}$$

where: ρ_{soil} is the resistivity of the soil (Ωm); a = the spacing distance between the electrodes (m) and R = resistance (Ω).

The effectiveness of an electrode depends not only on its size, but also on its geometry: its shape and orientation with respect to the earth's surface. In this experiment, the concrete is composed by a mixture of cement and water absorbed from moisture of soil.

The procedure to bury the horizontal UFER grounding (counterweight, cross and grid) is based on the following steps:

1. a trench of approximately D = 0.10 m deep, wide W = 0.025 m, length L = 0.015 m and with the shape in accordance with each type of grounding must be dug (see Fig. 5);
2. the grounding should be placed in the center of the trench;
3. the concrete must be poured over the wire. The dry concrete will shape up, staying thicker near the center. The wire must then be lifted slightly so that it is completely enclosed;
4. the soil must be covered carefully so as not to displace the concrete and it must be tamped down slightly;
5. the trench must then be backfilled with earth and tamped.

In the case of the test considering conventional grounding (without concrete), steps 3 and 4 must be skipped.

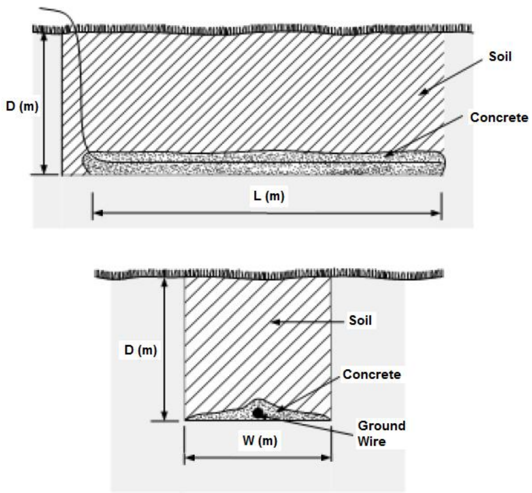

Figure 5. Horizontal installation.

The procedure to bury a vertical UFER grounding rod (1gr) and 2 grounding rods (2gr) is based on the following steps:

1. a 0.02 m diameter hole for the rod must be augured, using Fig. 6 to determine the depth. The depth should be equal to the rod length, in this case L = 0.12 m;
2. the rod must be centered in the hole;
3. the rod then must be backfilled with concrete;
4. top of the rod and tamp must be backfilled with soil.

In the case of the test considering conventional grounding (without concrete), step 3 must be skipped.

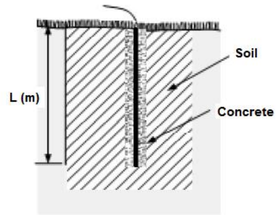

Figure 6. Vertical rod installation.

The waveform was parameterized and generated through software (Tektronix *ArbExpress*) and then transferred to the generator. The impulse voltage and current were measured by the oscilloscope. To represent the lightning wave shape, a double exponential function was used in accordance with (2),

$$v(t) = V_{peak} \cdot (e^{-\alpha t} - e^{-\beta t}) \quad (2)$$

where: $v(t)$ is the voltage impulse (V); V_{peak} is the peak voltage of the impulse (V); α is the inverse of the half time of peak value (s^{-1}); β is the inverse of rise time (s^{-1}).

A double exponential voltage impulse 5V (8 x 20) μs, was considered. The value of the amplitude of the injected current was measured with a current clamp in order to calculate the grounding impedance and subsequently compare the variations of different types of grounding in test.

Wave and data recording parameters can be set in *ArbExpress* generator software. Some of the relevant parameters considered in the tests were: 5 V peak to peak amplitude, α = 8 μs and β = 20 μs; length of the signal = 40k points; total time 160 μs and sampling rate = 250 S/s.

Electrical quantities values were selected according to local security aspects. High current values are inadequate to laboratory security criteria in the reduced scale experiment. Wave-form characteristics were set as recommended in [13]-[14].

Concrete resistivity might vary with voltage, temperature, humidity and time [15]. For this reason, all measurements were made at the same site on the same day in the same time interval. Thus, the behavior and variations of impulsive impedance of the different types of groundings in reduced scale can be accurately evaluated.

IV. MEASUREMENTS RESULTS

This section presents the results of the measurements obtained from the different tests performed to evaluate all types of analyzed grounding configurations (1gr, 2gr, ctw, cross and grid). Measurement data were analyzed with *MatLab* software. Based on the voltage and currents obtained, the impulsive grounding impedance can be estimated using (3),

$$Z_0 = \frac{V_{Max}}{I_{Max}} \quad (3)$$

where: Z_0 is the impulsive grounding impedance (Ω); V_{Max} is the maximum amplitude of the injected voltage (V); and I_{Max} is the maximum amplitude of the injected current (mA).

Two different soils were evaluated: low resistivity soil (55 Ωm) and high resistivity soil (5000 Ωm). Fig. 7 and Fig. 8 present the voltage and current curves to a soil with 55 Ωm for 1gr and 1gr UFER respectively. Based on the maximum value of the voltage and current, the impulsive grounding impedance for each type of grounding configuration can be obtained according to (3).

Fig. 8 shows the current signal, where it can be seen that it reaches its peak value before the voltage achieves its maximum value. The change of polarity can also be observed, a phenomenon that can be interpreted as a reflection of nonlinear behavior of the grounding. In other words, this phenomenon can also be interpreted as the predominance of capacitive grounding behavior: the current is advanced in relation to the injected voltage producing an energy saving effect when the current changes its polarity.

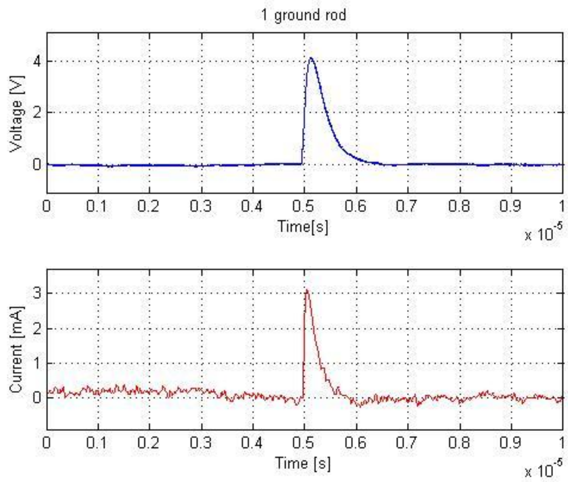

Figure 7. Waveform obtained from grounding 1gr type for a soil with ρ_{soil} = 55 Ωm (V_{Max} = 4.14 V, I_{Max} = 3.11 mA, Z_0 = 1327 Ω).

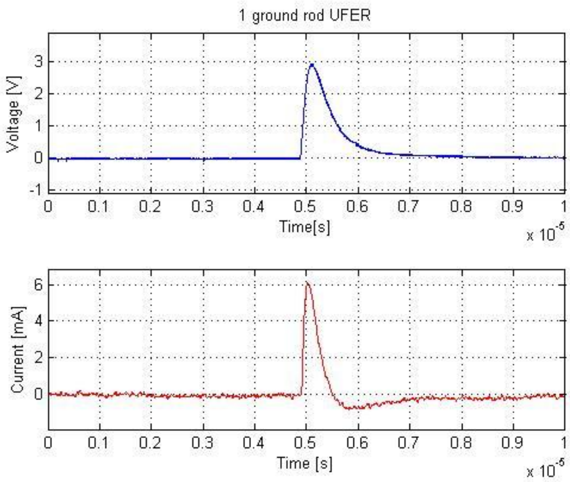

Figure 8. Waveform obtained from grounding 1gr UFER type for a soil with ρ_{soil} = 55 Ωm (V_{Max} = 2.90 V, I_{Max} = 6.10 mA, Z_0 = 474.79 Ω).

Table II and Fig. 9 present a summary of the results considering all the grounding configurations analyzed for a soil resistivity of 55 Ωm. The table shows the impulsive grounding impedance, the relation between conventional and UFER grounding and the percentage of impedance reduction.

Based on Table II and Fig. 9, an expressive reduction in the impulsive grounding impedance can be observed, especially in the case of 1gr. Depending on the grounding configuration, the reduction can range from 23% to 180% considering the use of grounding encapsulated in concrete.

TABLE II. CHARACTERISTICS OF THE GROUNDING IMPEDANCE ρ_{soil} = 55 Ωm

Grounding Type	Z_0 (Ω)	Conv./UFER	Reduction of Z_0 (%)
1gr	1327	2.80	180
1gr UFER	475		
ctw	1327	2.80	180
ctw UFER	475		
2gr	645	1.68	68
2gr UFER	385		
cross	667	1.71	71
cross UFER	390		
grid	561	1.39	39
grid UFER	404		

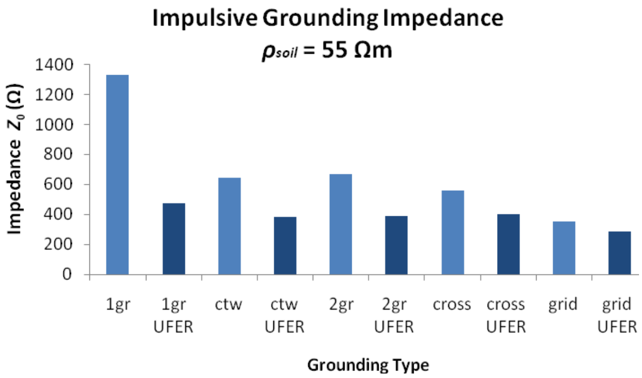

Figure 9. Comparison of different impulsive grounding impedance ρ_{soil} = 55 Ωm.

Table III and Fig. 10 present test results summary of the reduced-scale grounding configurations, but this time considering a high resistivity soil (5000 Ωm). The figures for impulsive grounding impedance, the relation between the two types of grounding and the percentage of impedance reduction can also be observed.

Differently from the case of soil with low resistivity, in the high resistivity soil case the maximum reduction was observed in the grounding grid configuration. Fig. 10 presents a comparison of the impulsive grounding impedance for all the analyzed cases.

TABLE III. CHARACTERISTICS OF THE GROUNDING IMPEDANCE ρ_{soil} = 5000 Ωm

Grounding Type	Z_0 (Ω)	Conv./UFER	Reduction of Z_0 (%)
1gr	2324	1.10	10
1gr UFER	2113		
ctw	1841	1.14	14
ctw UFER	1615		
2gr	1910	1.25	25
2gr UFER	1529		
cross	1487	1.12	12
cross UFER	1330		
grid	1120	1.32	32
grid UFER	849		

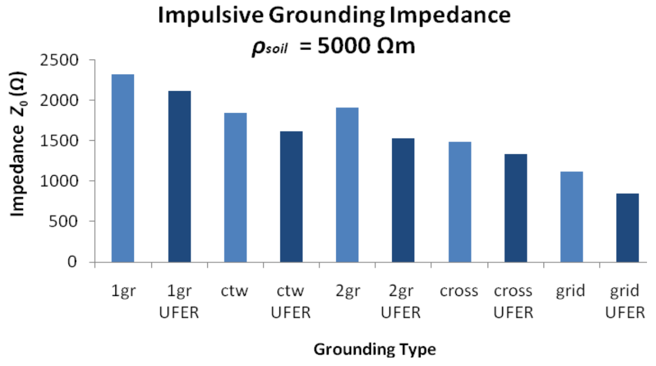

Figure 10. Comparison of different impulsive grounding impedance ρ_{soil} = 5000 Ωm.

According to Table II, Table III and their corresponding figures, it can be observed that when using grounding embedded in concrete, the impedances decrease for all evaluated soils and grounding configurations.

Fig. 11 and Fig. 12 show a summary of the results of all the tests mentioned before.

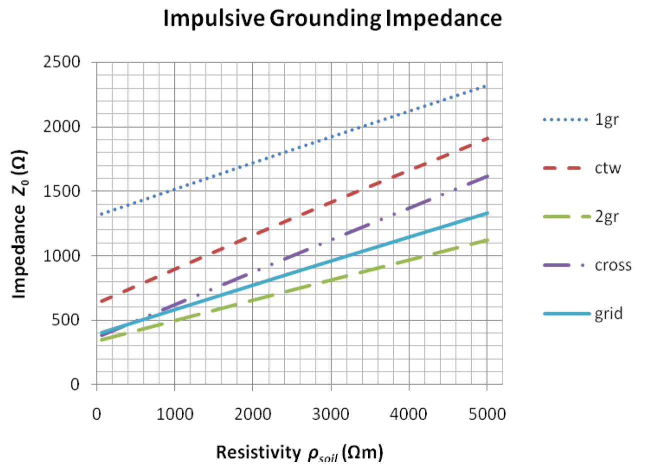

Figure 11. Impulsive grounding impedance Z_0 x resistivity (conventional grounding).

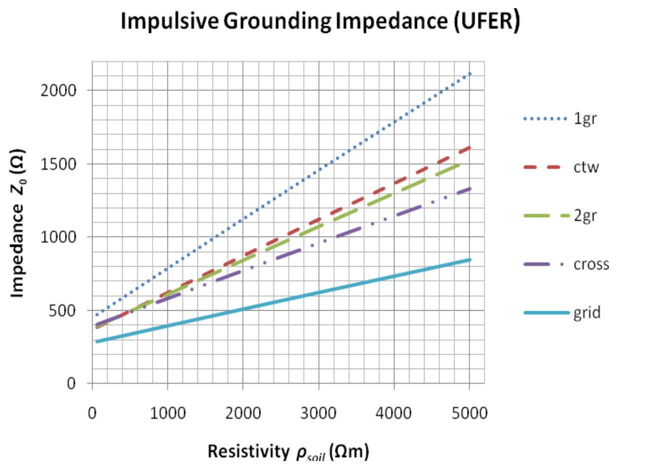

Figure 12. Impulsive grounding impedance Z_0 x resistivity (UFER grounding).

According to Fig. 11 and Fig. 12, it can be seen that for low soil resistivity (55 Ωm) the impulsive grounding impedance is more concentrated. For high values of soil resistivity (5000 Ωm) the grounding impedance is more dispersed. For the two cases analyzed (conventional grounding and grounding embedded in concrete), the highest impedance corresponds to 1gr and the lowest impedance corresponds to the grounding grid type. These observations can be made based on a trend (straight-line equation).

The following system of equations (4) and (5) represent the behavior of the impulsive grounding impedances as a function of the soil resistivity considering the experiments. However, further investigation must be done in order to verify the generality of the observed trend to be used as a reference to configurations with different lengths. Additionally, the effect of the conductor radius should be evaluated.

$$\begin{aligned} Z_{1gr} &= 0.20\rho_{soil} + 1319 \\ Z_{ctw} &= 0.25\rho_{soil} + 638 \\ Z_{2gr} &= 0.23\rho_{soil} + 340 \\ Z_{cross} &= 0.25\rho_{soil} + 374 \\ Z_{grid} &= 0.19\rho_{soil} + 396 \end{aligned} \quad (4)$$

$$\begin{aligned} Z_{1grUFER} &= 0.33\rho_{soil} + 461 \\ Z_{ctwUFER} &= 0.25\rho_{soil} + 374 \\ Z_{2grUFER} &= 0.23\rho_{soil} + 381 \\ Z_{crossUFER} &= 0.19\rho_{soil} + 396 \\ Z_{gridUFER} &= 0.21\rho_{soil} + 277 \end{aligned} \quad (5)$$

where: ρ_{soil} is the soil resistivity (Ωm) and Z_0 is the impulsive grounding impedance (Ω).

V. CONCLUSIONS

This paper presents a reduced scale grounding systems performance evaluation. Special attention is given to embedded in concrete grounding systems (UFER). This component is important both for personal safety and for power systems reliability. In this context, obtaining low values of impulsive grounding impedance is highly desirable. The magnitude of the impedance is one of the main technical parameters to ensure the efficient performance of the lightning protection system (LPS). Therefore, grounding embedded in concrete can be used for this purpose.

In this work, the impedance behavior of the grounding encased in concrete was obtained based using reduced-scale models associated with measurement experiments. The results have shown that grounding systems embedded in concrete reduces significantly the value of the grounding impedance.

The dielectric characteristics and the high conductivity of concrete can be applied so as to improve the performance of the LPS. Test results show that grounding systems embedded in concrete can reduce both the contact resistance between the grounding and the soil and the resistance to leakage current to the earth.

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