CHARACTERISTICS OF EARTHING SYSTEMS UNDER LIGHTNING SURGES

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ABSTRACT

Overvoltage protective devices such as surge arresters and protective gaps are used to divert high lightning surges from line to earth through an earth electrode. An effective design of earthing systems is therefore important to dissipate fault current to earth effectively regardless of the type of fault. The characteristics of earthing systems at power frequency, low-voltage and low-current magnitudes have been extensively researched and fairly well understood. However, the behaviour of earthing systems under transient conditions is still not fully clarified. This paper is to provide a better understanding of the characteristics of earthing systems under lightning impulse, as well as to present an informative review on previous work on soil ionisation phenomena under high impulse currents.

Keywords: *Earthing Systems, High Impulse Currents, Soil Ionisation Phenomena*

1. INTRODUCTION

Ideally, the earthing system should be designed with 'zero impedance' to provide effective discharge of fault currents and to avoid the potential rise at and around the substation. However, in practice, 'zero impedance' could never be achieved. British and American Standards: BS 7430-1998 [1], ANSI/IEEE Std 81-1983 [2], IEEE Std. 142-1991 [3], IEEE Std. 80-2000 [4] have outlined the design, measurement and testing of earthing systems impedance, methods for installing the earth electrodes, and useful data on soil resistivity of earthing systems at power frequency voltages and low-level conduction currents in the soil. However, it has been known from previous studies [5-20] that the response of earthing systems to impulsive lightning current may be quite different from power frequency currents, where 'non-linear' soil behaviour would occur.

This paper is to present a useful review for researchers in the earthing systems, and to understand why and how the earthing systems behave nonlinearly under high impulse currents. Also from the knowledge of previous work, further analysis can be identified, and new work on this nonlinear earthing characteristic topic can be addressed. In addition, this review reveals that despite of much research work presented in previous years, the study on the soil characteristics under high impulse currents still require further investigation.

2. NON-LINEAR SOIL BEHAVIOUR

Two main observations were made by previous authors [5-20] to explain the non-linear soil behaviour;

i) v-i curves form 'loops' due to differences in front and decay times between voltage and current traces (see Figure 1a),
ii) reduction in earth resistance from its steady-state value and its decrease with current magnitude (see Figure 1b).

It was found from published work [5-20] that the resistance of an earthing system has the most significant non-linear voltage-current characteristics compared with other elements; capacitance or inductance elements. In recent years, there have been many reported studies [5-20] of non-linear soil behaviour under high impulse currents, and this non-linear soil behaviour under high currents was found to be dependent on a number of factors, such as: soil properties, electrode dimensions, current front times and impulse polarity.

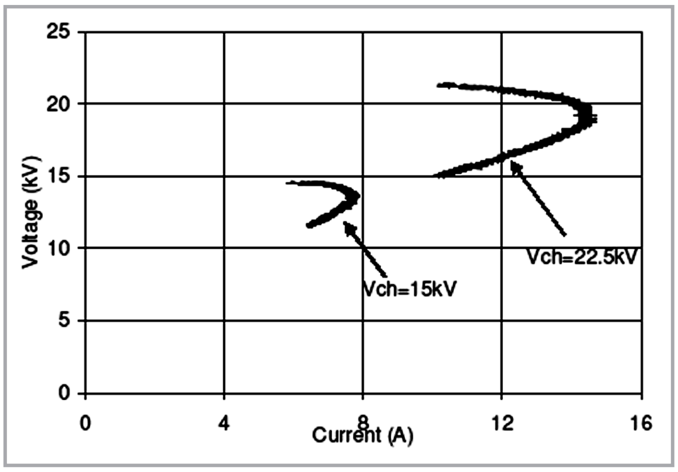

Figure 1a: V-i curves form loops at different charging voltages (reproduced from Mohamad Nor [5]).

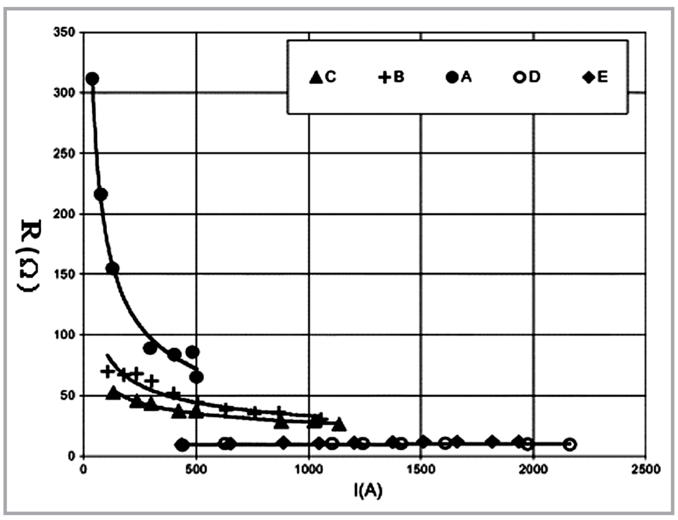

Figure 1b: Reduction in earth resistance from its steady-state value and its decrease with current magnitudes (reproduced from Mohamad Nor et al [6]).

Two main conduction processes have been suggested to cause non-linear soil behaviour under high current; a thermal process and an ionisation process. These discharge processes in soil are also discussed in this present paper.

3. EARLY STUDIES ON EARTH ELECTRODES UNDER HIGH CURRENTS

As early as the 19th century, it was thought that soil would behave nonlinearly when subjected to high transient currents. However, no study has been reported nor published until 1928, when Towne [8] published his paper on the impulse tests injected on three types of test loads; water tube resistances, galvanised-iron pipe electrodes, and a surge arrester in series with the earth electrodes.

Discharge currents of $20\mu s$ to $30\mu s$ rise-time with peak currents of up to 1500A were used. It was found that the v-i curve of the water tube is linear for increasing currents. However, for the case of the surge arrester in series with the earth rod electrode, the v-i curves were found to form 'loops' and the resistances under these impulse conditions were found to be lower than the 60-cycle values, which shows the non-linearity in soil behaviour. This new finding has motivated a number of studies and within a short period, many more improved test and analytical techniques were conducted in order to obtain a better understanding of the subject. The studies were based on field and laboratory measurements and using computational methods for determining the performance of earth electrodes.

4. TESTS ON EARTH ELECTRODES

The approaches to identify the non-linear behaviour can be divided into three categories; field tests, laboratory tests and computational methods. These investigations not only contribute to the study of soil behaviour, but also confirm the validity of the techniques.

4.1 Field Tests

A number of impulse investigations on soils have been performed in at field sites [5-20]. The studies were classified according to the type of earth electrode: vertical rods, horizontal electrodes and the mesh and other special electrodes. The type selected may depend on the type of soil encountered and the available depth or area available. Generally, a number of significant observations were made:

a) The impulse resistances were found to decrease with current magnitudes and lower magnitudes than the 60Hz earth resistance. The study has shown the effects of impulse currents on earthing systems.

b) The degree of reduction of impulse resistance, which is determined by the ratio of impulse resistance to 60-cycle resistance, is dependent on the type of soil and arrangement of the electrodes, but independent of the current rise time.

c) The study confirmed that there is only a small reduction of impulse impedance for an electrode of lower AC earth resistances.

d) Another finding is that the lower impulse coefficient of earthing systems in higher resistivity soils was observed.

e) Some studies [9-10] observed that the earth impedance increases under transient voltages, which could be due to inductive effects caused by the electrodes.

4.1.1 Horizontal Earth Electrodes

They are normally buried at smaller depths than vertical rods, and usually are installed near the surface when sand or bedrock is encountered.

A few observations from previous work using these configurations are:

a) Bewley [11] observed that under high impulse conditions, the earth resistance can be reduced even at low currents, less than 150A

b) The lower the AC earth resistance of the grid (with larger dimension), the lower the current-dependent characteristics of earth resistance during the passage of high currents, which is similar to the results obtained in section 3.1 in which the earth resistance current-dependence during the passage of high currents was found to be related to the DC earth resistance R_{DC} value.

4.1.2 Vertical Earth Electrodes

Similarly to the horizontal electrodes, soil ionisation contributes towards the reduction of the earth resistance of horizontal electrodes. This nonlinear effect is found to be dependent on the current density which is determined by the soil resistivity and dimension of earth electrode.

4.1.3 Mesh Electrodes and Other Practical Geometries of Earth Electrodes

The results from these studies indicated that the lower the steady state resistance, the lower the nonlinearity effects, which are similar to that presented in sections 3.1.1 and 3.1.2.

From these findings, it can be concluded that the degree of ionisation in soils is dependent upon the R_{DC} value; the lower R_{DC}, the lower the ionisation effect on the earthing system under high impulse currents, thus the impulse resistance becomes less dependent on current magnitudes. This can be explained by the simple relationship between electric field, E, and current density, J, $E=\rho J$, where ρ is the soil resistivity. The threshold ionisation field, E_{th} will require higher current densities for soils with low resistivity. However, in some field studies, even though the earthing system has a low R_{DC} and produces high current magnitudes, low current density could be obtained due to an extensive electrode dimension, which consequently reduces the electric field to be less than E_{th}.

4.2 Laboratory Tests on Earth Electrode Systems

This review is to examine closely the laboratory tests that are conducted to study soil ionisation effects. Typical test cells used in high voltage laboratory conditions by previous authors in investigating soil behaviour under high currents are: hemispherical and cylindrical test cells.

The observations from this work are:

a) A reduction in earth resistance was observed, indicates the nonlinearity in soil.

b) The effect of rise times on earth resistance are similar to those published by Liew and Darveniza [12] where the resistances were found to be higher for shorter rise times. However, Cotton [13], Loboda and Scuka [14] and Bellaschi et al. [15] found that soil behaviour is not affected by rise times of current.

4.3 Computational Modelling and Equivalent Circuits of Earthing Systems

The computer earth analysis techniques not only help to verify the field and laboratory tests, but also contribute to a better understanding of soil behaviour and provide detailed analysis of soil parameters effects. The published work of earthing systems including the soil ionisation phenomenon using computational method is summarised here:

a) Velazquez and Mukhedkar [18] found that the effect of capacitance becomes pronounced only when the soil resistivity is higher than 1000Ωm.

b) Mohamad Nor et al. [7] and Kosztaluk et al. [16] proposed an equivalent circuit consisting of a linear inductance in series with parallel network of the nonlinear resistance and the capacitance, where it was simulated using PSPICE circuit transient analysis program. The simulated voltage and current traces are found to be in agreement with measured values.

c) Mazzetti and Veca [19], Nixon et al. [20], Chisholm and Janischewskyj [17] proposed lumped R-L-C components of a transmission line model where each parameter was derived from the dimensions of electrodes and soil properties.

d) Liew and Darveniza [12] and Geri et al. [9] represented the nonlinear soil resistivity parameter as a function of time and the radius of the electrode.

The mathematical analyses and computational techniques not only provide the equivalent circuit representation of the earthing systems under impulse conditions, but also provide the critical electric field value (E_{th}) and prediction of lightning. This shows that a better understanding of soil behaviour and detailed analysis of soil parameters effects can also be obtained from the computational study.

5. SOIL CONDUCTION MECHANISMS

Two main conduction processes have been advanced as the processes which occur in soil: thermal and ionisation processes. However, these processes are still not well understood to fully explain the breakdown in soil. A number of related studies have been conducted to explore the effects of these processes in terms of soil breakdown [21-25].

5.1 Thermal Heating in Soil

During this process, the current is conducted by water filled paths. Due to heating in the soil, the temperature of the water increases, which increases its conductivity and reduces the resistivity of the bulk soil. Thus, there is an increase in current magnitude and a relative reduction in resistance. The thermal process in soils could also be enhanced by ionic conduction depending on the amount of water, types of salts and composites that exist in the soil, as described by Schon [26].

In some cases, however, excessive heating might occur, and could lead to water vaporisation, as suggested by Snowden and Erler [21] and Snowden and van Lint [22]. This vaporisation can lead to a reduction in conductivity, and hence, an increase in the resistivity of the soil, thus, increasing the soil resistance. Therefore, it could be expected that if the soil conduction mechanism is governed by thermal processes, the resistance of the earth electrode could either increase or decrease with current depending on the total amount of energy absorbed by the earthing system.

From all of these tests and findings, it is worth noting that the heating process has a role in the occurrence of soil breakdown.

5.2 Soil Ionisation

Most published investigations assumed that soil breakdown is due to soil ionisation. In this section, soil ionisation breakdown phenomena are reviewed. Numerous tests have been conducted to suggest that the measured nonlinear conduction and breakdown phenomena are a consequences of soil ionisation [23-24]. This mechanism was often described as being due to field enhancement in voids enclosed within the soil. When Snowden et al. [25] measured a relative dielectric constant of wet soil with an AC parallel plate test, they found that for sand with 4% of water content, the relative dielectric constant can be as high as 1000 at 50Hz, and is highly dependent on frequency. It was further verified by Visacro and Portela [27] who found that the dielectric constant of wet soils can be as high as several millions at 50Hz but reduces to only several tens at 1MHz. Due to the large dielectric difference between wet soil and air voids, it would therefore be possible for the electric field inside the air voids to be enhanced and, under high enough fields, the ionisation process in air voids would occur.

From these investigations, the nonlinear soil behaviour under high impulse currents can be described to be due to the ionisation process in the soil and some other possible thermal processes.

6. FUTURE RESEARCH STUDIES

This paper presents an extensive review of soil ionisation under impulse conditions. The studies from previous work are presented, reviewed and discussed in this paper in order to obtain a better understanding of the non-linearity in soil under high impulse conditions. Previous work have shown a number of observations which can lead to some of the future research:

a) It has been observed in some studies that the degree of non-linearity of the soil is dependent on the current density which is determined by the soil resistivity and the electrode length. It is therefore worth while to look into a correlation between the degree of non-linearity of earthing and current density of earthing systems by conducting the tests on practical earthing systems using both low-magnitude ac test and high-magnitude impulse application.

b) Some studies have shown that the rise time were influenced by soil resistivity and applied field, thus it is worth to see the correlation on the current rise time with the ionisation effect.

c) From the review of previous work, no concluding results were obtained in the literature on the effects of current rise time, sand type and grain sizes and electrode dimensions on the earthing systems characteristics. Further studies will help clarify and quantify this effect. The effect of impulse current rise time, impulse polarity, sand grain sizes and electrode dimensions on the earthing system characteristics also requires further investigations.

d) A number of E_{th} values have been proposed in the literature. In the future, a more accurate E_{th} value may be obtained.

By including the 'non-linear' effect of soil under high currents, more accurate modelling of protective devices and their performance could be achieved. In addition, consideration of the ionisation process can help the optimum design of earthing systems. ■

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PROFILE

Normiza Mohamad Nor received her degree with First Class Honours in Electrical and Electronic Engineering from University of Wales, College of Cardiff, UK in 1996. She obtained the Ph. D degree in Electrical Engineering from the same university, in 2001. She became a research fellow for almost a year to Telekom Research and Development Sdn Bhd to advise on the earthing systems under high impulse currents. She has also delivered a seminar on the earthing systems and protection to the technical staff of Malaysia Airport Berhad. She has so far published 20 international journals and conferences. She is currently a Lecturer of Electrical Engineering at the Multimedia University, Malaysia. Her research interests include high voltage, earthing systems and lightning protection.