Characterisation of soil ionization under fast impulse

M.A.Abdallah
Electric Eng. Dept., Alexandria University, Alexandria Egypt
S.Srisakot and N.M.Nor
Cardiff University, Wales, UK

The response of earthing system to fast surges is very important to the control of power system overvoltage and can also affect the protective levels of surge arresters . When the surge current is high, the earthing system attains very high potentials . Consequently, electric fields of high sufficient magnitudes are generated in the soil medium causing ionisation and temperature variations. This paper describes a laboratory experiment in which voltage surge up to 30 kV is used to test homogenous soils with controlled moisture contents. A hemispherical test cell is used to facilitate field computations and analysis of results. Three distinct conduction regions are identified during the impulse tests of the soil; i) the non-linear regime, ii) the ionisation regime and iii) the breakdown regime. The threshold of ionisation is determined from the current impulse records and the breakdown voltage from statistical testing according to IEC-60 [1]. A computer programme is then used to derive the corresponding threshold electric field for ionisation.

إن لمدى استجابة نظام التأريض للموجات العابرة السريعة أهمية كبيرة في التحكم في الارتفاع المفاجئ للجهد على نظام التأريض في نظم القوى الكهربية, كما يحدد مواصفات أجهزة الحماية اللازمة. وارتفاع تيار الموجات العبرة يؤدى إلى ارتفاع في هد نظام التأريض مما يؤدى إلى ارتفاع المجال الكهربي في التربة المحيطة بنظام التأريض وبالتالي تأينها وارتفاع درجة حرارتها. وفى هذا البحث نقدم نتائج اختبارات معملية على تأثير هذه الموجات على نظام التأريض في ظل وجود تربة متجانسة مع التحكم في درجة رطوبة التربة. ومن النتائج يتضح أن التيارات آلتي تمتص في التربة نتيجة الموجات العابرة السريعة تتكون من ثلاث مراحل متتالية هي: المرحلة الغير خطية ثم مرحلة التأين فمرحلة الانهيار. ولقد تمت التجارب وفقا للمواصفات العالمية(IEC-60) . وكذلك تم تحليل المجالات الكهربية الأرضية باستخدام برنامج كمبيوتر (Boundary Element Software).

Keywords: Soil Ionisation, Earthing system, Fast transient, Overvoltage

1. Introduction

Protective devices such as spark gaps and surge arresters are used to divert surges to earth. The correct design of the earthing system and a better understanding of its performance under fault current conditions are therefore important. The distribution of the discharged current into the earthing system is affected by both the electrode geometry and the soil properties. It is now well known that highly non-linear behaviour is exhibited by earthing system under high current discharge [2]. This non-linearity has been attributed to two main electrical conduction processes; a) thermal effects due to high current and b) soil ionisation due to field enhancement in trapped air voids in the soil. These processes are still not understood [3]. The development of better equivalent circuit models for earthing system requires the evaluation of the thresholds and factors affecting the non-linear behaviour. The critical field (Ec), at which non-linear behaviour is initiated, has been investigated by many researchers [4,5]. Values ranging from 3 to 20 kV/cm have been reported. Leadon [6] reported that similar Ec values were measured for positive and negative impulses. This was further verified by Cebrera [7] for low resistivity of sand soil medium. Examination of the published literature revealed that equivalent circuit representations of earthing system, need to include the impulse response and soil ionisation effects.

In this paper, a laboratory hemispherical test rig is described. A fast impulse current generator was used to investigate the response of two grades of sand wetted with various water contents. Both positive and negative polarities have been used. Simulation of the geometry allowed accurate computation of per unit electric field magnitudes around the electrodes. The threshold critical electric field is determined from careful examination of the voltage and current records, and the computed per unit field. The breakdown voltage of the test cell is measured according to IEC-60.

2. Experimental work

2.1. Test set-up

The double exponential test circuit fig. 1. is capable of generating high voltage up to 50 kV and high current impulse up to 5kA. Three low inductance capacitors of 0.15 μF rated at 65 kV were arranged in parallel and connected to the DC charging unit with an output of up to 55 kV. A triggered SF6 spark gap is used for fast switching. A tail resistor of 21 kΩ and front resistor of 50Ω were chosen.

Current measurements were achieved with a commercially available current transformer of sensitivity 0.1V/A and a response time of 20 ns. A D-Dot probe system [8] with a ratio of 10300:1 and a response of 40 ns was used for voltage measurement. The voltage and current signals were captured on a Lecroy 9350A, 500 MHz Digital storage oscilloscope (DSO). The DSO was linked to a personal computer via a GPIB bus. Labview software was utilised for data acquisition and analysis.

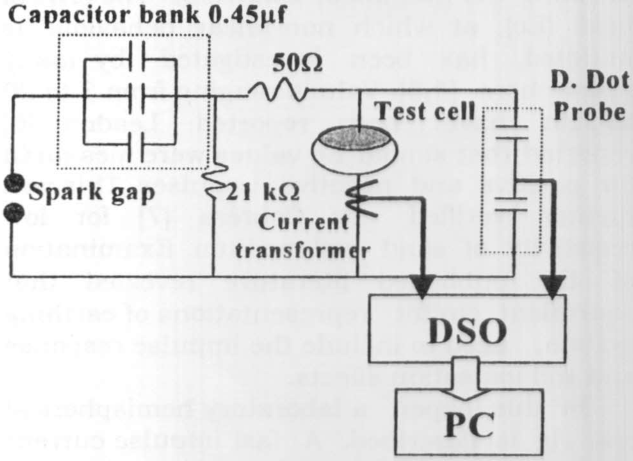

Fig. 1. Impulse current test circuit..

2.2. Test cell

The test cell consisted of a hemispherical container of 47.5 cm diameter. Connections for the current measurement are fixed on the cell circumference to ensure uniform distribution. The earth electrode consisted of another hemispherical electrode of 6.25cm diameter.

2.3. Soil preparation

Two grades of sand were used in these experiments, fine grain size of diameter 35 micron and medium grain size of diameter 75 micron. In this paper, only results for medium grains sizes are shown. Similar trends are observed for fine grain sand, but the resistance values are higher. Sand is chosen since it is easily wetted and dried without loss of properties. A sand mixer was used to ensure uniform wetting of the sand. The sand is then poured into the test container and compressed. The electrode is half buried in the sand to avoid sharp edges and air discharges. An oven was used for drying the sand prior to subsequent experiments. Sand samples with water content of 1%, 3%, 5%, 7% and 10% were used.

2.4. Test cell parameters

2.4.1. Field distribution

In order to compute the electric field distribution in the test cell, a boundary element software was used. fig. 2-a. shows the computed equipotentials for a soil with $\xi r=10$, $\rho=500$ Ωm when a voltage of 1kV is applied to the live electrode. As expected, the voltage gradient is highest nearest the live-electrode. Fig. 2-b. Shows the per-unit electric field which was used to determine the critical electric field magnitude corresponding to the ionisation inception voltage in sand.

2.4.2. Breakdown voltage

In order to determine the range of voltage and current magnitudes that could be used during the tests, the breakdown voltage of the test cell was measured for various water contents of sand. The up-and-down method recommended by IEC-60 was adopted. At least

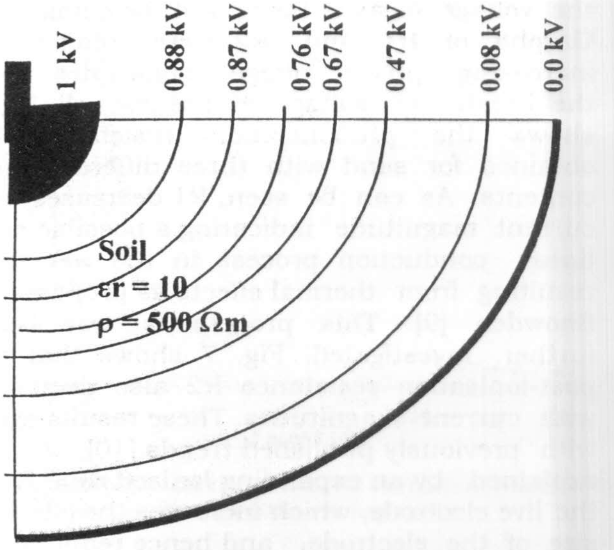

Fig. 2-a. Typical equipotential plot of the test rig (applied voltage 1kV).

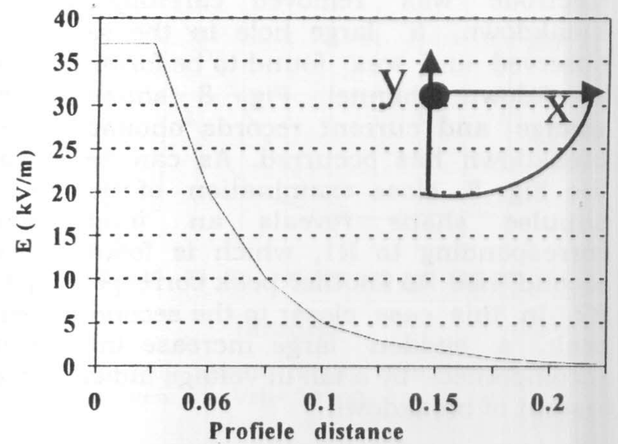

Fig. 2-b. Electric field profile along the electrode and soil surfaces.

20 shots were used to determine the U_{50}, for each water content in the sand. Fig. 3 shows the measured values of the U_{50} for various sand conditions. It can be seen that there is only a weak influence of water content (sand resistivity) on the U_{50} level in the range of water content studied. The average value of U_{50} obtained from these tests is 25.5 kV which corresponds to an electric field of 9.6 kV/cm at the live electrode surface.

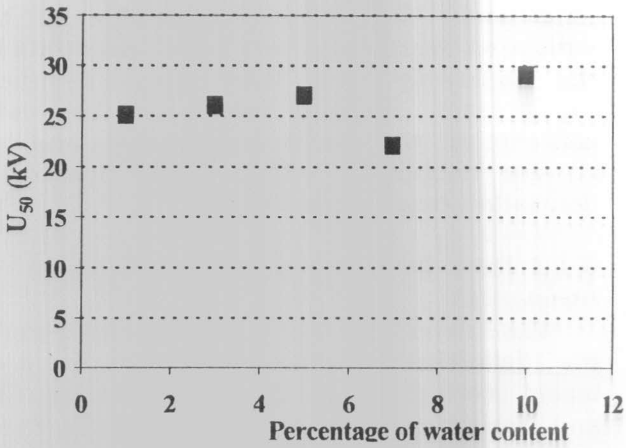

Fig. 3. Breakdown voltage for various water contents of the sand.

3. Investigation of soil ionisation under impulse conditions

Impulse tests with increasing current magnitudes have been conducted with both positive and negative polarities in order to determine the effect of ionisation on soil resistance.

3.1. Positive polarity tests

3.1.1. Current impulse shape observations

During these tests, it was found that at very low current magnitudes, the current impulse shape showed a very fast rise time with some initial oscillations, fig. 4. These initial oscillations are attributed to capacitance effects because when a resistive solution was used as a test medium, these effects were negligible. As the charging voltage was increased, higher current magnitudes were obtained. It was observed that above a threshold level, the current impulse shape exhibited a second peak while the voltage shape continued to decrease smoothly, fig. 5 Careful examination of the measured voltage and current traces revealed that this second current peak started to occur for applied voltages above 15kV. This corresponds to a critical electric field Ec=5.6kV/cm at the surface of the active electrode. This second peak was found to be initiated after about 20μs. Its corresponding rise-time was much slower (approximately 50μs). It is postulated that this second peak is caused by soil ionisation. The slow propagation of the ionisation within the wet sand accounts for the relatively long time delay. In these experiments, it was found that the water content of the sand (resistivity) and the current magnitude influence the time delay (ionisation propagation time).

3.1.2. Pre-ionisation and ionisation impulse resistances

The existence of two current peaks leads to the definition of two resistances for each tested configuration; the pre-ionisation (R1) and the post-ionisation resistance (R2). These resistances can be determined at the current maxima and their corresponding instantaneous voltages from:

$R_1 = V(\text{at } I_{peak1}) / I_{peak1} \quad R_2 = V(\text{at } I_{peak2}) / I_{peak2}$

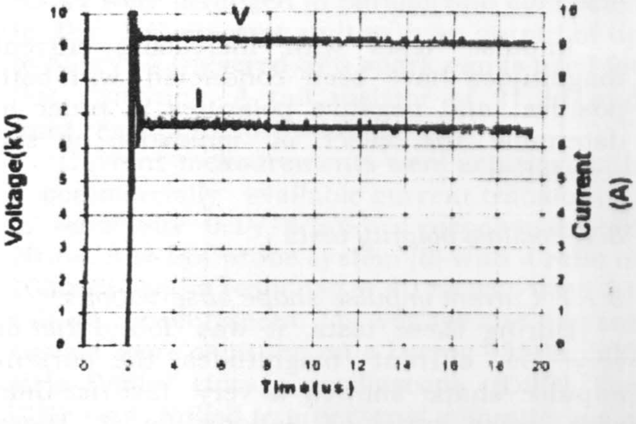

Fig. 4. Voltage and current records in the pre. Ionisation/non-linear region (water content 3% Vch=9kV).

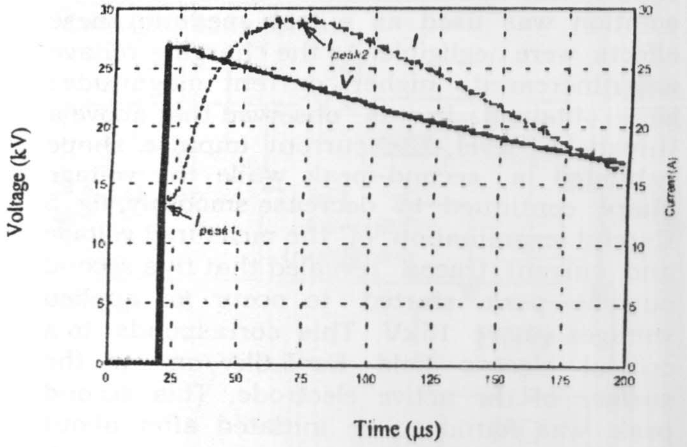

Fig.5 Voltage and current records in ionisation region (water content, wc=3%,V_{ch} = 27 kV.

In this way, any inductive component in the voltage measurement will be eliminated. Graphs of R1 and R2 were obtained for increasing applied voltage magnitudes up to the breakdown voltage of the test cell. Fig. 6 shows the pre-ionisation resistance R1 obtained for sand with three different water contents. As can be seen, R1 decreases with current magnitude indicating a possible non-linear conduction process in the wet sand resulting from thermal effects as proposed by Snowden [9]. This process is now being further investigated. Fig. 7 shows that the post-ionisation resistance R2 also decreases with current magnitudes. These results agree with previously published trends [10], and are explained by an expanding ionised zone, from the live electrode, which increases the effective size of the electrode, and hence reduces the resistance of the cell when one of the ionisation channel extends to reach the other electrode, a breakdown occurs. When the live electrode was removed carefully after a breakdown, a large hole in the sand was observed and was found to be formed by the breakdown channel. Fig. 8 shows typical voltage and current records obtained when breakdown has occurred. As can be seen in the Fig. 8, close examination of the current impulse shape reveals an initial peak corresponding to R1, which is followed by a second rise to another peak corresponding to R2. In this case, closer to the second current peak, a sudden large increase in current accompanied by a fall in voltage indicated the instant of breakdown.

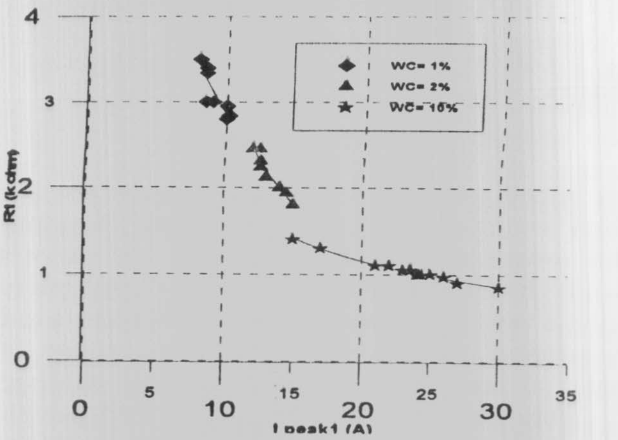

Fig. 6. Pre-ionization resistance, R1 vs. current (water contents wc=1%, 3% and 10%, +ve impulse).

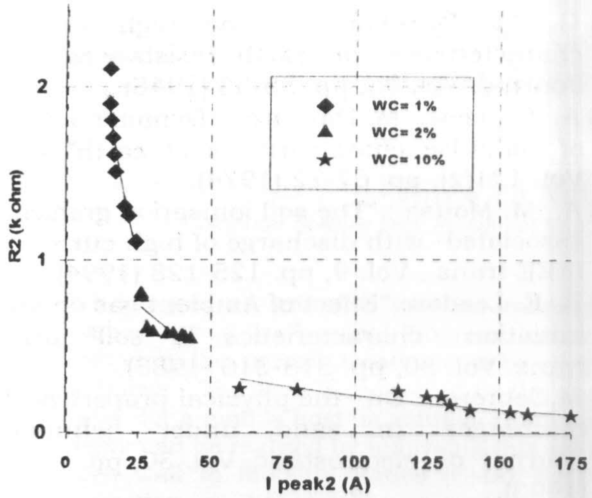

Fig. 7. Post-ionization resistance, R2 vs. current (water contents wc=1%, 3% and 10%, +ve impulse).

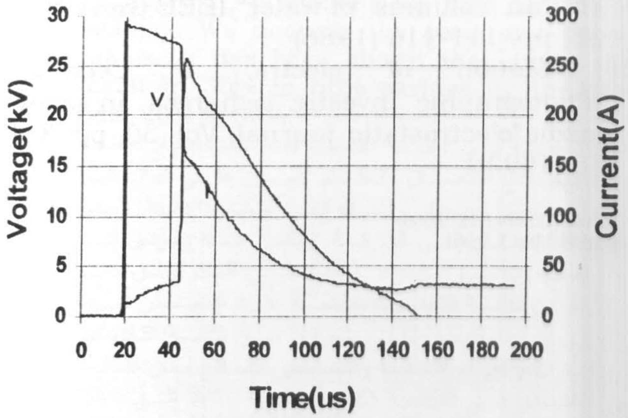

Fig. 8. Voltage and current records in the breakdown region (water content 3%, Vch= 29 kV).

3.2. Negative polarity tests

Tests with negative impulses were also conducted. Similar trends of current impulse shape were observed with increasing charging voltage of impulse generator. The calculated values of R1 and R2 for 5% water content are shown in Figs. 9-a. and 9-b. As can be seen, the two curves follow the same trend as for positive polarity.

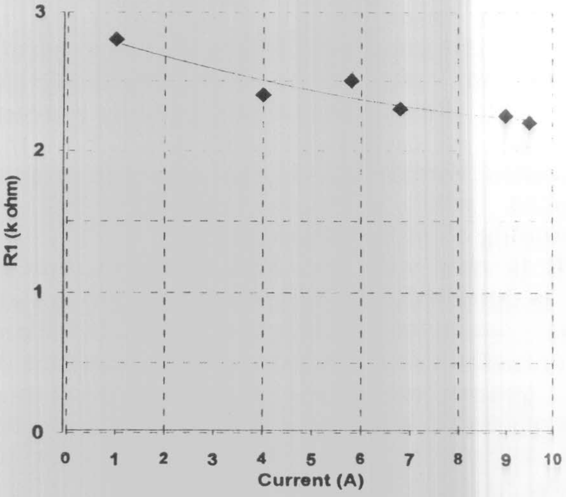

Fig. 9-a. Pre- ionization resistance, R1 vs. current (water contents wc=10%, negative impulse).

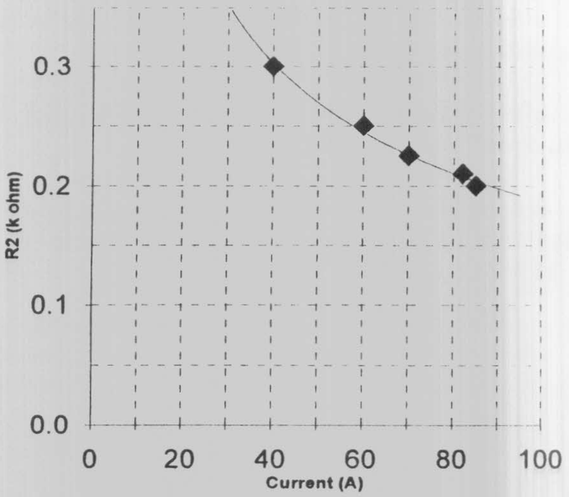

Fig. 9-b. Pre- ionization resistance, R1 vs. current (water contents wc=10%, negative impulse).

4. Conclusions

A laboratory earth electrode test set up is used to investigate the non-linear conduction process occurring in sand with different water contents. It was found that the effect of water content on the breakdown voltage of the cell is negligible in the range studied (1 - 10%). The critical electric field magnitude, above which ionisation is initiated, is estimated to be 5.6kV/cm and is independent of water content.

It was found that wet sand subjected to fast current impulses undergoes two separate conduction phases as the magnitude is increased. First, thermal effect due to current flow reduces the resistance, then above the ionisation threshold, the resistance is further reduced with a time constant due to expanding of ionisation regions.

It is now well accepted that ionisation in soil is initiated by field enhancement in air voids enclosed within the soil. Field enhancement is caused by irregular shapes of soil (grains/particles) and the difference between soil and void dielectric properties. This ionisation leads to the formation of several parallel streamers propagating away from the active electrode, the speed of propagation and final length of these streamers are closely dependent on the applied voltage.

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