# Modelling of soil ionisation under impulse surges

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In this work two models based on previously suggested interpretation of ionization process have been investigated: (a) an arc model in which the ionization is simulated as a partial arc extending from the electrode, and (b) a shell model in which the ionization region grows as a shell. Based on a simple electrode system, successive stages of the ionization process were characterized by determining the equivalent circuit components (R and C) using (I) a computer technique using boundary element software and (ii) a purpose built laboratory test rig implementing a physical representation of the ionization. High current impulse tests were also carried out to investigate the suitability of the models.

يقدم هذا البحث نموذجين لعملية التأين الكهربي للتربة المحيطة بنظام التأريض نتيجة تعرض النظام لموجات عابرة سريعة , وهما نموذج القوس الكهربي : وفية يتم تمثيل عملية التأين بقوس كهربي يمتد من سطح الإلكترود ويزداد طولا في إتجاة التربة. ونموذج القشرة : وفية يتم تمثيل عملية التأين بقشرة تحيط بسطح الإلكترود وتنمو ويزداد نصف قطرها في إتجاة التربة. وتم تمثيل الدائرة الكهربية المكافئة للتربة وتعتد على المقاومات والمكثفات. وتم مقارنة النتائج المعملية بنتائج تحليل المجال الكهربي باستخدام برنامج الكمبيوتر (Boundary Element software) لكل من النموذجين

**Keywords:** Earthing system, Lightning surges, Ionization process, Arc and Shell models

## 1. Introduction

Earthing systems are subjected to high magnitude currents generated by short circuit conditions, switching surges and lightning strikes. Switching and lightning overvoltage are normally limited by surge arresters resulting in high currents, which give rise to localized high potentials and electric fields. Above a threshold magnitude of the electric field, which is dependent on the medium and the electrode geometry, soil ionization is initiated.

Previous investigations and preliminary work conducted by the authors [1] have identified that ionization reduces the earth impedance of an earth electrode system. This earth impedance reduction, under high impulse current, is highly non-linear, and depends on the medium and geometry of the electrode [2,3]. Although soil ionization, due to electric field enhancement, has been identified as the main cause of earth impedance reduction [4], some findings suggest that thermal effects may also be present [5,6].

To understand the soil ionisation process, the threshold magnitude of electric field was determined experimentally for each type of soil (such as light clay, sand and loamy sand). Such experimental procedure is given in references [7,8]. Models describing the nature of the process have also been extensively investigated by many researchers. Petropoulos [9] "theory of the soil ionization model" is based on the existence of non uniform discharge around the electrode fig. 1-a. The non-uniformity is attributed to the non-homogeneity of the soil in practice. A simpler model fig. 1-b. which assumes the ionization zone to be uniform, was proposed by Liew [10]. However, Oettle [11] have shown that the ionization process in soil may not only be presented as uniform sparking zone around the earth electrode, but also as a streamer discharge at higher current levels fig. 1-c. This work investigates these proposed interpretations. In this paper, two simple models of the ionization process are considered (a) an arc model in which the ionization is simulated as a partial arc extending from the electrode and (b) a shell

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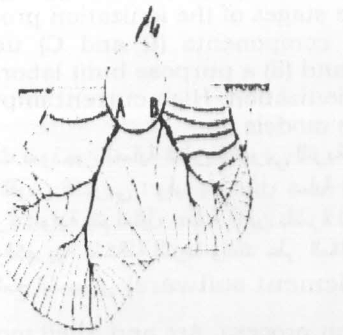
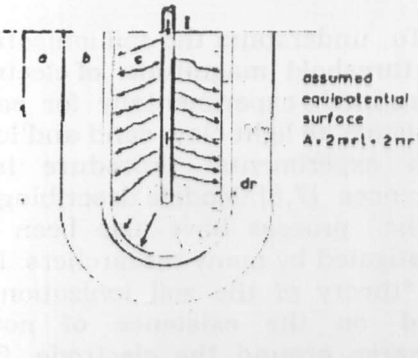
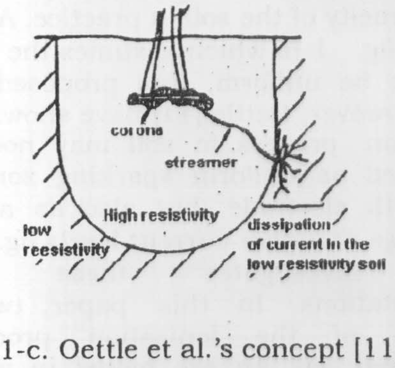
model in which the ionization region grows as a shell. The successive stages of the ionization extending process are represented by increasing arc length and increasing shell size respectively in a computer technique using boundary element software. The computation is, then verified with a purpose built laboratory test rig using simple electrode systems to simulate the two proposed ionization mechanisms. Finally, the predicated results are compared with impulse tests in order to assess the validity of the models.



1-a. Petropoulos' concept [9].



1-b. Liew et al.'s concept [10].



1-c. Oettle et al.'s concept [11].

Fig. 1. Shapes of ionization process proposed by various researchers.

## 2. Proposed models

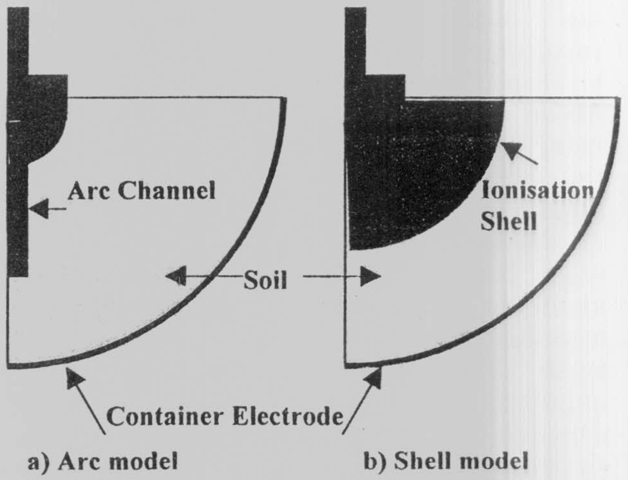
In order to assess the merits of the two models, a simple geometry approach is developed. The system consists of two hemispherical electrodes between which a soil medium is contained. The container electrode is 47.5 cm diameter and the live electrode which is connected to the high voltage terminal of the generator is 6.5 cm diameter.

### 2.1. The arc model

In this model, we assume that ionization is represented by a single arc channel extending from the live electrode towards the low voltage container electrode. This propagating arc channel is simulated as a 2 mm diameter conductor of increasing length [4]. Fig. 2-a. shows a schematic diagram of the model.

### 2.2. The shell model

In this model, we assume that the ionization region has a shell shape bound by an equipotential surface. The shell expands to low level equipotential surfaces as the ionized region grows. Fig. 2-b. shows the shell model geometry.



a) Arc model b) Shell model

Fig. 2. Proposed models of soil ionization process.

## 3. Computer simulation

A boundary element program, ELECTRO, was used to carry out the simulation of the proposed model with expanding ionization regions. A voltage of 1 pu. was assigned to the live electrode and 0 V was assigned to the container electrode. The soil medium is represented by its permitivity and conductivity. A relative permitivity value of 10 was used in the simulation. However, the conductivity values were determined experimentally and they were found to vary significantly with the water content of the medium. Table 1 summarizes the values adopted in this study.

Table 1
Resistivity of soil medium of different water contents

| %Water content | 1% | 3% | 10% |
|---|---|---|---|
| Resistivity (Ω m) | 1087 | 662 | 225 |

In ELECTRO, current density and its x-coordinates can be extracted for a defined path. Integration of the numerically determined current density (J) over the container electrode surface (S), gives the total current flow (I), between the two electrodes.

$$I=\iint J\, dS.$$

The resistance between the live electrode and the container electrode was then calculated. A similar approach was adopted in calculating capacitance. Using the computed profiles of the electric field, the charge induced on the container electrode can be calculated using,

$$Q=\iint E\, dS.$$

This induced charge was then used to calculate the capacitance. The computed capacitance curve for various lengths of the ionisation region is given in fig. 3. for both models. No experimental data was obtained since the conduction in the tested media dominated the capacitive effect at 50 Hz. The results of the resistance computations are shown in the next section and compared to the measured results.

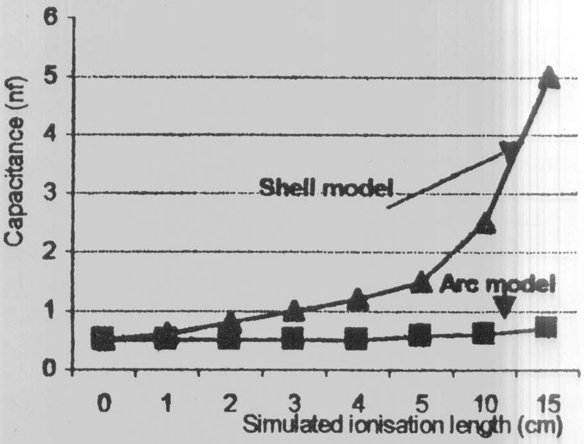


Fig. 3. Computed capacitance vs. ionization length.

## 4. Experimental verification of models

### 4.1. Test circuit

A simple electrode system was used to verify the computation. For the arc model, threaded steel rods of 2 mm diameter were connected to the active electrode in order to simulate various arc lengths. For the shell model, hemispherical containers of various diameters were used to simulate the growing shell.

Since sand is easily wetted and dried without loss of properties, sand of medium grain size (75 micron) was chosen in these experiments. To ensure uniform wetting of the sand, a sand mixer was used. Sand with water contents of 1%, 3% and 10% were used, and prior to subsequent experiments, an oven was used to dry the wet sand.

The test rig was supplied with a low magnitude AC 50Hz voltage. Currents in the range of 2 to 20 mA (rms) were recorded. Fig.4 shows the circuit diagram for laboratory experiments, which is also adopted for the low current impulse tests. A HEAFELY recurrent surge generator type 481 was used to generate impulse voltages up to 500 V peak. Tests were carried out with currents in the range of 25 mA to 1 A.

In both AC and impulse tests, 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 utilized for data acquisition and analysis. Voltage measurement was achieved using attenuators and fast voltage probes. AC current was measured using 10Ω shunt resistor, and the impulse current was measured using a current transformer with 0.1 V/A sensitivity and 20 ns rise time.

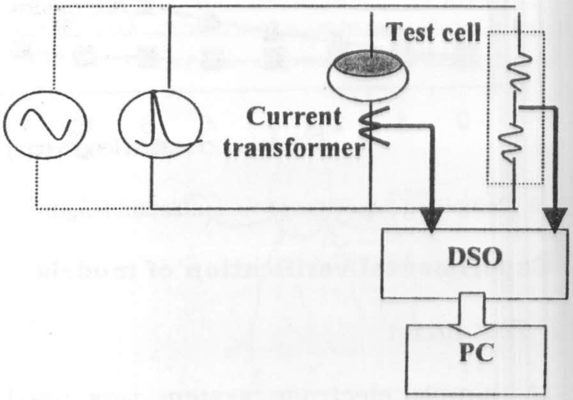
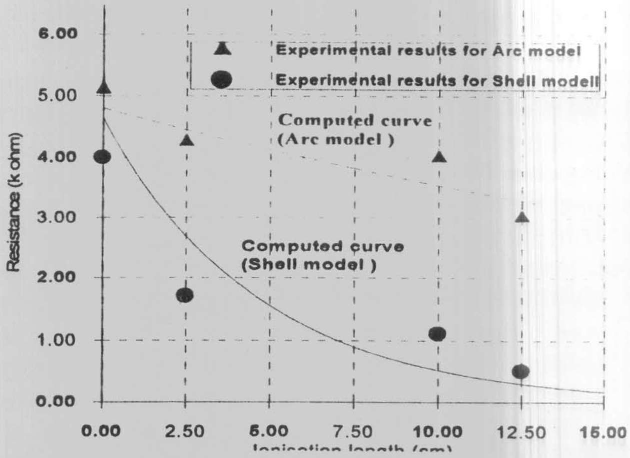


Fig. 4. Experimental arrangement.

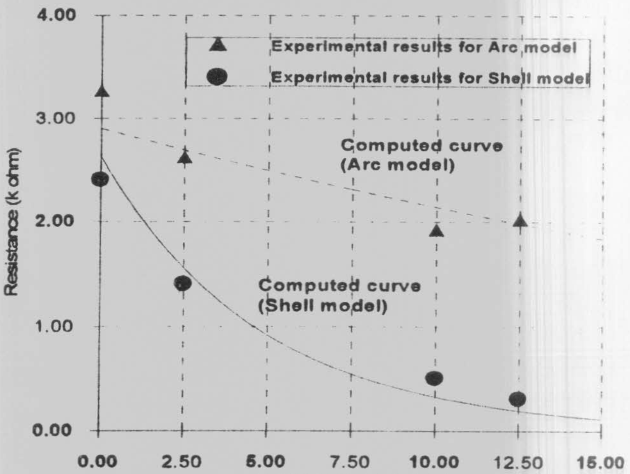
## 4.2. Resistance measurements

Plots of computed and measured (AC) values of resistance are shown in fig. 5. For both models, reasonable agreement between computed and experimental values is observed for sand with water content of 1% and 3%. Discrepancies in the case of sand with 10% water content are likely to be caused by the settling process of water within the test cell. The arc model exhibited larger differences in this case. The variability in measured data is due to difficulties in controlling the uniformity of water content. Similar agreement is obtained for low-level impulse tests fig. 6. This indicates that supply wave shapes do not affect the equivalent resistance of the system under low conduction conditions.

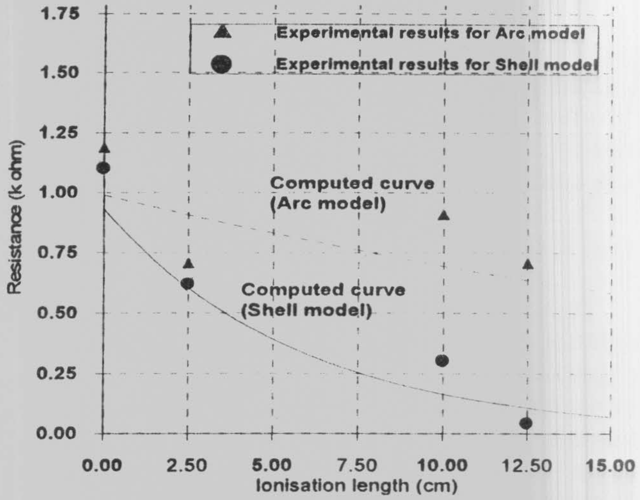
These low voltage experiments showed that both computer models calculated resistance accurately when compared with the same physical arrangement mimicking the ionization. However, to investigate their suitability for soil ionization, high current impulse tests were conducted to determine lengths of ionization.



5-a. 1% water content (soil resistivity= 1087 ohm.m)

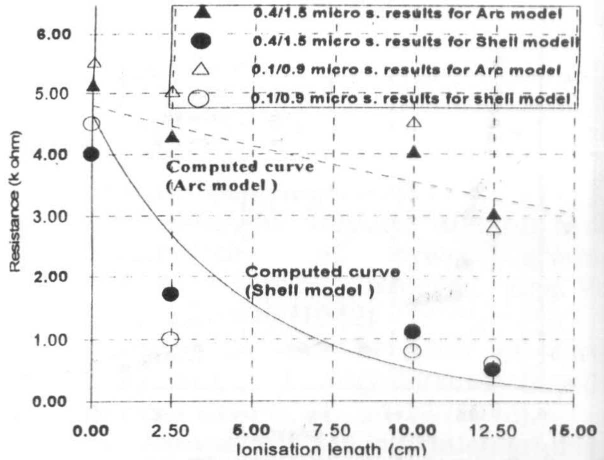


5-b. 3% water content (soil resistivity= 662 ohm.m)

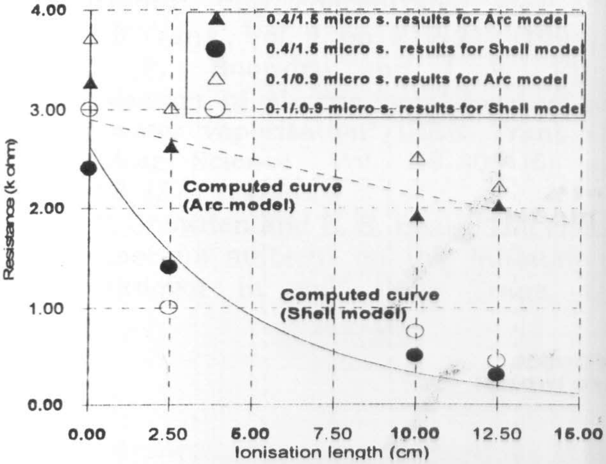


5-c. 10% water content (soil resistivity= 225 ohm.m)

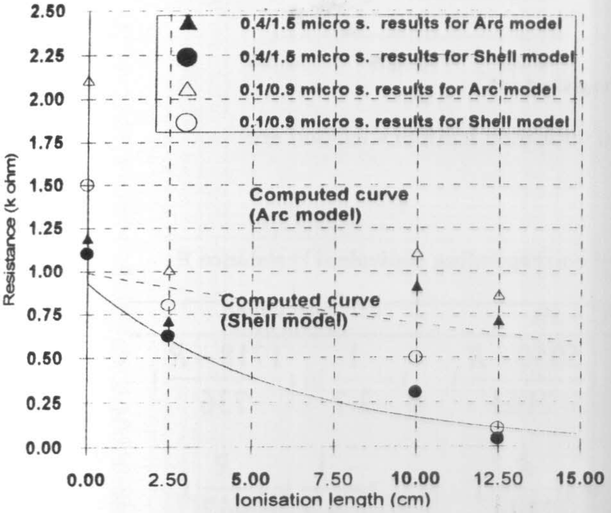
Fig. 5. Comparison between computed results and low voltage A C test results.



6-a. 1% water content (soil resistivity= 1087 ohm.m)



6-b. 3% water content (soil resistivity= 662 ohm.m)



6-c. 10% water content (soil resistivity= 225 ohm.m)

Fig. 6. Comparison between computed results and low voltage AC test results.

### *4.3. Analysis of high current impulse tests*

After a satisfactory verification of the computation, the predicted values of each model are compared with high current impulse test data [1]. The test rig dimensions and soil conditions are identical. Fig. 7. shows typical voltage and current records in the ionization region. The existence of the two current peaks, $I_{peak1}$ and $I_{peak2}$, led to the definition of two resistance; the pre-ionization resistance, R1 and post ionization resistance R2. The post ionization resistance is a result of developed ionization zone. Fig. 8. shows R2, versus current for various wetness conditions of the sand.

### *4.4. Water content (WC)=1%*

Arc model Matching R2 values fig. 8. with the computed equivalent resistance R figs 5, 6 due to each proposed model will yield prediction of corresponding ionization lengths. In doing so, relationships between ionization length (L) and computed resistance R are required. The empirical relationships shown in table 2, were obtained from the computed curves of figs. 5, 6. The predicted ionization lengths corresponding to R2 are shown in fig. 9. for the arc and shell models. It can be seen that for the arc model, the predicted ionization lengths exceed the test cell perimeter. This shows that the arc model is not suitable and the shell model is a better representation of the soil ionization phenomena than the arc model.

## 5. Conclusions

Two models of ionization in soil were investigated; the arc model and shell model. The accuracy of the computation was demonstrated by simple experimental setup. The validity of these models was checked with high impulse currents causing ionization in the soil medium. From predictions of the ionization region length, it is concluded that the arc model cannot account for the ionization process. However, the shell model gives acceptable results.

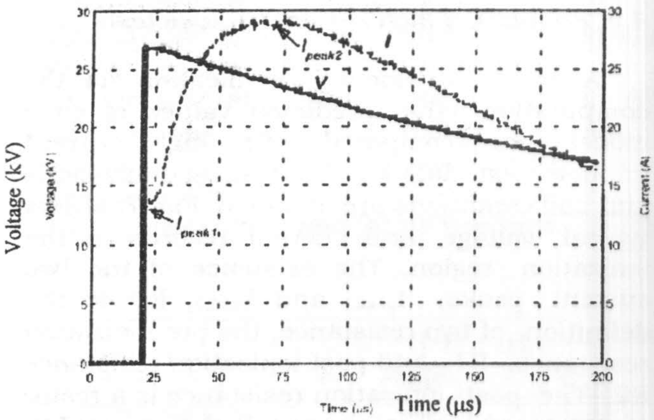


Fig. 7. Voltage and current records in the ionization region (water content, wc = 3%, $v_{rh}$ = 27kV).

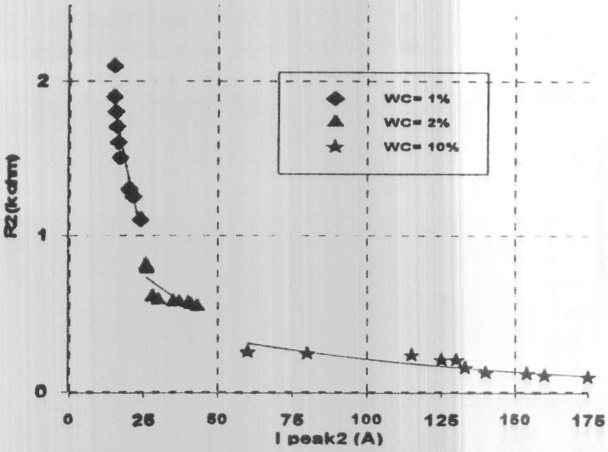


Fig. 8. Post-ionization resistance, R2 vs. current (water contents wc = 1%, 3% and 10%, +ve impulse.

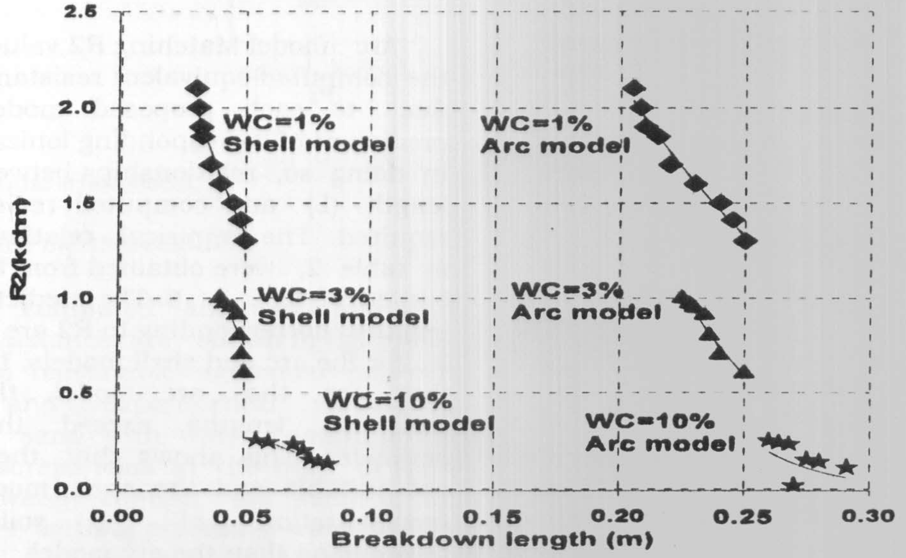


Fig. 9. Post-ionisation resistance, R2 vs. predicted ionisation lenth of shell and arc models.

Table 2
Derived relationships between ionisation length L, and corresponding equivalent resistance R

| | WC = 1% | WC = 3% | WC = 10% |
|---|---|---|---|
| Arc model | $L=\frac{1}{2.7}\ln(\frac{828-R}{3549})$ | $L=\frac{1}{2.7}\ln(\frac{5050-R}{2163})$ | $L=\frac{1}{2.7}\ln(\frac{1718-R}{736})$ |
| Shell model | $L=\frac{1}{2.7}\ln(\frac{R}{4667})$ | $L=\frac{1}{2.7}\ln(\frac{R}{2844})$ | $L=\frac{1}{2.7}\ln(\frac{R}{967})$ |

## References

[1] M. A. Abdallah, N. M. Nor. and S. Srisakot. "Characterisation of soil ionisation" Accepted for publication at 26th ICLP, Septempe2002.

[2] P. L. Bellaschi "Impulse and 60 cycle characteristics of driven ground" Trans..of American .Inst.Elec. Eng. Vol. 61, pp. 221-225 (1942).

[3] K.Berker " the behavior of earth connections under high intensity impulse currents" CIGRE, pp. 24-28 (1946).

[4] M. A. Mousa "The soil ionisation gradient associated with discharge of high currents into concentrated electrode" IEEE Trans., Vol. 9, pp. 212-217 (1994).

[5] D. P. Snowden and J. W. Erler "Ionisation of electric breakdown of soil by water vaporisation" IEEE Trans. On Nuclear Science, Vol. NS-30 (6), pp. 4568-4571 (1983).

[6] D. P. Snowden and E. S. Beale "The effect of gaseous ambient on the initiation of breakdown in soil" IEEE Trans. On Nuclear Science, Vol. NS-33 (6), pp. 1669-1674 (1986).

[7] T. M. Flanagan "Electrical breakdown properties of soil" IEEE Trans. Vol. 28, pp. 89-94 (1981).

[8] R. E. Leadon "Effect of ambient gas on arc initiation in soil" IEEE Treans., Vol. 30, pp. 77-81 (1983).

[9] G. M. Petropoulos "The high voltage characteristics of earth resistances" Jurnal of IEEE, Vol. 95, pp. 112-116 (1948).

[10] A. C. Liew " Dynamic model of impulse charactaristics of concentrated earths" Proc.IEE, Vol. 121, pp. 56-70 (1974).

[11] E. E. Oettle "results of impulse tests on practical electrodes at the high voltage laboratory of the national electrical inistitute" Trans. Of South Africa Institute, pp. 114-118 (1988).

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