3rd International Conference on Automation, Control, Engineering and Computer Science (ACECS'16)
Proceedings of Engineering & Technology (PET)
pp. 790-795
Copyright IPCO-2016

Experimental Investigation of High Current Impulse Characteristics of Enhanced Electrode Systems

S.Mousa[1], A.Bashkar[1], D.Clarck[2], H.Griffths[2], N. Harrid[2], A. Haddad[2]

[1]*Electrical and Electronic Department, University of Zawia Libya*
[2]*Electrical and Electronic Department, Cardiff University UK*
`mousasm@zu.edu.ly`

***Abstract*— Non-linear soil behaviour under high current magnitudes have been investigated by many researchers, and they found that the impulse resistance decreases when increasing the current magnitude but with dependence on the factors such as soil resistivity, area of earth electrode and current magnitude. However, no detailed studied to examine different length rods with horizontal enhancements at the same location were investigated.This work deals with the behaviour of an earthing system, under high impulse current. A large number of experiments in high voltage tests in the field around the vertical electrodes with and without horizontal earth electrodes were investigated. It was observed that when a sufficiently high current magnitude is injected through vertical electrodes, a significant reduction in the impulse resistance by increase in current with a sudden fall of voltage is observed which is called soil ionisation. Such phenomenon does not occur when the vertical electrodes with horizontal enhancements is tested, where the current through all earth electrodes is small.**

***Keywords*— earthing resistance, impulse resistance, earth potential rise, high impulse current, soil inoisation**

I. INTRODUCTION

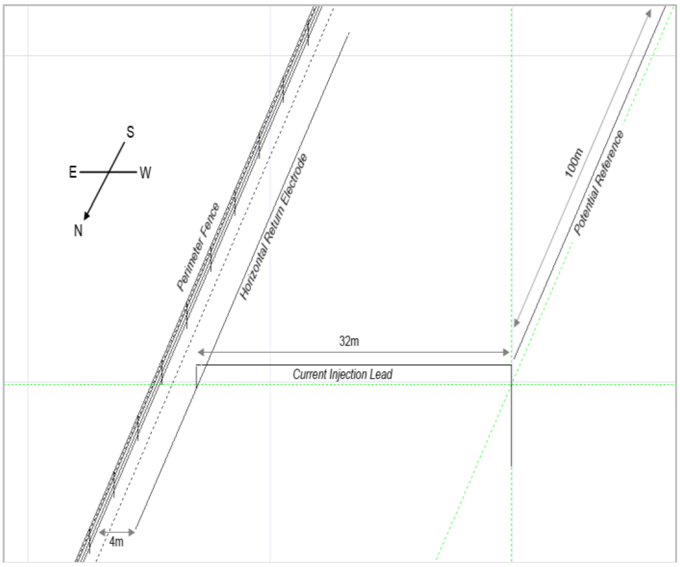
Earthing systems are designed to dissipate high magnitude fault current to earth and provide safety to persons working in or living near power system installations. It is also necessary that earthing systems are designed with low-magnitude earth impedance so that the high magnitude and fast transient surges are dissipated to earth. High voltage distribution and transmission systems are protected from lightning, and effective protection requires a good connection to earth. In high voltage substations, buried earth grids, vertical rods and horizontal electrodes are used in combination to provide a low impedance connection to earth.

Many authors have investigated the behaviour of earthing systems subjected to high impulse current, using both field measurements [1-4] and laboratory tests [5-9]. However, field tests are commonly performed in non-uniform soil structures with both lateral and vertical variations in resistivity, and these conditions are difficult to reproduce in the laboratory. In general, the conclusions of these investigations attribute the reduction in electrode earth resistance at high impulse current magnitudes to soil ionisation. While the high current impulse performance of vertical rod electrodes has been widely explored and documented, comparative tests on rods with horizontal enhancements have not been performed to date. In this work, the behaviour of soil breakdown of the vertical electrodes with and without horizontal enhancements were investigated experimentally.

II. COMPUTER SIMULATION

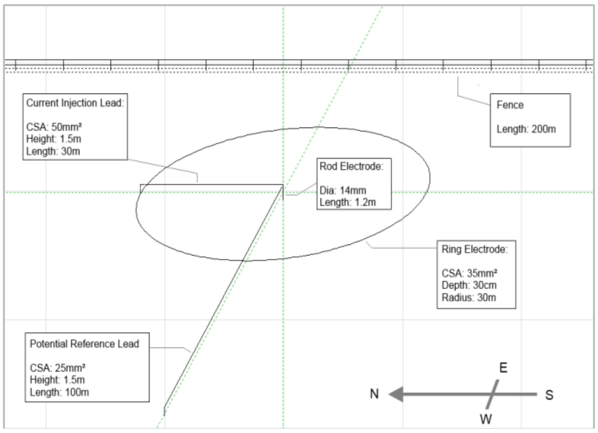
To ensure the safety of test personnel, site employees and members of the public in the vicinity of the test location, computer simulations were performed using CDEGS software [10] prior to high voltage tests to determine the worst-case earth potential rise (EPR) and step voltage contours, and to identify any hazardous touch potentials developed by exposed metalwork at the site perimeter. Fig.1 shows the CDEGS models of the test circuit using horizontal and ring current return electrodes.

Fig.2 illustrates the computed transient peak touch voltages for persons standing 1m from the perimeter fence (both inside and outside the field), for a 200kV, 1.2/50 impulse. Use of the ring electrode reduces the worst case touch voltages from 4.5kV to 600V for persons inside the perimeter, and from 2.2kV to 600V for persons outside, which is acceptable according to BS EN 50522-2010[11]. The touch voltage profiles are depicted in Fig.2.The magnitude of transferred potentials towards the clubhouse is also reduced.



(a)Horizontal current return electrode

ISSN: 2356-5608



(b) Ring current return electrode

Fig. 1: Physical layout of the simulated test configurations

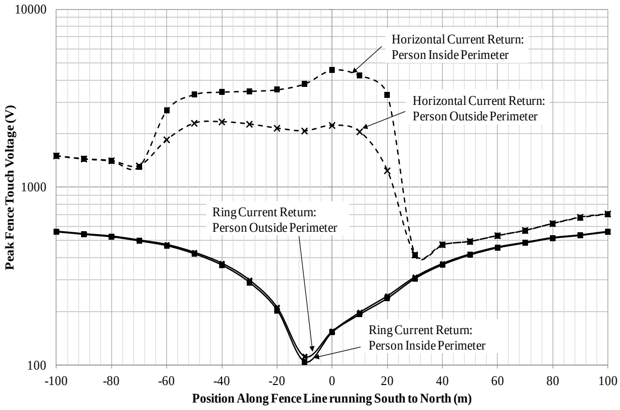
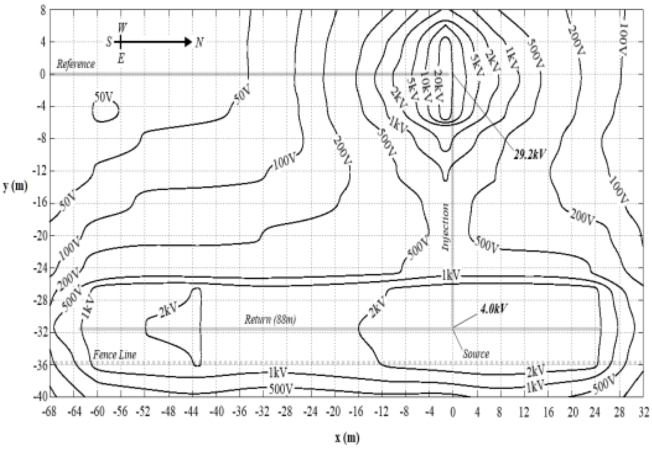
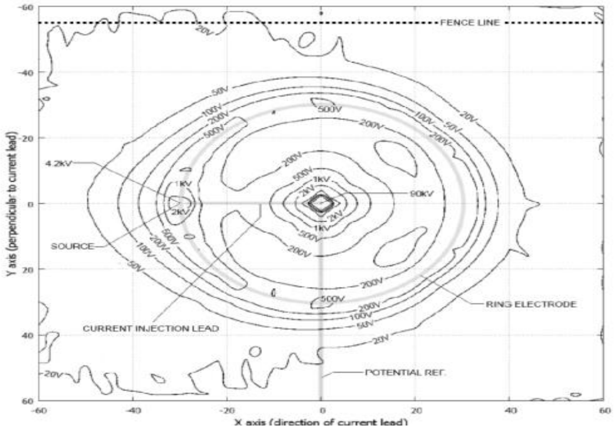


Fig.2: Peak Touch voltage profiles at 1m either side of perimeter fence line for both return electrode arrangements

Fig.3 shows the step voltage maps for both circuit configurations. It can be observed from the figure that, using the installed linear horizontal electrode, transient step voltages in excess of 2kV peak are developed beyond the boundary fence, rising to 4kV at the location of the source. However, using the ring electrode, positioned 20m from the fence line at its closest point, step voltages beyond the perimeter are limited to a peak value of less than 200 V.



(a) Horizontal current return



(b) Ring current return

Fig.3: Step Voltage Contour Plots for 200kV impulse test

III. TEST SETUP

The experimental setup consists of an impulse voltage generator (IG) with maximum output of 200kV, used to generate a high impulse current up to 10kA, its charging unit is supplied from a 25kVA diesel generator. The high impulse current was generated by connecting the two, low inductance (0.25μH), resistor in parallel. A 4.8kΩ tail resistor was used to obtain the required waveform tails. A 30m current injection line connects the impulse generator to the electrode under test, suspended from wood poles to a height of 1.6m as shown in Fig.4. The earth potential rise (EPR) at the top of the 1.2m, 2.4m, 3.6m and 4.8m vertical rod earth electrodes were measured with reference to a remote potential imported via a second transmission line using a capacitive divider having a ratio of 2000:1. The remote potential reference lead was arranged orthogonal to the current injection path so as to minimise circuit coupling. The current was measured using a current transformer (CT) (Lilco) with a 50MHz bandwidth, 0.01V/sensitivity and a peak impulse current rating of 50 kA. Following the initial safety simulation studies, a bare copper ring earth electrode was installed to act as a concentric current return electrode. The ring conductor has a length of 188.5m and a cross sectional area of 20mm^2, and is buried to a depth of 30 cm, with eight junction boxes allowing reconfiguration and current measurement in the electrode segments. A developed wireless data transmission system was used and located at the electrode under test with data acquisition achieved using a real-time PC integrated digital storage oscilloscope. A PC-based oscilloscope was configured with a wireless LAN adapter and antenna for communication via a point-to-point link with a control laptop/PC located inside the equipotential working zone established in the equipment trailer. A remote desktop server (Tight VNC) was installed on the oscilloscope and remote control of the scope and established by means of the associated client running on the control PC.

To accommodate the relatively long distances, and based on preliminary on-site tests, long range wireless LAN adapters were adopted at both ends to achieve high-reliability data transfer. The main advantage of this system is the inherent electrical isolation achieved between equipment at the test electrode and the control desk at the test trailer [12].

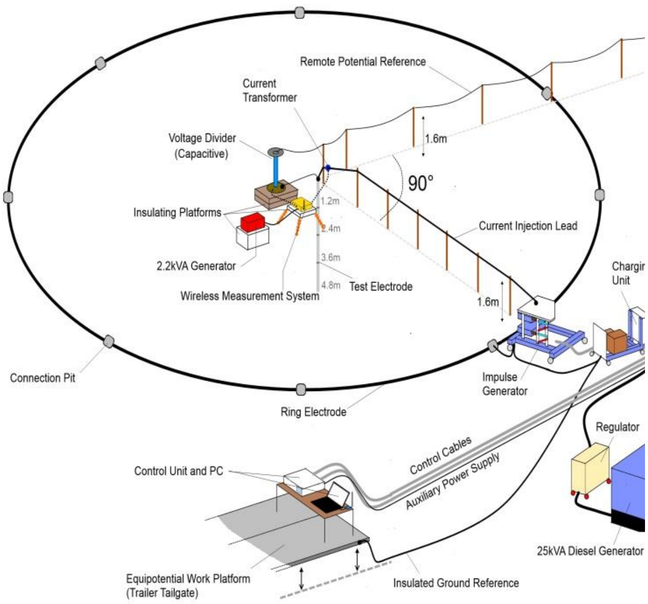


Fig. 4: High-current field test configuration

IV. TEST RESULTS

Prior to commencing the high current tests, the DC resistance of the rod and ring electrodes was measured using the four pole method by means of a MEGGER DET2/2 resistance meter. The equivalent low-current impulse resistance was determined using a Haefely recurrent surge generator. These measurements are summarised in Table 1. It can be observed that from the table, the dc resistance decreases with an increase in rod length, and only slight differences between the impulse and the dc resistances of each earth rod. According to [13,14], the earth resistance of the current return electrode must be significantly lower than the earthing electrode under test. The ring electrode was found to have a dc resistance at least an order of magnitude smaller than that of the test electrode, which helps to minimise the EPR occurring at the chassis of the impulse generator.

TABLE 1: Measured DC and Impulse resistances of rod electrodes

Rod length (m)	1.2	2.4	3.6	4.8	Ring
DC resistance (Ω)	184.4	106.2	74.4	58.6	3.85
R_{imp} (Ω)	183	104.4	69	54.2	4.73

Extensive measurements were carried out on 1.2m, 2.4m, 3.6m and 4.8m vertical electrodes at the field test site: firstly, for low current DC and impulse, and then for high impulse currents up to 7kA. Each rod has a diameter of 14mm and installed into two layer soil resistivity at Cardiff University earthing facilities. Fig.5 shows the voltage and current recordings for the tests on the 4.8m rod. Impulse test result for the rod electrode shows that a second current peak occurs after a short time delay, due to the breakdown of soil in the ionised region surrounding the electrode. Therefore, it is important to investigate the aspect of inception time (T_i) and introduce another new value, time to second peak [15], as shown in Fig. 5. As can be seen from the figure, the indication of the soil ionisation occur at the inception time (T_i) corresponding to inception current I_{pi} and voltage V_{pi}. After ionisation starts, current increases and is accompanied by a sharp fall in voltage. Table 2 presents the comparison of amplitude of voltage reduction (ΔV), the ionisation times and earth resistance magnitudes obtained at low and high voltage for the 4.8m vertical electrode.

There are two different current peaks which can be used to define two different resistances. The pre-ionisation resistance (R1) corresponds to the soil properties prior to the influence of soil ionisation [16]. It represents the pre- breakdown behaviour of the electrode resistance and is subject to thermal effects. Additionally, the pre-ionisation resistance decreases with increasing current magnitude, which may be due to non-linear thermal effects in the soil. The post-ionisation resistance (R_2) is a measure of the effective electrode resistance following soil breakdown [16]. The resistances R_1 and R_2 can be calculated by using the following equations [17]:

$$R_1 = \frac{V@I_{p1}}{I_{p1}} \text{……..(1)}$$

$$R_2 = \frac{V@I_{p2}}{I_{p2}} \text{………(2)}$$

Where, $V@I_{p1}$ is the voltage at the instant of the first current peak and $V@I_{p2}$ is the instant of the voltage at the second current peak. From theses equations, the inductive effect is eliminated in these results at the instant of peak current, di/dt=0. As can be seen from Table 2, the pre-ionisation resistance R_1 falls slightly in comparison to the dc resistance. By contrast, a significant reduction in R_2 is observed, which may be attributed to a fully developed and highly conductive ionised region in soil.

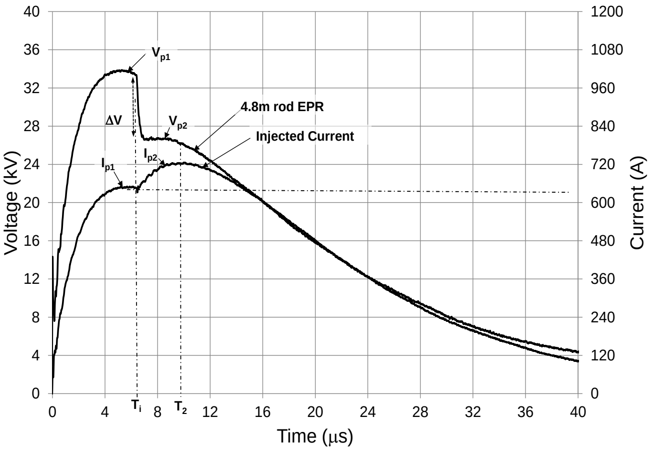


Fig. 5: Measured results of voltages and applied currents of the 4.8m earth rod electrode

Table 2: Measured the time of ionisations, ΔV, R_{dc} and $R_{impulse}$ of test 4.8m electrode

Rod length (m)	4.8
R_{DC} (Ω)	58.6
ΔV (kV)	8
T_i(μs)	6
T_2(μs)	10
I_{p1} (A)	640.7
I_{p2}(A)	722.6
$V_{1@Ip1}$ (kV)	33.4
$V_{2@Ip2}$ (kV)	25.7
R_1(Ω)	52.1
R_2(Ω)	35.6
Difference between R_{DC} and R_1 (%)	11.1
Difference between R_{DC} and R_2 (%)	56.3

Fig.6 shows the impulse resistance values obtained for different applied voltages. As can be seen from the figure, the impulse resistance values (R_1) are close to the dc earth resistances at the lowest applied voltage. However, the earth resistance values were found to decrease slowly when the current magnitudes increased which might be due to the soil ionisation behaviour of the earthing system under high impulse current. This reduction of the impulse resistance was also reported in the literature [14-21]. The authors [8, 19] attribute this reduction to thermal processes, where the temperature of the soil is increased by I^2R (heating the soil), reducing the soil resistivity and hence the overall earth resistance. However, the post-impulse resistance R_2 decreases gradually to an asymptotic value as the current increases, eventually becoming independent of the current. This trend in the relationship between impulse resistance (R_2) and current may be due to the formation of an increasingly uniform hemispheric at ionisation region. As the current increases from 125A to 6.8kA, the impulse resistance falls by 94% for a 1.2m rod, 91% for a 2.4m rod, 87% for a 3.6m rod and 81% for a 4.8m rod, thus exhibiting similar results to those observed in previous research work [18-22].

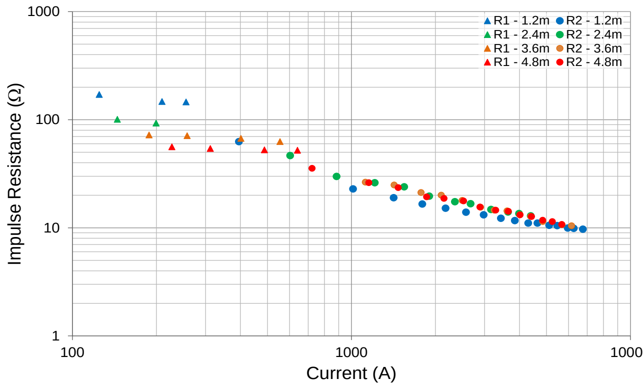


Fig. 6: Measured impulse resistances of 1.2m, 2.4m, 3.6m and 4.8m rod

The impulse resistance was calculated as the percentage of the DC resistance of earth electrodes up to 4.8m as shown in Fig. 7. It was observed that the percentage reduction of the resistance R_1 values, were found to decrease slightly with increasing length of earth electrodes at current magnitudes up to 641A. However, this fall in resistance R_2, increases markedly for the earth rod which has the highest R_{dc} (1.2m rod) which indicates that the fall of earth resistance can be linked to its DC earth resistance.

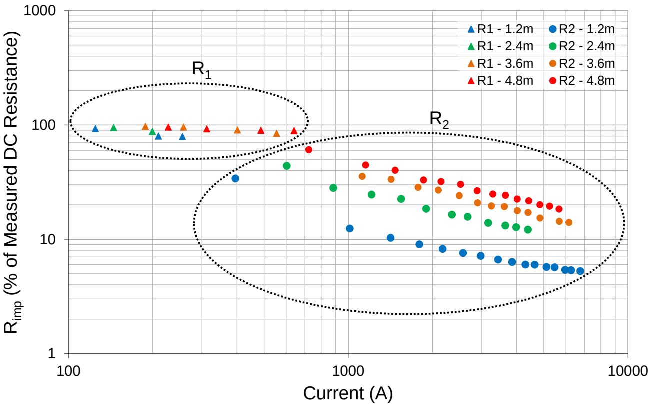


Fig.7: Measured impulse resistances of 1.2m, 2.4m, 3.6m and 4.8m rod with current magnitude

The horizontal enhancements were bonded with the vertical earth electrodes to reduce the earth potential rise (EPR) and investigate the behaviour of the soil ionisation. The horizontal enhancements were buried at a depth of 30cm; each horizontal electrode has length of 1m and diameter of 8 mm. Impulse currents up to 2.4A magnitude with different rise times were injected into rods with 8-point star enhancement. Table 3 shows the DC and impulse resistances of the enhanced vertical electrodes.

As can be seen from the table, the dc resistances for all configurations are close to the impulse values. Fig.8 shows the effect of additional horizontal enhancements on the impulse resistance of the vertical rods. It is clear from the figure that the percentage decrease in impulse resistance in comparison with the rod alone is small. This small reduction is due to current division between the horizontal enhancements and the rod. As can be calculated from Equations (3) and (4) [18], due to the increased surface area of earth electrode, a lower current density (J_c) is developed which reduces the critical field intensity (E_c), and hence, no non-linear behaviour was observed in the electrode resistance. Soil ionisation can thus be said to have the greatest effect with short electrodes having small surface area.

$$E_c = \rho J_c \text{……..(3)}$$

$$J_c = \frac{I_c}{A} \text{……..(4)}$$

Table 3: Measured the dc resistance of the vertical rods with additional horizontal enhancements

Configuration	DC resistance (Ω)	Impulse resistance R_{imp}(Ω)
1.2m rod with 8-point star	56.6	53.3
2.4m rod with 8-point star	51.3	51.4
3.6m rod with 8-point star	42.6	42.1

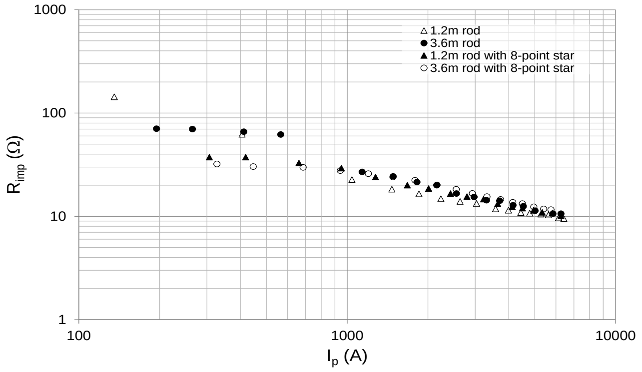


Figure 8: Variation of impulse resistance with current magnitude for 1.2m and 3.6m rod with and without horizontal enhancements

V. CONCLUSIONS

High current tests on practical grounding electrodes have been performed at the Cardiff University earthing test facility. As a precursor to the field tests, extensive computer simulations using CDEGS were undertaken which showed that, by employing a ring current return electrode, step and touch voltages in the vicinity of the test electrode area could be kept to a safe level. The characteristics of full scale vertical rod electrodes up to 4.8m in length subjected to impulse currents of low and high-magnitude have been studied. At low current magnitude, the impulse and DC resistances of vertical electrodes were found to have slightly different values. Generally, the impulse resistance of all vertical electrodes decreases with increasing current magnitudes. This fall in impulse resistance was attributed to two different factors affecting the soil medium. When the impulse current increases, the conductivity of the soil increases, therefore, the resistivity of the soil reduces. Above a certain level of voltage applied, the ionisation process starts to take place leading to a further reduction of the impulse resistance as the ionisation region expands. The largest fall in impulse resistance was obtained for the shortest vertical rod having the largest low-current DC resistance, as only a relatively small current is required to initiate soil ionisation. Vertical electrodes with horizontal enhancements, by contrast, showed only small reduction due to their large surface area. Finally, to demonstrate a reduction in the impulse resistance of enhanced vertical electrodes for both low and high current magnitudes, the addition of horizontal enhancements is recommended as the best earthing design.

REFERENCES

[1] P. Bellaschi, ‘‘Impulse and 60-Cycle Characteristics of Driven Grounds’’, AIEE Transactions, Vol.60, pp.123-128, March 1941

[2] P. Bellaschi, R. Armington and A. Snowden ‘‘Impulse and 60-Cycle characteristics of driven grounds-II’’, AIEE Transactions, pp.349-363, 1942

[3] G. Petropoulos, ‘‘The high-voltage characteristics of earth resistances,’’ Journal of the institution of Electrical Engineers Part II: Power Engineering, Vol. 95, pp. 59-70, February 1948

[4] M. Victor, M. Cabrera, S. Lundquist and V. Cooray, ‘‘On the physical properties of discharges in sand under lightning impulses,’’ Journal of Electrostatics, pp. 17-28, 1993.

[5]I. Cotton, ‘‘The soil ionization process,’’ ERA Conference, pp. 4.4.1-4.4.11, 2000

[6]C. Pritindra, ‘‘Impulse impedance tests on laboratory model ground electrodes,” IEE Proceedings on Generation, Transmission and Distribution, vol. 150, no. 4, pp. 427-433, 2003

[7]Y. Chen and C. Pritindra, ‘‘Correlation between laboratory and field tests on impulse impedance of rod-type ground electrodes,” IEE Proceedings on Generation, Transmission and Distribution, vol. 150, no. 4, pp. 420-426, 2003

[8]N. Mohamed Nor, A. Haddad and H. Griffiths, ‘‘Characteristics of ionisation phenomena in soil under high impulse currents,” IEEE Transaction of Power Delivery, vol. 21, no. 95, pp. 353-361, 2006

[9]N. Mohamed Nor, S. Abdullah, R. Rajab and K. Ramar, ‘‘Field tests: performances of practical earthing systems under lightning impulses’’, Electric Power Systems Research, Vol. 45, pp. 223-228, 2013.

[10]SES (Safe engineering services). Current distribution electromagnetic grounding analysis software (CDEGS), Available http://www.sestech.com/products/softpackages/cdegs.htm

[11]BS EN 50522:2010, ‘‘Earthing of powerinstallations exceeding1 kV a.c. ’’, October 2010

[12]D. Clark, H. Griffiths, N. Harid, D. Guo and A. Haddad, ‘‘Wireless measurement system for a large-scale grounding electrode test facility,’’ in Proceedings of the 48th International Universities Power Engineering Conference (UPEC), Dublin, Ireland, September 2013.

[13]IEEE guide for safety in AC substation grounding. ANSI/IEEE standard 80- 2000

[14]IEEE guide for measuring earth resistivity, ground impedance, and earth surface potentials of aground system. ANSI/IEEE standard 81- 1983

[15]N. Harid, N. Ullah, M. Ahmeda, H. Griffiths and A. Haddad: ‘‘Experimental Evaluation of Potential Rise and Step and Touch Voltages at High Voltage Towers under Lightning Impulse’’ 16th International Symposium on High Voltage Engineering (ISH), pp. 1651-1656, Cape town South Africa, 24-28 August 2009.

[16]B. Zedan,” Characterisation of substation earth grid under high frequency and transient conditions,’’ Ph.D. dissertation, Cardiff University, 2005

[17]N. Mohamad Nor, S. Srisakot, H. Griffiths and A. Haddad, ‘‘Characterisation of soil ionisation under fast impulse,’’ in Proceedings of the 25th International Conference on Lightning Protection (ICLP) ,Rhodes, Greece, pp. 417-422 September 2000

[7.18]S. Skioka, H. Hayashida, T. Hara and A. Ametani, “Measurement of grounding resistance for high impulse currents,’’ IEE proceedings Generation, Transmission and Distribution, vol. 145, pp. 693-699, 1998

[19]N. Mohamad Nor, A. Haddad and H. Griffiths, “Determination of threshold electric field Ec under high impulse currents,’’ IEEE Transactions on Power Delivery, vol. 20, pp. 2108-2113, 2005

[20]B. Hee Lee, G. Hun Park, H. Gu Kim and K. Sun Lee, ‘‘Analysis of soil ionization behaviours under impulse currents,’’ Journal of Electrical Engineering& Technology, vol. 4, pp. 98-105, 2009

[21]N. Harid, H. Griffiths, N. Ullah, M. Ahmeda and A. Haddad, ‘‘Experimental investigation of impulse characteristics of transmission line tower footings,’’ Journal of Lighting Research, vol. 4, pp. 36-44, 2012

[22]N. Mohamad Nor, S. Abdullah, R. Rajab and K. Ramar, “Field tests: Performance of practical earthing systems under lightning impulses,’’ Electric Power System Research, vol. 45, pp. 223-228, February 2013