CURRENT AND VOLTAGE DISTRIBUTION IN HORIZONTAL EARTH ELECTRODES AND A TECHNIQUE TO INCREASE EFFECTIVE LENGTH

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Abstract: Horizontal earth electrodes are commonly used to enhance earthing systems located in areas with high soil resistivity. However, the ability of a horizontal earth electrode in reducing earth potential rise is limited because, beyond a certain length known as the effective length, no further reduction is obtained. In this paper, field experiments and computer simulations of two sectionalised horizontal earth electrodes are presented. The electrodes were energised using different sources (dc, variable frequency ac and transients of different shapes), and current and voltage distributions along the length of the electrode were examined. Furthermore, by incrementally increasing the length of the test electrode, the effective lengths of the earth electrode was determined. The experimental and simulation results show reasonably close agreement and also that quite good prediction of the effective length is possible. A new proposed method to increase the effective length of the horizontal earth electrode was investigated by installing an additional insulated parallel conductor which is bonded to the bare underground horizontal electrode at points along its length. The results show that the current and voltage distributions are changed such that a greater length of buried conductor is utilised and that this contributes to an additional reduction in the earth impedance, and hence the earth potential rise at the point of current injection.

1 INTRODUCTION

The ability of a horizontal earth electrode to enhance earthing systems is limited because no further benefit is obtained by increasing its length beyond a certain distance from the main earth electrode, which is known as the effective length. It is also well known that, under impulse conditions, horizontal electrodes dissipate current to earth more rapidly than under power frequency resulting in shorter effective lengths. The effective length under impulse conditions depends on soil resistivity, impulse risetime and electrode geometry. Many investigations have been carried out on the transient performance of the horizontal earth electrode and empirical formulae for calculating the effective length have been proposed [1-9].

In this paper, results of experimental measurements of transient voltages and currents at points along two buried horizontal test earth electrodes are described. The impulse resistance was calculated for different conductor lengths and, from these results, it was possible to determine experimentally the effective length. The experimental results are compared with those obtained by computer simulations, and show close agreement. Also, it is demonstrated that satisfactory prediction of the effective length using a simplified analytical formula is achievable.

Recently, a new method [10, 11] has been proposed by the present authors to increase the effective length of the horizontal earth electrode by installing an additional insulated parallel conductor bonded to the bare underground horizontal electrode at points along its length. Here, further experimental tests and computer simulations investigating this technique are reported.

2 FIELD TESTS ON HORIZONTAL EARTH ELECTRODES

2.1 Tests on horizontal electrode A

Figure 1 shows a diagram of the experimental setup used for the current injection tests. Test electrode A is an 88.5m-long conductor with a cross-sectional area of 1.25cm^2, buried at a depth of 30cm. The electrode follows an arc of 30m radius as shown in Fig. 1.

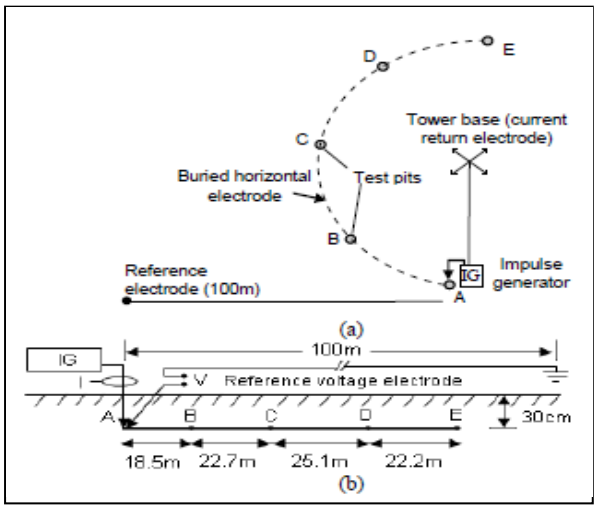

Figure 1: Experimental set-up of horizontal earth electrode A: (a) top view (b) side view

The earth electrode is divided into sections of different lengths with test pits located between sections to enable access for voltage and current measurements. These junctions are indicated by points A, B, C and D on the figure and the lengths of the conductor sections are given in Fig. 1(b). Current transformers of 0.1V/A and 0.01V/A sensitivities, and high-bandwidth differential voltage transducers were used for these measurements. The current was injected between one end of the electrode (point A) and a purpose-built transmission tower base which was used as the auxiliary return current electrode. A low voltage recurrent surge generator was used for impulse current injection. The generator delivers double-exponential impulse voltages of variable amplitude and shape. The electrode earth potential rise (EPR) was measured with reference to a rod electrode placed a distance of 100m from the injection point.

2.1.1 Impulse test results for earth electrode A

An example of the applied impulse current and the resulting earth potential rise at the current injection location (point A) is shown in Fig. 2. As can be seen on the figure, the current has a rise time of 5.8μs and a time to half value of 16μs, with a peak value of 5.4A. The corresponding peak EPR is 44.4 V. The significant influence of the electrode inductance is indicated during the front of the impulse by a sharp rise in electrode potential. A soil resistivity survey at the site gave a two-layer soil with a bottom layer of 30Ωm resistivity and a 200Ωm resistivity upper layer of about 8m depth.

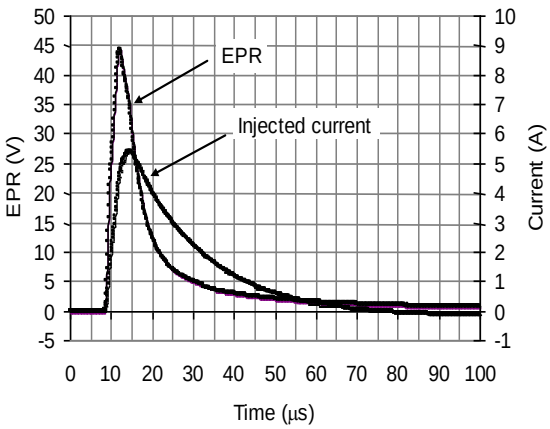

Figure 2: Voltage and current shapes at injection point of horizontal earth electrode A.

2.1.2 Current and voltage distribution along electrode

The impulse currents measured at points A, B, C and D of the horizontal electrode are shown in Fig. 3, and the corresponding electrode voltages measured at these points and at the end point E are shown in Figure 4. As the current impulse travels along the electrode length, it undergoes attenuation of its magnitude and a change in the rate of rise. This is attributed to the current leaking into the ground during propagation. The time delays observed on the current impulse shapes measured at points B (18.5m), C (41.2m) and D (66.3m) correspond to travel time along the horizontal electrode. In the first 18.5m section of the horizontal electrode (section AB), 37% of the injected current is dissipated into the ground, whereas in the three sections AB, BC and CD together (66.3m of electrode length), the current dissipated is 85% of the injected current. As shown, it was found that the reduction in the peak magnitude of current is not linear, with the highest proportion of current dissipated in the first section AB of the electrode which has the shortest length, compared with sections BC and CD.

Similarly, the magnitude of the voltage along the electrode shows a significant reduction with length, and there is a change in shape both on the front and tail of the impulse (Fig. 4). The percentage reductions in EPR are 39% at point B, 62% at point C and 66% at points D and E.

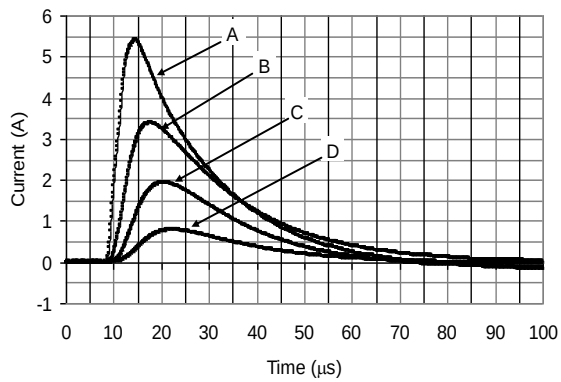

Figure 3: Measured impulse currents along the horizontal electrode at points A, B, C and D

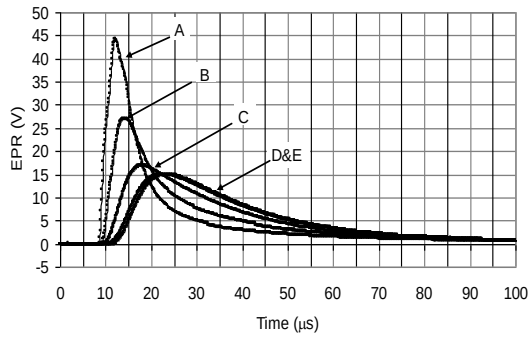

Figure 4: Measured impulse voltages along the horizontal electrode at points A, B, C, D and E

Figure 5 shows the peak current distribution over the electrode length for injected impulse currents having peak values between 1A and 6A. Over this range of magnitudes, the current dissipation in the ground is independent of the injected current magnitude. The corresponding peak EPR magnitudes are shown in Figure 6. As can be seen on the figure, the electrode potential falls rapidly over the first 40m, then decreases very slowly beyond this distance. As observed with the current, the reduction in voltage over the electrode length is

independent of the injected current magnitude for the range of impulse currents used in these tests.

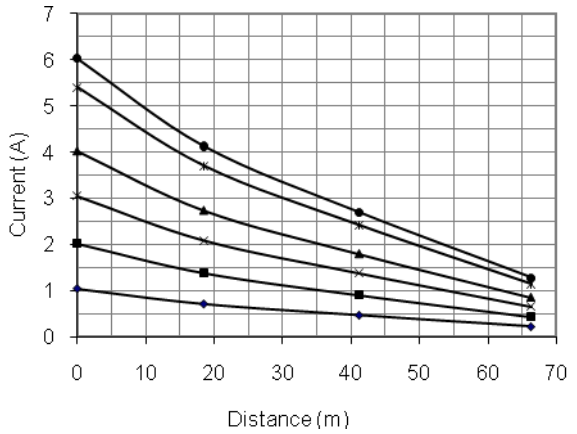

Figure 5: Peak current distribution at various locations along the horizontal electrode length

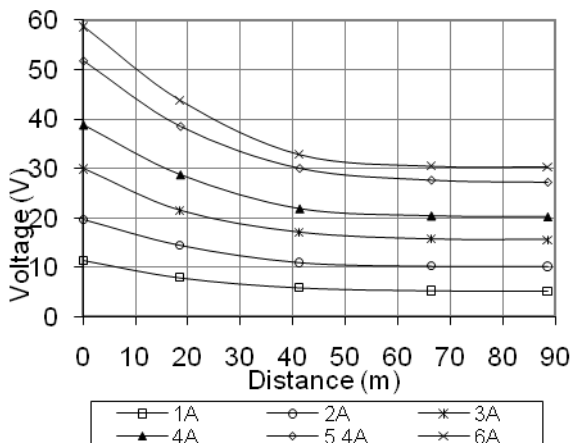

Figure 6: Peak voltage distribution along the horizontal electrode length

Table 1 gives the peak values of current (I_p) and the voltage at the instant of current peak ($V_{@Ip}$) at the test points along the electrode, for an injected current of 5.4A. The ratio $V_{@Ip}/I_p$ characterising the electrode impulse resistance was calculated to be 6.54Ω at the injection point of the electrode. This ratio remains approximately constant at this value over the first three sections of the electrode, and increases to more than three times towards the end of the electrode. This means the largest proportion of the injected current is dissipated into the ground over the first sections of the electrode and, only, a small portion is dissipated by the last section.

TABLE 1: Measured peak current and voltage along horizontal electrode.

Distance (m)	0	18.5	41.2	66.3
I_p (A)	5.41	3.7	2.4	1.15
$V_{@Ip}$ (V)	35.4	21.9	16.2	14.6
$V_{(@Ip)}/I_p$	6.54	6.46	8.36	18.54

2.1.3. Effective *length* of horizontal electrode A

Additional tests were carried out on individual and combined sections of the horizontal electrode. Initially, the current was injected onto the first section when isolated (section AB), and then the other sections were added in sequence to increase the electrode length. The current injected into the first section was 5A, and the current injected after adding all the other sections was 5.5A. Fig. 7 shows the recorded voltage impulse traces for increasing electrode length. The EPR is reduced by 29%, when the conductor length is increased from 18.5m to 41.2m, with insignificant reductions as additional sections are added. To determine the effective length of the electrode from these measurements, the impulse resistance R_i defined by the ratio $V_{@Ip}/I_p$ was calculated, and its variation with electrode length is plotted in Figure 8. The impulse resistance for an electrode length of 18.5m is 12.4Ω which decreases to a value of 6.7Ω as the electrode length increases beyond 41.2m. This length can be taken as an indication of the effective length of the electrode since no significant reduction in impulse resistance is achieved by increasing the electrode length. In contrast, the DC resistance, also shown in Figure 8, falls to a much lower value with electrode distance. This implies that substantial increases in electrode length may be effective in dissipating low frequency currents, but only a much more limited length is effective for dissipating impulse currents.

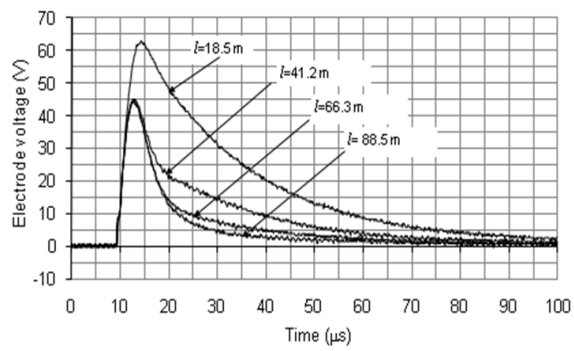

Figure 7: Measured voltage for different horizontal electrode total lengths.

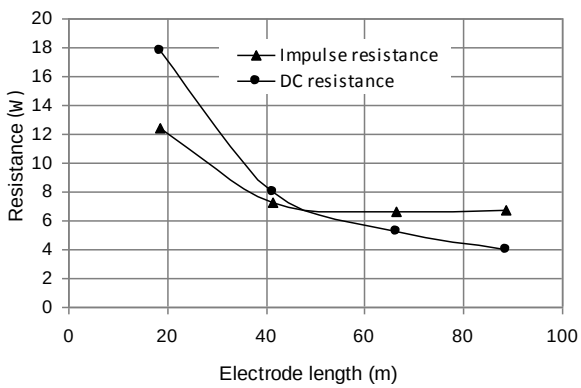

Figure 8: Variations of impulse and DC resistances with total length of horizontal electrode.

The above measurement results were compared with predicted effective length using a published empirical formula [6]:

$$l_{eff} = A(\rho\tau)^{0.5} \qquad (1)$$

where ρ is the soil resistivity, τ is the wave front time, and A is a constant which depends on the point of current injection, and is 1.4 for current injected at one end.

The calculated effective length using the present test data is 48m for a uniform soil resistivity of 200Ωm. However, since the soil at the test site consists of two layers and Equation (1) applies to uniform soil only, an equivalent uniform resistivity can be assumed to account for the lower layer resistivity. As an approximation, if this equivalent resistivity is taken as the average of the upper layer and lower layer resistivities, the calculated effective length is 38m. Hence, the effective length of (not greater than) 41.2m is reasonably close to the value predicted by Equation (1).

2.2 Tests on horizontal electrode B

Figure 9 shows a schematic diagram of the experimental setup to test the second horizontal earth electrode (B) which was installed at the same earthing test facility. This straight horizontal copper test electrode is 88m long, has a cross-sectional area of 50mm^2, and is buried at a depth of 30cm. The electrode was divided into 13 sections of graded lengths, ranging from 1m to 10m such that the inter-sectional spacing is smallest nearest to the injection point and increases with distance along the horizontal electrode. Test junction boxes were installed above each intersection to enable different electrode lengths to be tested and to facilitate voltage and current measurements at different points. Current injection was made at one end of the electrode, as shown in Figure 9. A test transmission line tower base, located 100m away, was used as the auxiliary electrode current return. A reference potential electrode was also placed 100m away from the injection point but in a perpendicular direction to the test horizontal electrode in order to minimise mutual coupling effects. The same recurrent surge generator that was used as the source for the impulse tests on earth electrode A was also used for this test.

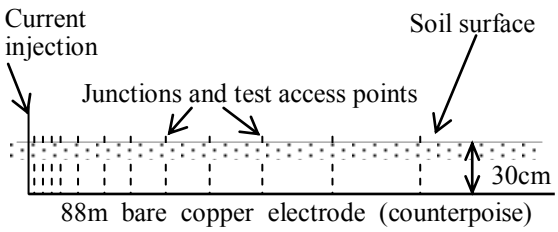

Figure 9: 88m horizontal test earth electrode (counterpoise)

2.2.1 Impulse test results for earth electrode B

Impulse tests were carried out on the 88m counterpoise for a range of impulse risetimes (~2-5μs). A typical set of recorded values of injected current and earth potential rise (EPR) at the point of injection is shown in Figure 10. As can be seen from the figure, the voltage rises sharply and the peak voltage occurs before the current peak indicating a significant inductive effect. The impulse resistance ($V_{@ip}/I_p$) was calculated to be 6.6Ω, and this compares with the measured dc resistance value of 6Ω.

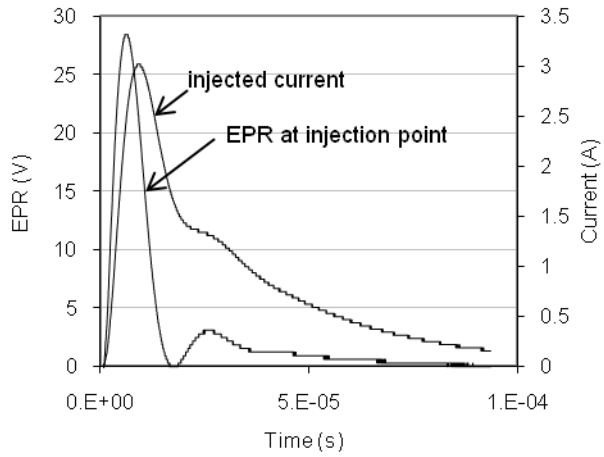

Figure 10: Voltage and current at injection point (conductor length 88m)

2.2.2 Current distribution along electrode B

Figure 11 shows the results of the measured peak impulse currents normalised to the peak injected current at different locations along the 88m horizontal electrode. The peak injected current was 3A with 4.8μs rise time. The results indicate, as was the case with electrode A, that a greater proportion of the current is dissipated over the sections of the electrode closest to the point of injection.

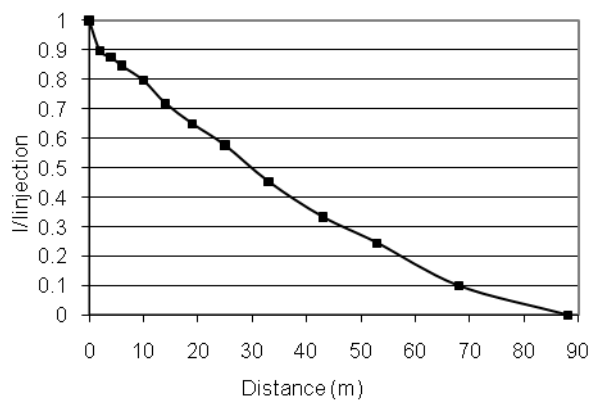

Figure 11: Peak current distribution over electrode length

2.2.3 Effective length under transient conditions

The impulse tests carried out on the 88m horizontal electrode were extended to all other possible electrode lengths by arranging open points in the section boxes, and for different impulse rise-times ranging from 2μs to 4.85μs. The impulse resistance was calculated for all cases, and the results are shown in Figure 12. From the figure, it can be seen that the impulse resistance decreases as the electrode length increases, reaching its asymptotic value at a particular length which is dependent on the impulse risetime. This indicates that the effective length is shorter for faster impulse risetimes.

The impulse resistance as a function of electrode length was also calculated using the CDEGS program [12] for a 4.85μs impulse risetime and an equivalent two-layer soil model derived from data obtained a detailed soil resistivity Wenner survey carried along the line of the electrode but prior to its installation. As can be seen from Figure 12, the simulated values are reasonably close to those measured at the corresponding risetime.

Figure 13 shows the effective lengths determined by computer simulation and Equation (1) as well as the measured values from the experiments, for a range of rise-times between 2 and 5μs. As can be seen from the figure, the results show reasonable agreement. It should be noted, however, that both the computer simulation and empirical equation predictions depend on the input data and assumed electrode parameters, which may affect the results shown in Figure 13.

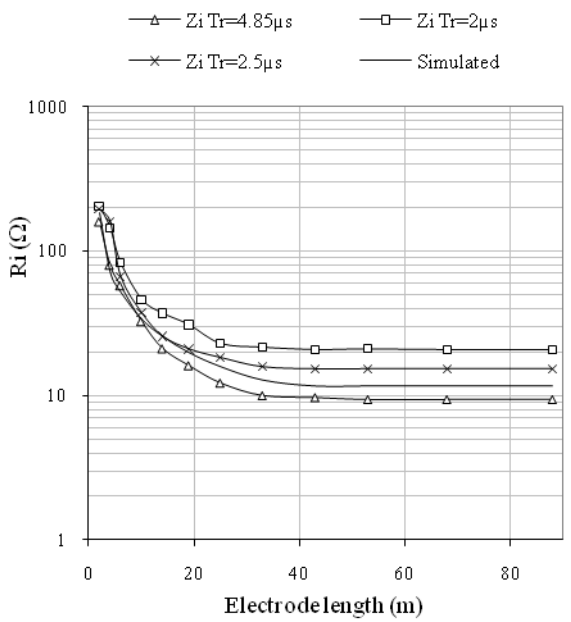

Figure 12: Impulse resistance vs. total electrode length for different rise-times for the straight horizontal electrode configuration.

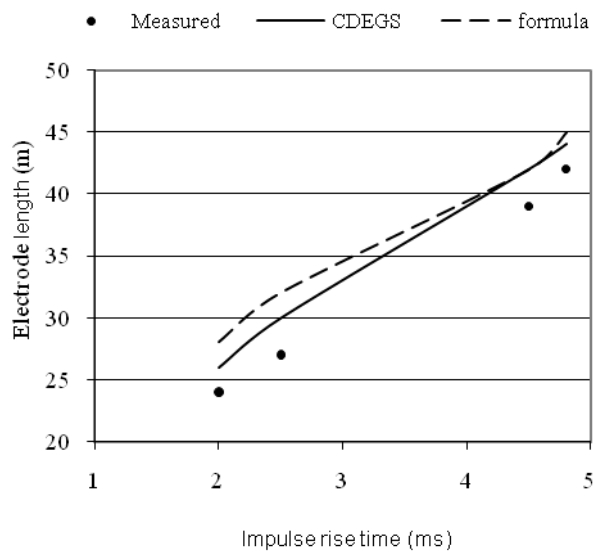

Figure 13: Predicted and measured effective length of a horizontal earth electrode

2.3 Proposed method to increase effective length

A recently reported newly-proposed method [11] to increase the effective length of the horizontal earth electrode suggests installing an additional insulated parallel conductor which is bonded to the bare underground horizontal electrode at points along its length. Computer simulations carried out based on a generic earth electrode model indicated significant potential benefits, including reduction of impulse resistance for a given length and extension of the effective length [11].

The proposed technique was applied in field tests to horizontal earth electrode, B by installing an additional PVC insulated copper conductor of cross-sectional area 25mm^2 running in parallel with the buried electrode. The insulated conductor, sectionalised in the same lengths as the bare buried electrode, was laid on the ground surface and bonded to the bare underground horizontal electrode at the sections points along its length. The impulse tests were carried out for increasing lengths of electrode both with and without the additional conductor. An impulse current having a 2.5μs rise time was injected at one end of the horizontal electrode. Figure 14 shows the calculated impulse resistance obtained from the voltage and current measurements for different electrode lengths. The higher impulse resistance values compared with those shown in Figure 11 is attributed to seasonal variations in soil resistivity.

As can be seen from Figure 14, the preliminary field tests of the new technique indicate that the addition of a parallel insulated conductor has reduced the impulse resistance by 22% which confirms the findings of the computer simulations. Further tests will be required to quantify the benefits of the technique under different impulse

shapes and to explore the optimal and most cost-effective arrangements for the interconnection of the insulated conductor to the buried bare conductor.

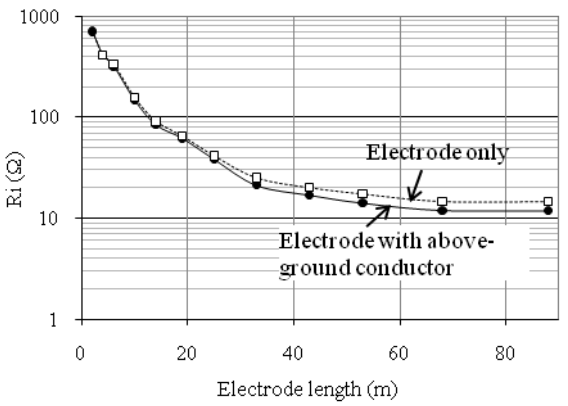

Figure 14: Effect of additional insulated conductor on impulse resistance as a function of horizontal earth electrode length

3. CONCLUSIONS

Experimental tests to investigate current and voltage distributions along two types of buried horizontal electrodes under impulse currents were reported. The results from both sets of tests show that a large proportion of the injected impulse current is dissipated into the ground along a length close to the injection point. The electrode potential also falls sharply with length starting from the injection point and then takes a constant value after a certain distance along the electrode. The effective length of the electrode was determined from the impulse resistance, and was found to be comparable to that predicted by a simplified empirical expression. This effective length is dependent upon the soil properties and the impulse shape. It was found that more current was dissipated over shorter distances along the horizontal electrode into the ground for fast impulses compared with the slow front impulse.

The test results obtained using a newly proposed method to increase effective length of earth electrodes, by installing a parallel insulated conductor, indicate that there may be promising potential for application in earthing systems practice.

3 REFERENCES

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