EARTH SURFACE POTENTIAL IN THE VICINITY OF TRANSMISSION TOWER UNDER LOW FREQUENCY AND TRANSIENT CURRENTS

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Abstract: In this paper, earth surface potentials and the corresponding step and touch voltages in the proximity of a transmission line tower footings due to low impulse and ac currents is investigated. The earth surface potentials were measured along diagonal and median profiles. The results show sharp potential gradients close to the tower footings. The earth surface potentials under impulse current are generally higher than those obtained using 50Hz ac current. However, the influence of frequency was also investigated, and it was found that high frequency ac current results in higher earth surface potential. The prospective impulse touch and step voltages measured at each tower footing were found to vary between footings and depend on the footing resistance. Tests with different auxiliary current return electrodes have shown that this has no noticeable influence on the magnitudes of measured earth surface potential and safety voltages.

1 INTRODUCTION

Under power frequency fault conditions the permissible values of step and touch voltages arising are available for outdoor transmission and distribution substations [1, 2]. However, there are no internationally-agreed safety thresholds for voltages arising under impulse conditions. When lightning strikes transmissions towers, the flow of current through the struck tower and adjacent towers may give rise to very high potentials, in excess of the tolerable power frequency voltage threshold values. However, in the absence of absolute transient voltage limits, qualitative measures may be implemented to control the magnitude of step and touch potentials, and this can be beneficial at often frequented tower locations. Studies related to the step and touch voltages in high voltage installations under lightning have been reported in the literature [3-5, 6].

Earth surface potentials developing near grounded structures under lightning and ac fault currents determine the magnitude of touch and step voltages in the immediate vicinity of the structure [7, 8]. These potentials may be of sufficiently high magnitude to endanger a person's life in the area. Thus, extra measures will be needed to minimise their magnitudes when designing earthing systems. The configuration and size of an earth electrode system and the soil resistivity determine the magnitude of the ground current.

The authors have previously reported on earth surface potential distribution near a full-scale 275kV tower base for low impulse and ac currents [9]. To supplement the previous work, the authors conducted additional experiments to study the influence of frequency and rise time on earth potential distribution. In addition, the influence of local resistivity around each individual footing on earth surface potential and the consequent step and touch voltages is also investigated. Finally, the effect of various configurations of return electrode on these voltages is examined.

2 EXPERIMENTAL SETUP

The test circuit, shown in Figure 1, consists of the current source, four 3m long tower footings arranged in a 7.25mx7.25m square, and a circular return current electrode. The impulse source is a low-voltage recurrent impulse generator with a maximum output voltage of 500V, and the ac source is a variable frequency impedance measurement system (IMS) developed for this type of tests [10]. The return electrode is composed of eight rods buried at a depth of 2.4m. These rods are distributed in the form of a circle of 30m diameter as illustrated in Figure 1. The rods can be interconnected by either bare or insulated conductors with cross-sectional area of 0.2cm^2, buried at a depth of 30cm. The earth surface potential (ESP) distribution was measured over four diagonal and two median profiles, which are 35m long each. The test probe method was used to measure earth potentials and the step and touch voltages [11]. In this method, rods of 53cm length, located at equal intervals, driven to 20cm depth were used [12]. A wide band current transformer having a frequency range from 1.5 Hz to 20 MHz with sensitivity 0.1V/A, and a high-bandwidth differential probe were used for these measurements. To eliminate interference including mutual coupling effects, a Nicolet fibre optic system was used.

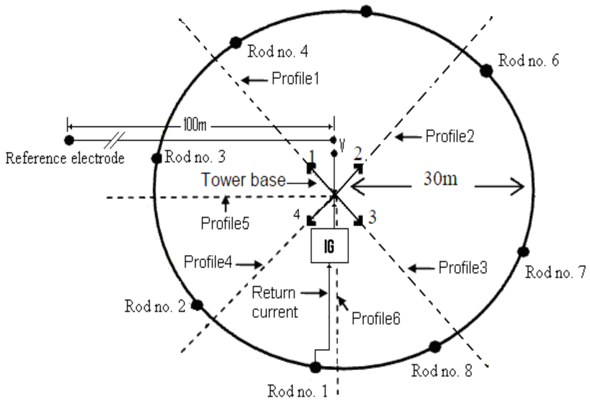


Figure 1: Experimental setup

Figure 2 shows an example of the applied low frequency AC current (2.5A) and the corresponding earth potential rise (EPR) of 65.8V at the injection point, measured with reference to a remote ground rod placed 100m away in the perpendicular direction to the return current line. As can be seen from the figure, the current and the earth potential rise are in phase, and the low frequency resistance of the tower base is 26.3Ω. In the case of the impulse source, a current of peak value 5.7A with a rise time of 2.7µs and a time to half value of 25µs is injected into the tower base and resulted in a potential of 126V as shown in Figure 3. The impulse resistance defined by the ratio of peak voltage to peak current is 22.2Ω.

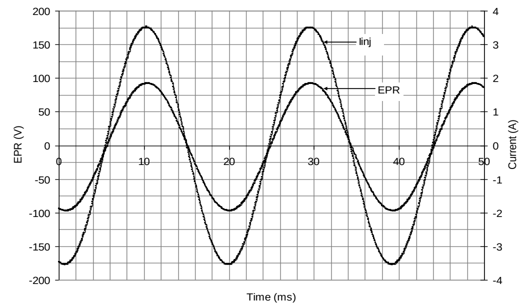


Figure 2: Injected AC current and tower base EPR (f=52Hz)

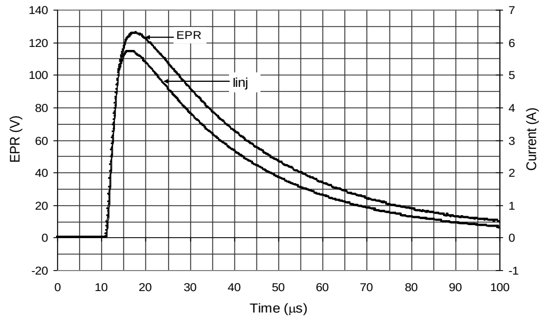


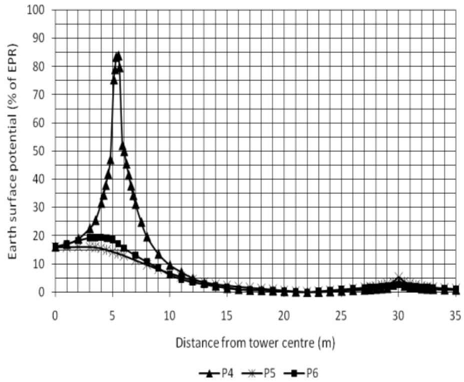
Figure 3: Impulse current and EPR

3 MEASURED EARTH SURFACE POTENTIALS

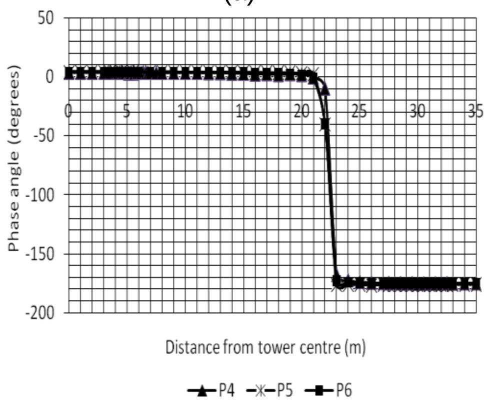
The surface potential was measured on profiles (P1 to P6) starting from the tower centre to 5m beyond the return current electrode as illustrated in Figure1. All ESP magnitudes are expressed in per cent of the tower EPR.

3.1 Low frequency AC voltage profiles

As can be seen from Figure 4.a, there is a marked difference in ESP distribution near the tower base between the diagonal (P4) and the median (P5, P6) profiles. In profile P4, the ESP reaches a maximum 83% of the tower earth potential rise, at a distance of 10cm from the tower footing. The potential decreases sharply with distance for the first 6 meters on the profile. Beyond this distance, its value is about 5% of EPR. For the median profiles P5 and P6, the maximum ESP magnitudes are only 16% and 19.5% of the EPR respectively. The differences between the P5 and P6 profiles may be due to variations in local soil resistivity. For distances longer than 12m, the potential distributions practically coincide, and decrease steadily to a minimum value at about 22m from the tower centre. At this distance, the potential due to the current entering the tower base is equal and opposite that due to the current leaving the return electrode. The effect of the ring electrode is indicated by the small rise in potential at a distance of 30m. Figure 4b shows the potential phase angle reversing at the location of minimum potential magnitude (22m).



(a)



(b)

Figure 4: ESP distribution under low frequency AC current (a) magnitude (b) phase angle

3.2 Low voltage impulse profiles

The peak impulse ESP distribution under low-magnitude impulse current is shown in Figure 5. The impulse peak potential reaches a maximum value of 94.7% of the impulse EPR 10cm away from the tower footing. Potential gradients near to the tower footings on profile P4 are much higher than those on profiles 5 and 6, and their trend is similar to that under AC current.

4 COMPARISON BETWEEN AC AND IMPULS PROFILES

Figure 6 shows the earth surface potential developed due to ac and impulse currents along profile P4. Close to the tower footings, the impulse ESP magnitude is slightly higher than the low frequency AC current magnitude. For instance, the maximum value of the impulse and AC ESP magnitudes are 94.7% and 83% respectively. In order to assess the anticipated hazard for a person in the proximity of the transmission tower, the touch and step voltages were measured for both cases. First, the touch voltage, due to injection of 2.5A ac current, on the diagonal profile at 1m from the tower footing is 38.5V corresponding to 58.5% of the tower EPR. With 5.7A impulse current, the touch voltage was 74.6V or 59% of the tower EPR. Second, the step voltage was measured at points 10cm, 20cm and 40cm away from the tower footing. The step voltages were 51.4%, 48.5% and 20.5% of EPR respectively under ac current, and 49%, 45% and 20% of EPR under impulse current.

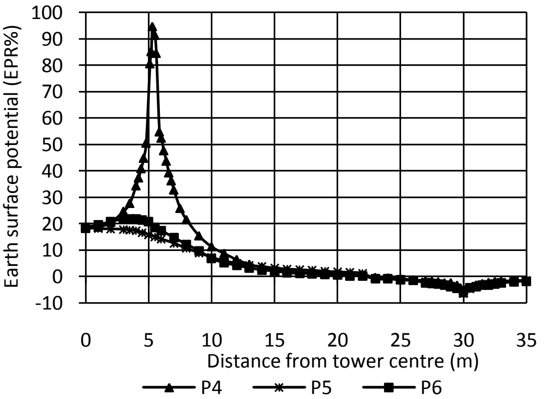


Figure 5: ESP distribution under impulse current

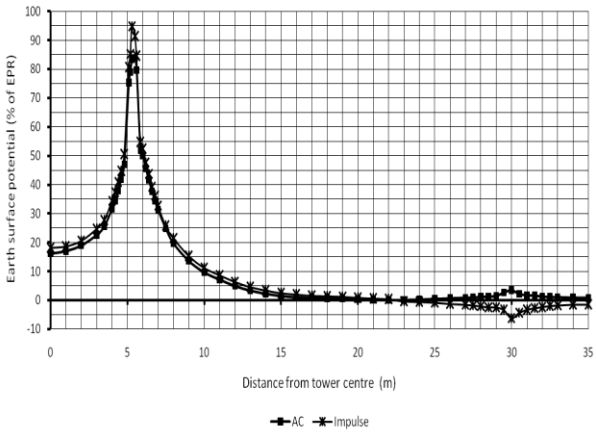
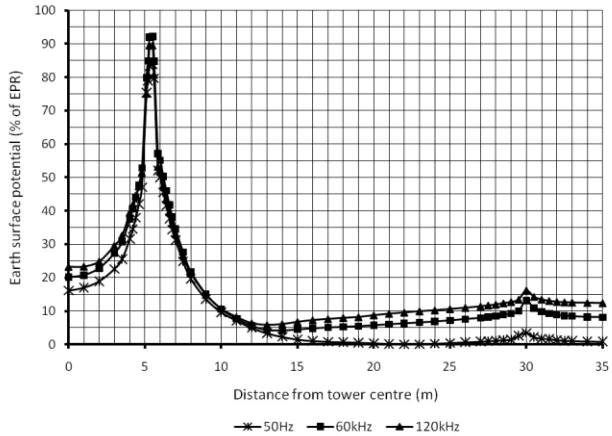


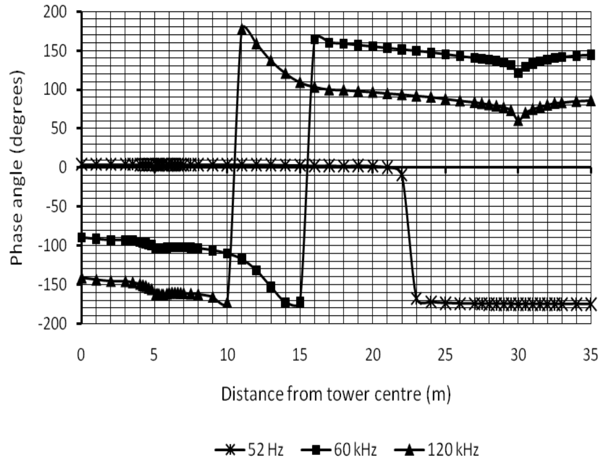
Figure 6: Comparison between ESP due to ac and impulse currents over profile P4

5 EFFECT OF FREQUENCY ON ESP

The ESP measured on the critical profile (P4) at different frequencies is shown in Figure 7. As can be seen, as the frequency increases, the earth surface potential increases proportionally for the range of frequency used in this experiment. Defining the zone of influence of the tower as the points where reversal of the ESP phase angle occurs for each frequency, a number of observations were made. Under low frequency current (52Hz), the influence of the tower base extended to a radius of 22m, while at frequencies of 60 kHz and 120 kHz its influence reduces to 15m and 10m, respectively. Figure 7b shows the extent of the zone of influence.



(a)



(b)

Figure 7: Measured ESP due for different frequencies (a) magnitude (b) phase angle

6 EFFECT OF CURRENT RISE TIME ON ESP

Figure 8 shows the impulse ESP distribution along profile P4 due to for three different current rise times, namely 1.2µs, 2.7µs and 6.9µs. As can be seen from the figure, an impulse current with fast rise time (1.2µs) gives rise to higher earth surface potential compared to other rise times. However, with fast impulse current, the touch voltage is smaller.

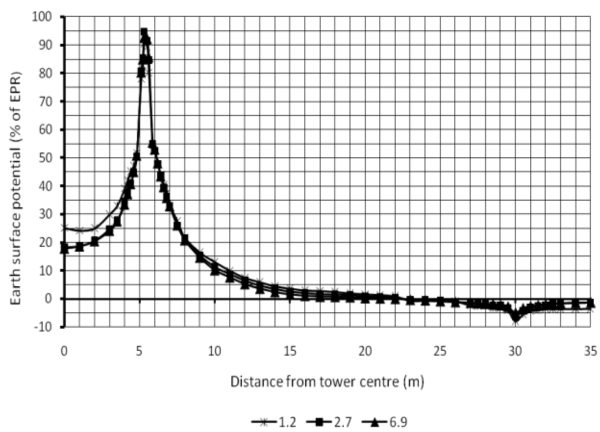


Figure 8: ESP profiles due to various rise times

For example, a current with 1.2µs rise time generates a touch voltage of 54.7% of the EPR while the touch voltage for a current with 6.9 µs rise time is 59.2%. This indicates that fast-rising impulse currents might be less hazardous to working personnel or public in close proximity to transmission tower.

7 ESP OVER DIAGONAL PROFILES

Most studies concerning the calculation of tower base earth surface potentials consider the transmission tower as a simple electrode and the surrounding soil to be homogeneous. This test has been carried out to understand the ESP distribution and to assess step and touch voltages around each tower footing in the context of lightning and DC currents. The DC resistances of the individual tower footings were measured as shown in Table 1.

Table 1: DC resistances of tower footings

	Footing 1	Footing 2	Footing 3	Footing 4
R (Ω)	117.6	67.2	80.7	64.2

7.1 Impulse voltage profiles

Figure 9 shows the ESP distribution measured over the four profiles passing through each tower footing, and it can be seen that the ESP distribution is dependent on the footing DC resistance. The highest and least changing ESP profile is associated with the footing with lowest DC resistance (Footing No4), while the lowest and steepest changing ESP occurs around the footing having the highest DC resistance (Footing No1). The highest step voltage was obtained along the profile which crosses the footing with lowest DC resistance. For example, as summarised in Table 2, the step voltage 1m away from Footing No4 in the outward direction is 17.4% of EPR whereas at the corresponding location of Footing No1, it is only 7.7% of ESP. The measured touch voltage in per cent of the earth potential rise is shown in Table 2. As expected, the highest touch voltage was obtained near the footing with the highest resistance (Footing No1), on the profile with lowest earth surface potential (P1).

7.2 DC voltage profiles

The earth surface potential along the four critical profiles was also measured using a DC source. Figure 10 shows the resultant earth potential per unit current along the diagonal profiles. As can be seen from the figure, a similar behaviour to the impulse source, in the previous section, was obtained, in which the steepest trend surrounding the tower footings was attained near Footing No4 and the flattest one near Footing No1.

8 EFFECT OF RETURN ELECTRODE ON ESP

This experiment was made to investigate the influence of the return earth electrode on earth surface potential distribution along the diagonal profiles and consequent step and touch voltages. Four return electrode configurations were used: a bare ring electrode (case 1), a bare ring electrode connected to eight vertical rods (case 2), a bare ring electrode with eight vertical rods and an insulated ring conductors (case3), and finally, the rod electrodes connected in parallel (case4) by an insulated ring conductor. Figure 11 shows the earth surface potential profiles for an impulse current magnitude of 5.7A with rise time 2.7µs. As can be seen from the figure, similar earth surface potentials were measures for all cases. The measured touch voltages (V_T) are not affected by the return electrode configuration as shown in Table 3.

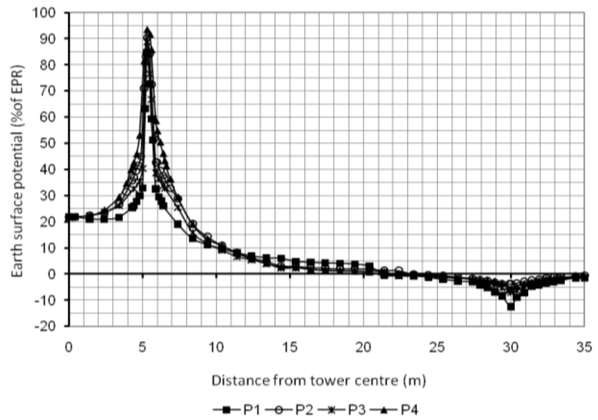


Figure 11: ESP profiles along each tower footing under impulse current

Table 2: Touch and step voltages around tower footings

	V_T (%of EPR)	V_S (%of EPR)
Footing No1	74.6	7.7
Footing No2	67.5	8.6
Footing No3	63	8.8
Footing No4	56.4	17.4

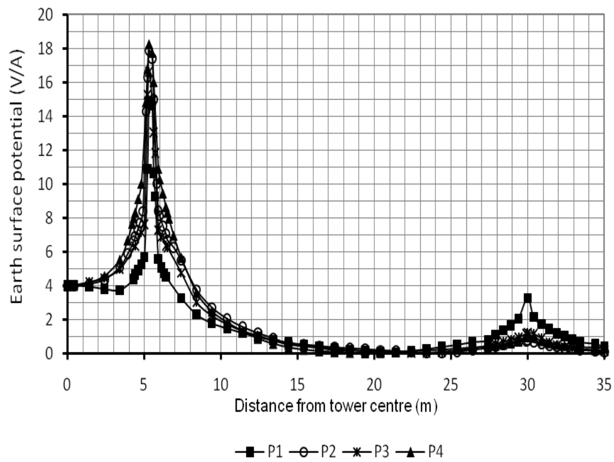


Figure 10: ESP profile over diagonal profiles under DC current

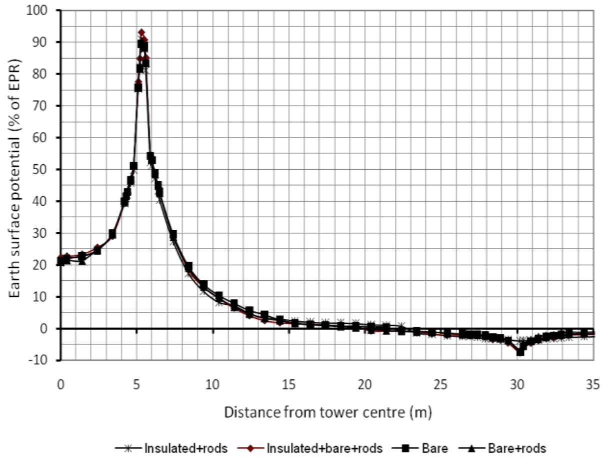


Figure 11: Influence of return electrode on ESP

Table 3: Touch voltage around tower footings

Touch voltage (% of EPR)				
	Case1	Case2	Case3	Case4
Footing1	75.64	76	76.91	76.85
Footing2	62.12	63.92	63.58	63.66
Footing3	65.74	66.91	67	67.34
Footing4	54.95	54.69	54.83	56.56

9 CONCLUSION

The earth surface potential, step and touch voltages in the vicinity of a full scale tower base have been measured over diagonal and median profiles under low impulse, ac and dc currents. High frequency currents produced high ESP magnitudes along the profile. It was found that impulse currents, having shorter rise times, generated a higher ESP in the vicinity of the tower base.

The dc resistance of tower footings were found to have different values due to differences in local soil conditions. Consequently, the impulse touch voltages at each tower footing depend on the resistance of individual footing, and the highest touch voltage was measured at the footing having the highest resistance. The impulse touch voltages measured around the footings were higher than the power frequency touch voltages.

The ESP distributions were different over the four profiles crossing each tower footing. The highest and flattest ESP profile occurs near the footing with lowest DC resistance, and the lowest and steepest ESP occurs near the footing having the highest DC resistance. The highest step voltage was obtained along the profile which crosses the footing with lowest DC resistance. The configuration of the return electrode did not have any influence on the ESP and step and touch voltages.

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