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Experimental investigation of high frequency and transient performance of earth rod systems

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ABSTRACT

The high-frequency performance of vertical earth rods is important for designing earthing systems and lightning protection systems. In this work, experimental investigations on the high-frequency and impulse response of vertical earth rods with horizontal electrode enhancements are described. The rod electrode systems are installed at the Cardiff University outdoor earthing test facility and variable frequency tests were carried over the range 50 Hz–10 MHz. In addition, a low voltage impulse generator was used to inject impulse current of variable magnitude and shape into the electrode under test. The application of '4-point cross' and '8-point star' enhancements to single-rod electrodes have not only demonstrated the expected reduction of low frequency earth resistance but have also helped with a reduction in impedance at higher frequencies. Such enhancements may produce a greater overall benefit compared with extending the length of the rod only. Numerical simulations of the experimental setups agree quite well with test results over a low frequency range but more significant differences are seen at higher frequencies.

1. Introduction

Earthing systems are designed to facilitate the flow of high magnitude fault currents to ground and provide safety to persons working in or living near power system installations. In high voltage substations, the combination of buried earth grids, vertical rods and horizontal electrodes provide a low impedance connection to earth. Vertical earth rods are widely used in earthing systems and, in lightning protection systems, either as main earth electrodes or as reinforcing electrodes to help reduce the earth impedance and improve the high frequency and transient performances. Their frequency and transient behavior has been the subject of experimental and theoretical studies [1–15]. However, no established technique is available to investigate experimentally the performance of these electrodes under variable high frequency up to the megahertz range.

In this work, we explore the high-frequency and impulse characteristics of different-length vertical rods with and without enhancements of horizontal electrodes in 4-point cross and 8-points star configurations under high frequency and impulse injections. The tests were carried out at the Cardiff University outdoor earthing test facility at Llanrumney fields. Low voltage variable frequency and impulse generators were used as sources, and measurements of current injected into the electrodes, and the resulting earth potential rise with respect to a remote potential reference electrode were taken. The test setups were modeled using the CDEGS earthing software [8], and the simulated results are compared with the measured values. The variable frequency tests reveal the benefits of extending rod length to low frequency performance. However, as is well-known, these gains diminish with length. At higher frequencies, the results indicate that rod length extension is not effective in reducing earth impedance. The impulse tests reveal a similar trend to that seen for low frequency and DC resistance tests. The horizontal 'cross' and 'star' enhancements to the rod provide benefits across the entire frequency spectrum and to the transient performance. Good agreement is obtained between experimental results and computer simulation.

2. Experimental setup

Fig. 1 shows a diagram of the experimental setup used for the high frequency and impulse tests. The test electrodes used are 1.2 m, 2.4 m, 3.6 m, 4.8 m and 6 m-long rods of 14 mm diameter. The rods were enhanced, in turn, with 'cross' and 'star' configured

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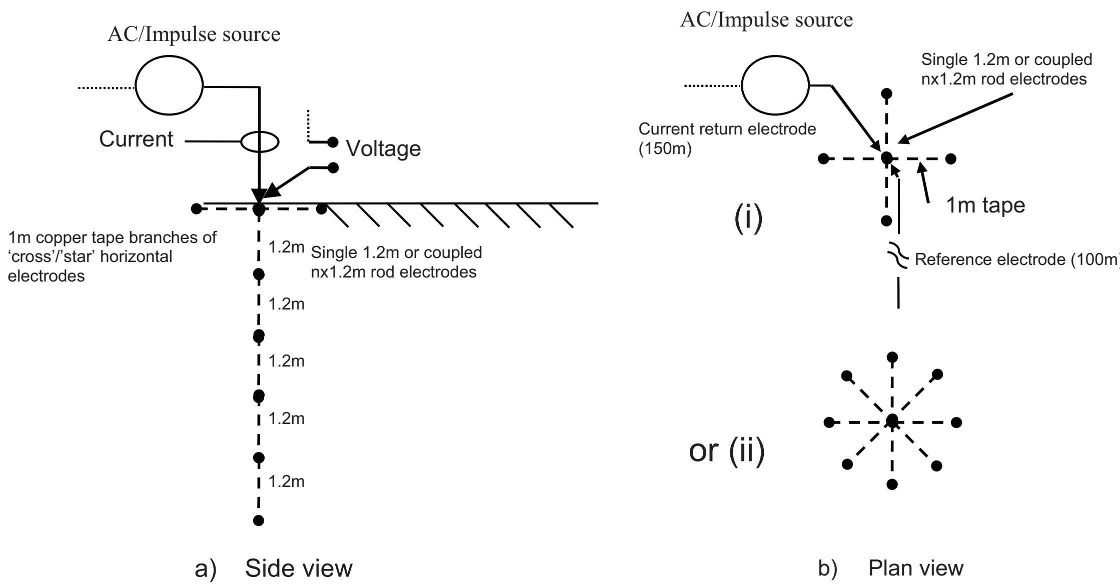

Fig. 1. Plan and side views of experimental set-up: rods with (i) 4-point cross and (ii) 8-point star enhancements.

horizontal rod conductors of 1 m length and 8 mm diameter and these were buried at a depth of 30 cm. Audio-frequency (AF) and radio frequency (RF) signal generators and corresponding AF and RF power amplifiers (up to 2.4 kW) were used to inject AC currents of several hundred milli-amperes and up to 10 MHz frequency. A Haefely recurrent surge generator was used to produce impulse currents of different shapes with amplitudes up to a few amperes. The current return electrode was located 100 m from the test object, and the reference potential electrode, fixed 150 m away, was connected by a lead placed orthogonal to the current return lead. Current transformers of 0.1 V/A sensitivity with a bandwidth of 20 MHz, and high-bandwidth differential voltage transducers were used for the current and voltage measurements. In addition to the ac and impulse tests, DC resistance measurements were carried out on the rods of different length with and without their cross/star enhancements. An evaluation of the degree of variation in electrode performance was made by repeating the DC resistance measurement several times over the testing period.

3. Analysis of measured results

3.1. DC resistance of rods and enhanced electrodes

The DC resistance of the different earthing configurations was measured with a Megger DET2/2 instrument using the standard '4-point' technique. The rod electrode sections were installed in stages over a period of 2 years. The first 1.2 m electrode was installed for an initial period of several months during which the cross and star enhancements were added. The 2.4 m electrode was formed by driving an additional 1.2 m electrode on top of the existing electrode and so on. The DC measurements were repeated at a frequency of about once or twice per month. Table 1 shows the average DC resistance of all the electrode configurations and as can be seen in table, as the earth rod length increases, the earth resistance decreases. Also, as is well-known, there is a slower rate of reduction of resistance as length increases. The addition of the star and cross electrodes reduces significantly the overall DC earth resistance for all rod lengths. Fig. 2 shows the variation of the DC resistance of the different length rods of the testing period. The greatest variation in resistance is seen with the 1.2 m rod and, although no detailed rainfall measurements were taken at the site, it was noted that the period March–April 2011 was particularly dry

Table 1
Average measured DC resistance of earth rod systems.

Configuration	DC resistance (Ω)
1.2 m rod	119
1.2 m rod with cross-shaped electrode	47
1.2 m rod with star-shaped electrode	37
2.4 m rod	57
2.4 m rod with cross-shaped electrode	29
2.4 m rod with star-shaped electrode	23
3.6 m rod	45
3.6 m rod with cross-shaped electrode	27
3.6 m rod with star-shaped electrode	20
4.8 m rod	35
4.8 m rod with cross-shaped electrode	25
4.8 m rod with star-shaped electrode	18
6 m rod	31
6 m rod with cross-shaped electrode	18
6 m rod with star-shaped electrode	16

and this corresponded to the highest recorded values of resistance. Also from figure it can be seen that, for the longer rods subsequently installed, there was less variation in measured resistance. This may be explained by the expected lower variation in soil moisture at depth.

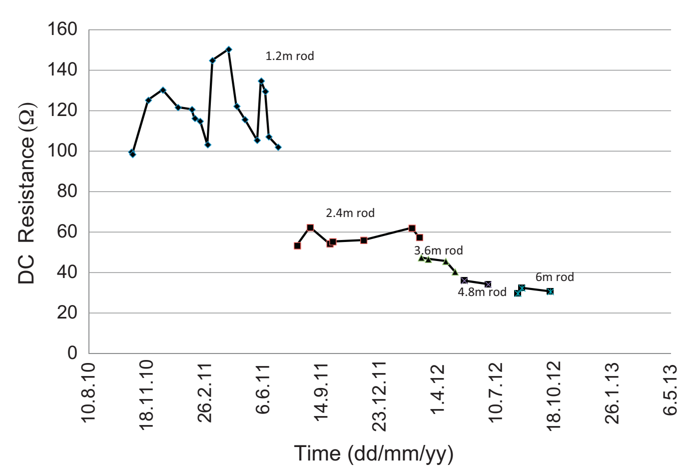

Fig. 2. Variation in measured DC resistance of rod electrodes.