

# MEASUREMENTS FOR TESTING EARTHING SYSTEM INTEGRITY

**A.M.Davies, Earthing Measurements Ltd, UK**  
**J.Queenan, GPU Power, UK**  
**T.E.Charlton, Strategy & Solutions Ltd, UK**  
**H.Griffiths, Cardiff University, UK**

## AUTHOR BIOGRAPHICAL NOTES

**Mark Davies** has recently completed a PhD investigating the performance of earthing systems under high frequency and transient conditions. He is currently a director of Earthing Measurements Ltd, who offer a range of measurement services for high-voltage substation earthing systems. He has carried out numerous measurements at electrical installations throughout the UK.

**John Queenan** is Head of Protection at GPU Power UK. He is responsible for company policy for both Protection and Substation Control Systems. In addition, he is responsible for company Earthing policy. He is a member of the Electricity Association Protection Approvals Panel.

**Trevor Charlton** is the Managing Director of both Strategy & Solutions Ltd. and Earthing Measurements Ltd. These companies supply earthing design, research, training and measurement services to most of the UK electricity companies and their contractors.

**Huw Griffiths** is a lecturer at Cardiff University and his research interests include the analysis and measurement of electrical earthing systems under power frequency and transient conditions.

## ABSTRACT

Measurements of newly installed earthing systems are required to confirm the design value of earth resistance and the integrity of joints etc. In addition, periodic measurements throughout the life of the earthing system are necessary to ensure continued satisfactory performance. Current Standards<sup>1,2,3,4</sup> suggest that maintenance checks are carried out at regular intervals e.g. every 5 to 6 years or after any major change to the earthing system.

However, presently, there is no single measurement which can verify the integrity of the whole earthing system. Therefore, to establish integrity, several measurements are made of sample parts of the earthing system such as earth rods, joints and bonding conductors. In addition, the whole earthing system resistance is also measured. This paper describes the various measurement techniques used.

The most important parameter to be measured is the overall earth resistance or impedance. Monitoring this quantity over a period of time can help to identify whether a substantial change to the integrity of the earthing system has occurred. Its usefulness as an indicator of integrity requires that measurements are carried out in a consistent manner, and that variations in impedance as a result of other factors are minimised. One of these factors, electrical noise, which is present in all electrical installations, is shown to effect measurements and methods are described that investigate its effect.

## **1. REVIEW OF MEASUREMENT TYPES**

This section describes the main tests used to check earthing system integrity. It should be noted that these measurements are used within a specific assessment methodology which includes both visual inspection, electromagnetic detection techniques and trial excavations. It is important to confirm that the installed earth electrode system corresponds to the records.

Periodic measurements are essential to monitor the earthing system condition and can help to identify deterioration in integrity, for example due to corrosion, damage or theft.

Accurate historical records and a consistent measurement procedure are necessary to achieve this.

### **1.1 Bonding Integrity Test**

This test checks the integrity of bonding conductors and associated joints between the main substation earth electrode and individual items of plant. This is achieved using a micro-ohmmeter in four-terminal mode to measure the resistance between a known (reference) point on the substation earth electrode and the item of equipment under test. The measured resistance can be compared to the calculated value for the bonding conductor(s). A measured value significantly higher than the calculated one may indicate corrosion of the copper earth electrode or defective joints, in which case further investigation is necessary.

### **1.2 Joint Integrity Test**

Normally, this test uses a micro-ohmmeter in four-terminal mode to check that the resistance of the length of conductor is similar to one without a joint. Ultrasonic testing is also sometimes used to check for voids in exothermic-weld type joints. If joints are found to have too high a resistance they need to be broken down and remade or replaced using an appropriate safety procedure.

### **1.3 Earth Resistance Measurement for Individual Components**

Some substation earthing systems include individual components (e.g. earth rods, earth plates or foundation piles) which can be disconnected by test links accessible from inspection pits. This sub-section describes two methods of measuring the comparative earth resistance of such components. The methods only provide satisfactory results when the resistance of the component is high (at least ten times) compared to the rest of the earthing system. If necessary, the fall-of-potential method, described later, can be used to check the results. This measurement can provide a useful means of monitoring the condition of the earthing system components over time.

#### **1.3.1 Clamp Type Meter**

This type of meter induces a current in the earthing system component under test which is returned in a loop via the rest of the earthing system. The current through and voltage across the loop are measured and the resistance calculated. The measured resistance is the earth loop resistance i.e. the resistance of the component in series with the rest of the earthing system. The

lower the resistance of the rest of the earthing system, the closer the measured loop resistance is to that of the component under test.

The advantage of this method is that the earth component under test does not need to be disconnected from the main earth grid. It provides a quick and simple test and avoids operational and safety issues associated with the disconnection of earthing system components. This is especially important in some installations, for example oil refineries.

### **1.3.2 Measurement by Comparison**

The earth resistance of an individual component can also be measured with a four-pole earth tester using a similar technique to the clamp-type meter. However, for this test, the individual component has to be disconnected from the main earthing system so that separate current and potential connections can be made to the component and rest of the earthing system.

## **1.4 Earth Resistance / Impedance Measurement**

The most important test used to check the integrity of an earthing system involves the measurement of its overall earth resistance or impedance. Some different methods for carrying this out are reviewed in this section.

After the installation of a new earthing system, tests are required to confirm its calculated (design) value and hence the predicted performance during fault conditions. These tests are also useful when carried out throughout the life of the earthing system. An increasing trend in the overall measured earth resistance may indicate a loss of integrity. Possible causes for this include corrosion, damage or theft of electrode and deterioration of joints. Also, some earthing system components may have become disconnected in error e.g. the loss due to damage or theft of an earth bond to a tower line earthwire or foundation electrode. In addition, the replacement of lead sheathed cables with plastic insulated types will deplete the earthing capability of the system.

Although the comparison of a series of earth resistance measurements can provide a useful check of earthing system integrity, there are a number of factors which can influence the measured earth resistance and could be misinterpreted as a loss of integrity. This aspect will be discussed in Section 2.

### **1.4.1 Fall-of-Potential Earth Resistance Measurement**

This is the standard method used to measure the earth resistance of an earthing system, as described by Tagg<sup>5</sup>. The method involves passing a current into the earthing system under test and returning it via a temporary current electrode some distance away. Measurements are taken at different potential probe positions, (usually between 80% and 20% of the distance to the current probe) to produce a curve of apparent resistance against distance.

There are different methods for interpreting the apparent resistance curve to arrive at the actual earth resistance. For the simplest case, Tagg showed that for a hemispherical electrode in uniform soil, the actual resistance value occurs at 61.8% of the distance from the electrode centre to the remote current electrode. This assumes that the distance is sufficient (5 to 10 times the largest dimension of the electrode is suggested). The Slope Method can be used when the

centre position of the earthing system is unknown and can provide an indication of whether the simplified model can be applied to the measured data.

Alternatively, in order to take into account the actual geometry of the earthing system and multi-layer soil conditions, detailed computer simulations<sup>6</sup> can be carried out.

### **1.4.2 Fall-of-Potential Earth Impedance Measurement (Low Current Injection)**

Most composite earth testers use a switched d.c. signal and therefore measure earth resistance. In order to measure earth impedance, a.c. signals are required. Due to the high magnitude of standing voltage on earthing systems, it is usually difficult to test using a low current magnitude at 50Hz. Measurements are often taken at frequencies of approximately 40Hz and 60Hz and the 50Hz value obtained by interpolation.

The in-line fall-of-potential method can be used for a.c. earth impedance measurements. However, because the current circuit is parallel to the voltage measuring circuit, significant mutual coupling occurs between them. A correction for this mutual coupling can be made. Mutual coupling can be avoided by using the '90° method', where the potential and current test leads are orthogonal. As it is often difficult to obtain two suitable test routes at 90° to each other, the in-line method is the most common in practice.

### **1.4.3 High Current Injection Impedance Measurement**

For this method, the four-terminal composite tester is replaced by instruments capable of passing and measuring significantly higher current (50 to 200A). Normally, the equipment would include a power source and the test current would be fed in via a power circuit (e.g. overhead line). Voltage measurements would be taken with reference to a remote earth, via a metallic type of telephone circuit.

These measurements are now less common and the readings obtained are not necessarily reliable. The main reason for this is the inability to account for the non-ground return component of the test current, which circulates between test and injection points via sheaths of underground cables interconnecting them. This measurement is mainly suitable at substations which have an isolated lower voltage network, i.e. interconnection with other substations does not exist or is only available via unearthed overhead lines.

It should be noted that this type of measurement may be the only one possible in urban areas, where there is no suitable measurement route near the substation. For accuracy, it is ideal if the test current mimics the network main fault current source, in terms of source impedance and circuit parameters. It is quite rare to be able to carry this out in practice and measure all the relevant data.

## **2. SOURCES OF ERROR ASSOCIATED WITH EARTH RESISTANCE MEASUREMENTS**

As mentioned in section 1.4, an increase over a period of time in the measured overall earth resistance or impedance may not necessarily indicate a loss of integrity, because the measurement results may be affected by other factors. In a previous paper<sup>7</sup>, some of these factors were identified and are summarised below:

- Insufficient traverse length compared to size of electrode system.
- The effect of soil structure on interpretation.
- The effect of buried metallic structures.
- Interference due to coupling with the test leads.
- Measurement equipment limitations.
- Seasonal variation.
- Interference due to standing voltage (noise) on the earthing system.

Experience has been gained by taking a large number of measurements at electricity substations throughout the UK. This has led to better understanding of these factors, especially noise. In the following section, typical standing voltage magnitudes are described and two case studies presented which illustrate the problems associated with taking measurements at noisy sites.

### **3. STANDING VOLTAGE (NOISE) ON A SUBSTATION EARTHING SYSTEM**

During normal operating conditions, a voltage is present on a substation earthing system with respect to true earth potential. When an earth resistance measurement is being carried out the standing voltage, or 'noise', may be significant enough to interfere with the measurement signal and adversely affect results. The noise measured at a typical 132kV substation over a range of frequencies from 20Hz to 200Hz with respect to a remote reference electrode is shown in Figure 1. As expected, the highest magnitude of noise occurs at 50Hz, the second highest at the third harmonic (150Hz) and a small peak is evident at 100Hz. There are 'quiet windows' away from these three frequencies where there is very little noise.

Some commercially available composite earth testers can be used successfully at sites where this type of electrical noise exists, provided they have a satisfactory noise filtration capability. Generally, the less expensive testers, tend to give unreliable results even with a relatively low level of noise.

At some sites, where there is a high level of electrical noise or the noise levels vary, it is not possible to use any of the existing commercially available composite earth testers with success. More specialised and noise tolerant equipment is then required. Two case studies are presented of such sites, which demonstrate the effect on composite instrument measurements and measured noise levels.

#### **3.1 Case Study 1 - Earth Impedance Measurement at a Railway Supply Substation**

The substation described in this case study provides a 25kV single-phase supply to an electrified railway via two 132kV/25kV single-phase transformers. The 25kV supply is provided by relatively long single-phase concentric cables.

Attempts to obtain a stable earth resistance measurement at this site using a composite instrument proved unsuccessful due to the high magnitude of standing voltage on the earthing system.

The standing voltage on the earthing system was measured using equipment developed with Cardiff University<sup>8</sup>. The measurements represent a 'snapshot' of the noise over the frequency range 20Hz to 200Hz at a particular time. The level of standing voltage was in fact varying

significantly, depending upon when the measurement was taken. For example, the results of three standing voltage measurements are shown in Figure 2, where the peak voltage can be seen to vary from approximately 1V to 45V.

The variation in earthing system standing voltage is due to the use of a single-phase cable system, one phase being earthed at both cable ends. Although most of the load current returns via the cable return conductor, a proportion returns via the ground. It is this current which causes the voltage rise on the earthing system at the source, and the variation in magnitude corresponds to the load (train) activity in the vicinity of the supply point. The current magnitude is a function of the cable type, size and length, the method of earthing and the source and receiving end earth impedances. It can be estimated using tables (e.g. EA ER S.34<sup>9</sup> Figures 7 to 17) or using computer simulation<sup>6</sup>.

A successful earth impedance measurement was taken by monitoring the standing voltage level and taking the measurements during relatively 'quiet' periods.

### **3.2 Case Study 2 - Earth Impedance Measurement at a Large Power Station Site**

Composite earth testers have also been found to be susceptible to relatively low-level unstable noise.

Figure 3 shows the standing voltage measured on a large power station earthing system. The magnitude of noise is not very high compared to some sites, but shows a significantly varying noise magnitude. Possibly, a dynamic variation of the standing voltage is more difficult for composite instruments to filter. Typical readings from a composite instrument affected by this type of noise show a large range in the measured values and sometimes a reduction in accuracy (e.g. from 3 to 2 decimal places).

Figure 4 shows the measured values for a fall-of-potential earth resistance measurement at the site for a traverse length of 1.6km using one of the better composite instruments. The error bars show the range of values obtained from up to 10 measurements at each potential probe position. The median values do not follow the standard 's' shaped curve which would normally be expected for this test.

For this site, specialised equipment was used to obtain an acceptable signal-to-noise ratio. This allowed the site earth impedance to be measured reasonably accurately, so that the earth potential rise could be determined with some degree of confidence.

## **4. CONCLUSIONS**

Different measurements which can be used to help assess the integrity of earthing systems have been reviewed. It is recommended that these measurements are used as part of an overall assessment methodology that monitors individual earthing components as well as the overall earth resistance or impedance.

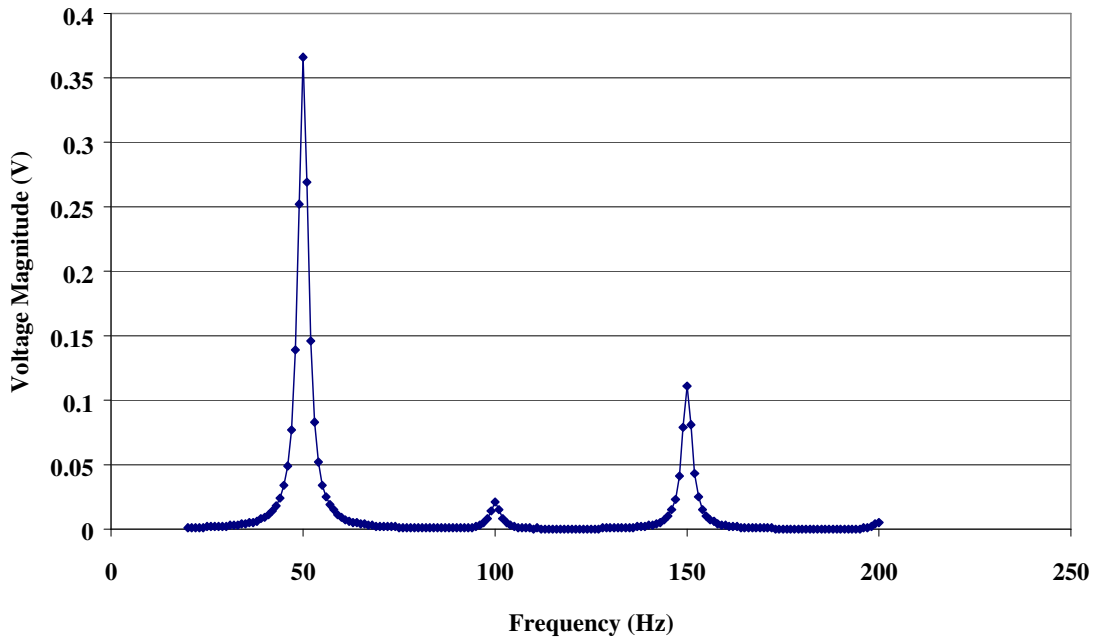
Measurement of the overall earth resistance is important and must be carried out using suitable equipment and techniques, in a consistent manner without being adversely affected by environmental factors. It should be noted that the tests are based on low magnitude current injection and therefore cannot guarantee that all of the earthing system components will be able

to carry the full earth fault current. A high-current injection test, or a staged earth fault, could be used for this purpose, but would be much more expensive and have operational implications. Standing voltage or noise on earthing systems can adversely affect composite instruments and provide inaccurate measurement results. Case studies have illustrated typical examples of this and highlighted the unsatisfactory behaviour of composite instruments in the presence of electrical noise. It should be noted that only the better quality, and noise tolerant, composite instruments have been used. At 'noisy' sites, specialised equipment is necessary to measure earthing system impedance accurately.

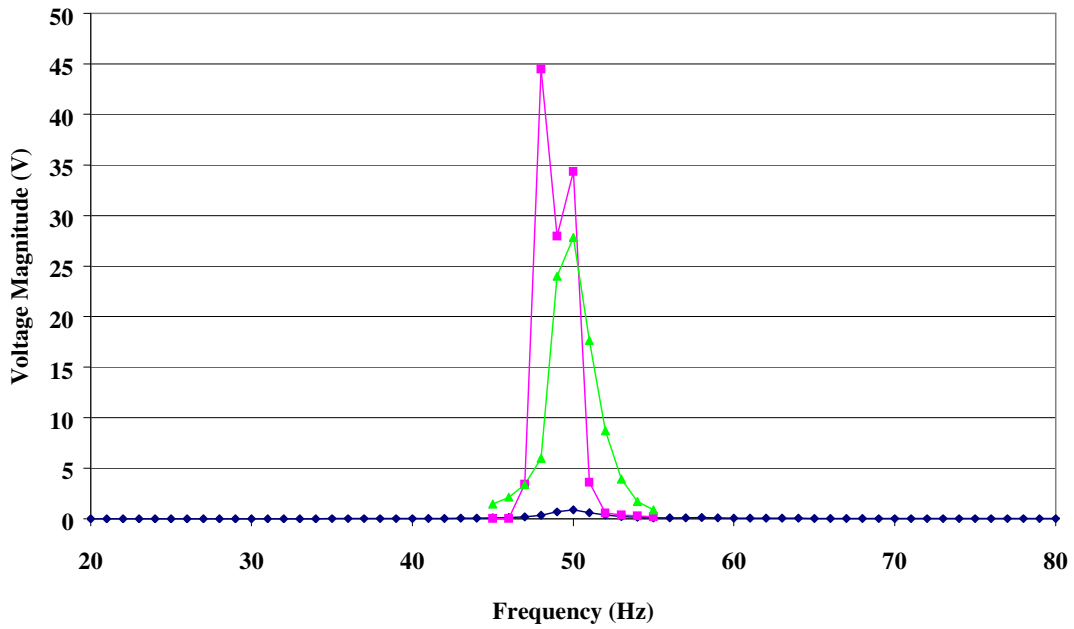
## **5. REFERENCES**

1. Technical Specification 41-24, Guidelines for the Design, Testing and Maintenance of Main Earthing Systems in Substations, Electricity Association, 1992.
2. BS 7430, Code of Practice for Earthing, British Standards Institution, 1991.
3. DIN VDE 0141:1989, Earthing Systems for Power Installations with Rated Voltages Above 1kV, (Technical Help to Exporters Translation, British Standards Institution).
4. HD637-S1, Power Installations Exceeding 1kV a.c, (formerly CENELEC prEN 509179), July 1999.
5. G.F.Tagg, Earth Resistances, George Newnes Ltd, London, ISBN 003210, 1964.
6. Current Distribution, Electromagnetic Interference and Grounding Analysis Software (CDEGS Version 8.0.0), Safe Engineering Services, Canada, 1999.
7. T.E.Charlton, P.Jones, A.M.Davies, Measurement of Earthing System Resistance: Problems Encountered and Some Ways of Overcoming Them, Earthing Solutions: Standards, Safety and Good Practice, ERA Report 97-0533, ERA Technology, Paper 3.3.1, 1997.
8. P.Jones, PhD research project, School of Engineering, Cardiff University, (In Progress).
9. Engineering Recommendation S.34, A Guide for Assessing the Rise of Earth Potential at Substation Sites, Electricity Association, 1986.

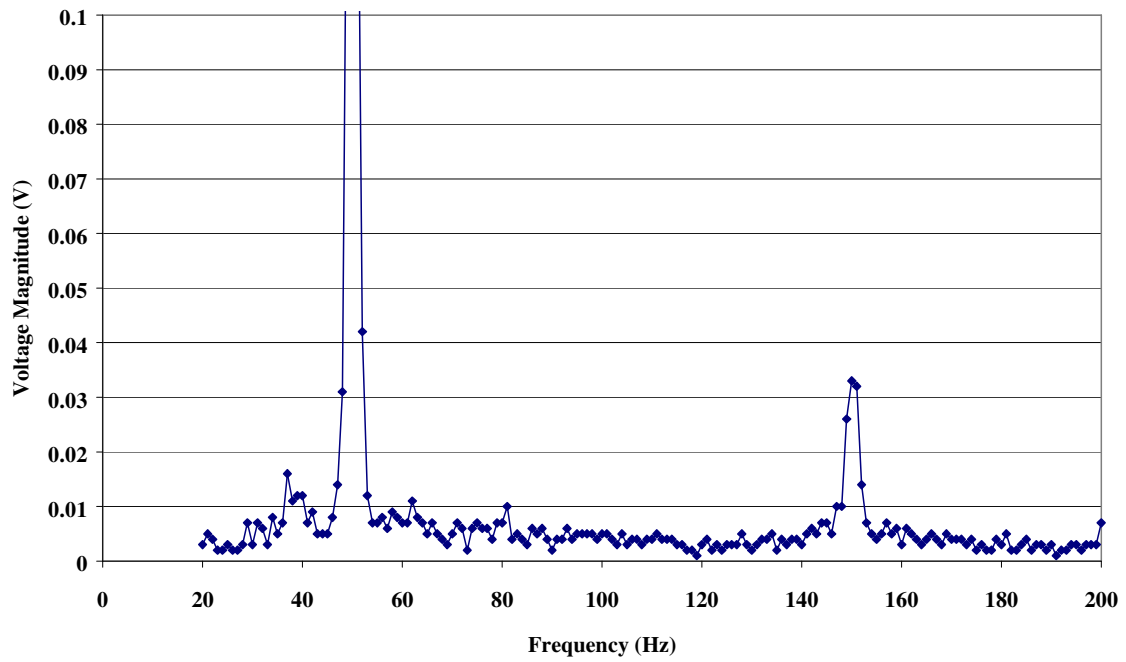
**6. FIGURES**



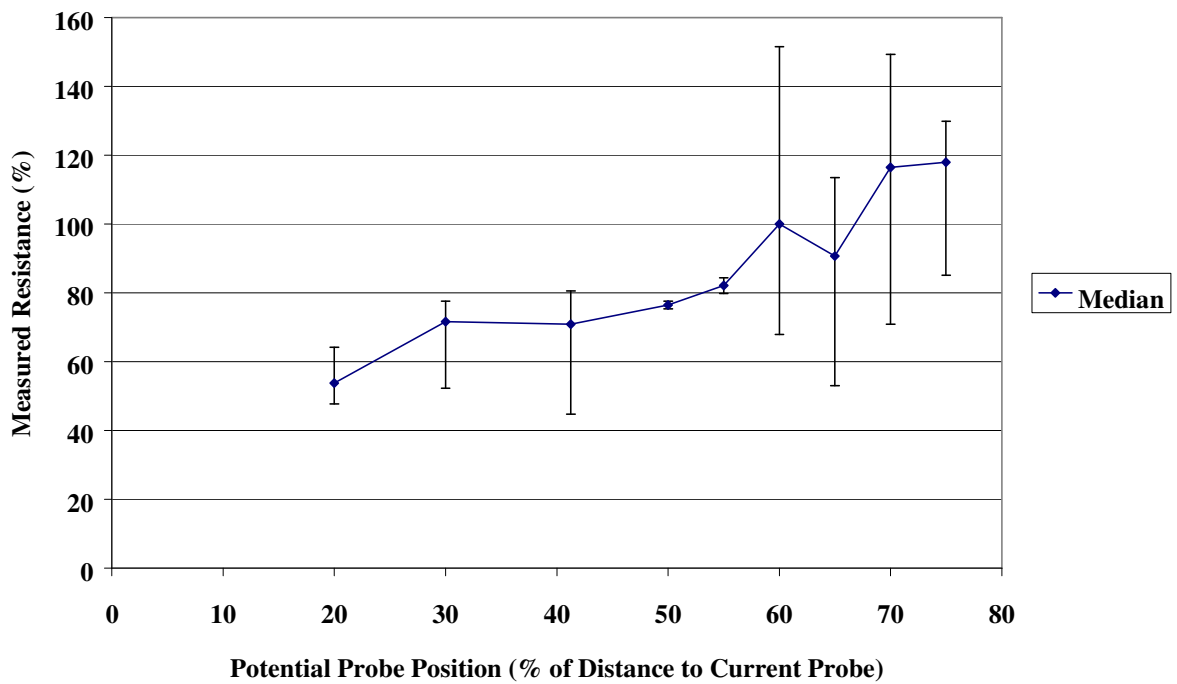
**FIGURE 1: Typical Standing Voltage (Noise) Measured on a Substation Earthing System**



**FIGURE 2: Railway Supply Substation - Standing Voltage on Earthing System (Different Curves Represent Measurements taken at Different Times)**



**FIGURE 3: Large Power Station - Standing Voltage on Earthing System**



**FIGURE 4: Large Power Station - Effect of Noise on Composite Earth Tester Measurements**