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Application of an Analysis Technique to Characterise Impulse Response of Grounding Systems

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***Abstract*— Transient response plays a key role in the evaluation of the performance of grounding systems and for the protection of electrical installations under lightning strikes. The frequency spectrum of the lightning impulse contains harmonics components up to the megahertz range. The measured transient response of grounding systems under test may be distorted by spurious high frequency interference in the acquired signals, which presents challenges for the accurate analysis of high frequency performance of such systems. In this paper, the high frequency performance of a rod electrode is investigated based on measurements of its transient response under impulse energisation. A practical method is implemented to eliminate the high frequency noise in the measured voltage and current shapes, which allows a frequency domain analysis based Fast Fourier Transforms.**

Keywords-Grounding system, grounding impedance, lightning strike, impulse response, harmonic noise, FFT analysis.

I. INTRODUCTION

Lightning performance is one the most important aspects in the design and operation of power systems. In this regard, grounding systems play a significant role in protecting the power system equipment when subjected to lightning strikes. Effective design of the grounding system requires a detailed knowledge of the response of such systems to power frequency faults as well as lightning impulses. Grounding systems of relatively small dimensions, such as ground rods, behave resistively under power frequency. However, these electrodes behave differently under lightning impulse currents, and may exhibit additional inductive and capacitive effects. Such effects depend mainly on the characteristics of the impulse shape, physical dimensions of the grounding electrode and properties of the soil medium [1-4].

Under low frequency energisation, the reactive effect of the grounding system is usually negligible and, hence, it is very common to characterise the grounding system by its low-frequency resistance R_{LF}. Lightning strikes currents, on the other hand, contain a large number of high frequency components. It is, therefore, possible to describe a complex grounding impedance for each particular harmonic component, which is known as high-frequency impedance Z_{HL} or harmonic impedance $Z(\omega)$ [2, 5].

Recent publications report developments in the understanding of the transient response of grounding systems, considering characteristics of the impulse shape, physical dimensions of the grounding systems and properties of the soil medium [2, 5-9]. In most of these works, however, the impulse responses of the test electrodes were evaluated in time domain in terms of impulse resistance and dynamic resistance.

Simulation and experimental work have been also performed to investigate frequency dependence of soil parameters, e.g. resistivity and permittivity, by analysing the transient response of test electrodes [5, 10-14]. The experimental evaluation of the transient performance of practical grounding systems, including grounding impedance measurement, involves a significant challenge regarding high levels of background noise. Most of the noise energy from practical installation is from the power frequency and its low order harmonics. There is some high frequency interference in the range for interest from radio transmitters [15]. Practical techniques have been proposed to overcome the difficulties regarding the background noise and to obtain an adequate signal-to-noise ratio (SNR) during power frequency tests [16-18]. Evaluating the correct impulse response, as well as, frequency response of the grounding system in the presence of high levels of noise requires suitable techniques to extract and analyse the signals.

In this paper, the high frequency performance of a vertical rod electrode is evaluated based on the impulse response. It is important to note that the electrodes, located at the Llanrumney university test field, implemented in this work are not connected to the power system and, therefore, the levels of power frequency noise are relatively low. High frequency background noise elimination, to extract the frequency response of the grounding system, is proposed and applied to the measured signals in this study. The results in frequency domain can be implemented to study the effect of high frequencies on the grounding impedance.

II. DESCRIPTION OF THE TEST ELECTRODE AND EXPERIMENTAL SET-UP

An experimental study, including variable frequency and impulse tests, was undertaken on a practical rod electrode. A description of the test electrode, measuring system and test configuration is presented in the following sections.

A. Test electrode

A vertical copper test electrode with a length of 1.2 m and a radius of 7 mm is placed at the center of a concentric ring ground return conductor with 15 m radius. The ring is made of a 7-strand, 35 mm^2 cross-sectional area copper conductor buried 0.3 m beneath the ground surface. The ring is made up of eight equal length sections with connection and measurement access points provided by eight corresponding inspection pits. The ring current return arrangement is utilised to encourage uniform current distribution around the test electrode. A 6 m×3 m metal cabin houses the test and measurement equipment. Low voltage power sources including DC, variable frequency and impulse test generators are available and conveniently located inside the test cabin. For all tests, the current is injected into the central electrode using a current injection lead, suspended from wood poles at 1.7 m height above ground surface. A reference 'remote' ground potential, for Ground Potential Rise (GPR) measurements, is imported from a distance of 35 m via a conductor arranged perpendicular to the current injection circuit and also suspended by a wood pole line having the same height.

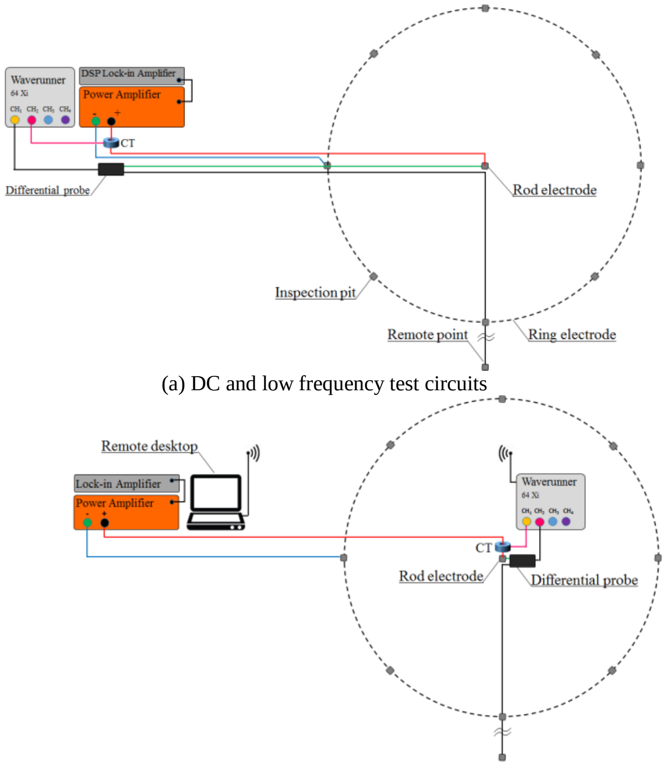
B. Test configuration

An Impedance Measurement System (IMS) [15] developed at Cardiff University was used for ac tests in the frequency range from 20 Hz to 100 kHz. A radio-frequency (RF) measurement system, consists of a Marconi 2019A signal generator and an Amplifier Research-type 25A250 RF amplifier was implemented for measurement at test frequencies higher than 100 kHz. A Haefely RSG481 recurrent surge generator with a maximum output voltage of 500 V was utilised for the impulse tests. Two different test configurations were developed to evaluate the performance of the test electrode for the frequency range from DC up to 1 MHz and for transient response, as shown in Figs 1-a and 1-b, respectively.

In the test configuration of Fig 1-a, the test sources, measuring and data acquisition equipment are located inside the test cabin. Voltage and current leads of the test circuit are laid in parallel between the test cabin and the injection point on the test electrode. This configuration can be used for DC and low frequency measurements due to the negligible effects of coupling between the tests leads under these conditions.

In the test configuration of Fig 1-b, the test sources are maintained and controlled from the test cabin but the measuring and data acquisition equipment are located at the injection point. In this way, mutual coupling between the current and voltage test leads are minimised. This arrangement involves the sending of the recorded voltages and currents back to the test cabin using a wireless system. A robust wireless system is used which provides a reliable remote desktop access to the oscilloscope up to a distance of about 100 m [19].

In both test configurations a current transformer with a 25 MHz bandwidth and 0.1 V/A sensitivity, and a DP 20 differential voltage probe were implemented for current and voltage measurements, respectively. The voltage and current signals are acquired by a PC based 4-channels oscilloscope (LeCroy Waverunner 64 Xi).



(a) DC and low frequency test circuits

(b) high frequencies and impulse test circuits

Fig. 1 Test configuration

III. Experimental Results

The ac variable frequency and LV impulse tests were performed based on the test configurations of Fig 1-b. To prevent the influence of current variations on the frequency response of the test electrode, the magnitude of the injected current was kept at a constant level of 100 mA RMS during the ac test. Furthermore, to minimise the influence that the soil moisture content may have on the changes of the test results, all tests were carried out continuously during one single dry day.

A. Variable frequency test

The ac variable frequency test was performed over the frequency range of 50 Hz to 1 MHz. The harmonic impedance is a useful quantity to evaluate frequency response of the test object in frequency domain, and can be calculate by [10]:

$$Z(j\omega) = \frac{V(j\omega)}{I(j\omega)} \qquad (1)$$

where $V(j\omega)$ and $I(j\omega)$ are phasors of the voltage and current at the injection point, and $Z(j\omega)$ is the harmonic impedance corresponding to the harmonic components of $V(j\omega)$ and $I(j\omega)$. The harmonic impedance of the test electrode at each test frequency was calculated based on (1), the results including the amplitude of the grounding impedance and phase angle versus test frequency are shown in Fig 2.

From the figure, it can be seen that, over the frequency range up to about 10 kHz, the grounding impedance of the test electrode is frequency independent. For this frequency range, the grounding performance has a strong resistive behaviour and can be characterised based on its low frequency resistance of R_{LF}=76.2 Ω. At higher frequencies, however, the grounding impedance is frequency dependant and decreases significantly, which shows a capacitive performance.

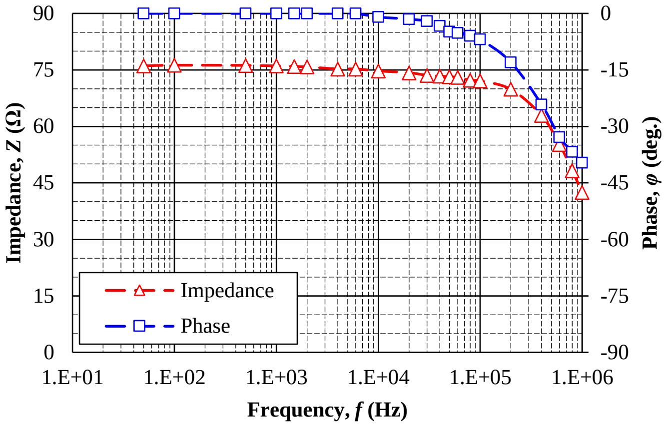


Fig 2 Amplitude and phase angle of grounding impedance of the test electrode

B. *Low voltage impulse response*

In the evaluation of the transient response of the grounding systems the sampling frequency f_s and time frame duration *TF* in time domain play major roles. The frequency spectrum of the signals in frequency domain, $F(\omega)$, is determined based on the time frame duration and sampling frequency of the signal $f(t)$ in time domain [20-22]. The transient response of the grounding electrode under test was recorded at a sampling frequency of f_s=10 MHz and a total time frame duration of *TF*=500 µs. The injected impulse current and Transient Ground Potential Rise (TGPR) at the injection point are shown in Fig 3.

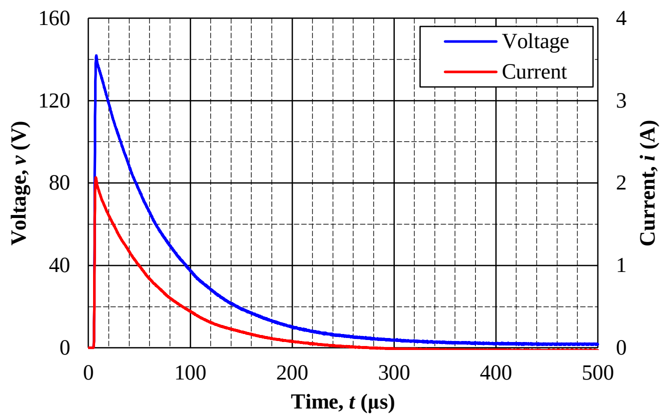


Fig 3 Transient response of the grounding rod under test

From Fig 3, it can be observed that the peak injected current is I_{pk}=2.04 A with a rise time of 2.2 µs, and the peak measured TGPR is V_{pk}=141.34 V with a rise time of 2.8 µs. Therefore, for this particular test electrode, soil conditions and energisation, current is leading which indicates a capacitive behaviour. The peak values, V_{pk} and I_{pk}, are the basis for definition of impulse resistance R_{imp}. Depending on the performance of the test object, two different definitions are available to calculate the impulse resistance [23]:

$$R_{imp1} = \frac{V_{pk}}{I_{pk}} \quad (2\text{-a})$$

$$R_{imp2} = \frac{V@I_{pk}}{I_{pk}} \quad (2\text{-b})$$

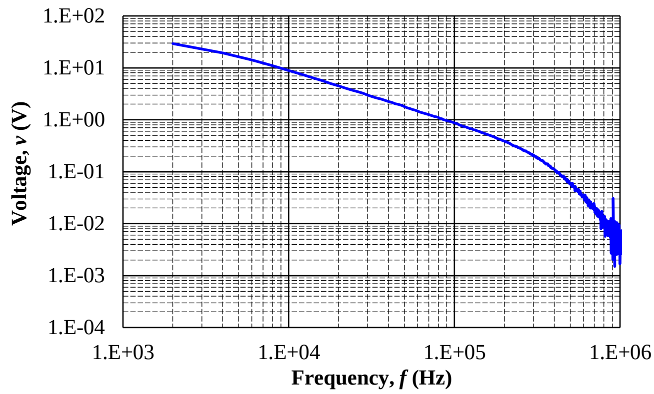
Equation (2-a) defines the impulse resistance as the ratio of peak values of the voltage and current impulses, and is valid when the earth electrode exhibits negligible reactive effects, i.e. when the impulse voltage and current peaks occur at the same instant. In case of high reactive performance, when the time of the impulse voltage and current peaks do not coincide, (2-a) is interpreted as the impulse impedance Z_{imp} [10, 14]. In order to eliminate any reactive effect in the test results, Equation (2-b) is defined as the ratio of the voltage at peak current to the peak current. On other word, (2-b) implies the resistive component of the grounding impulse impedance.

Using (2-a) and (2-b), the impulse resistances of the test electrode are calculated as R_{imp1}=69.55 Ω and R_{imp2}=68.87 Ω, respectively.

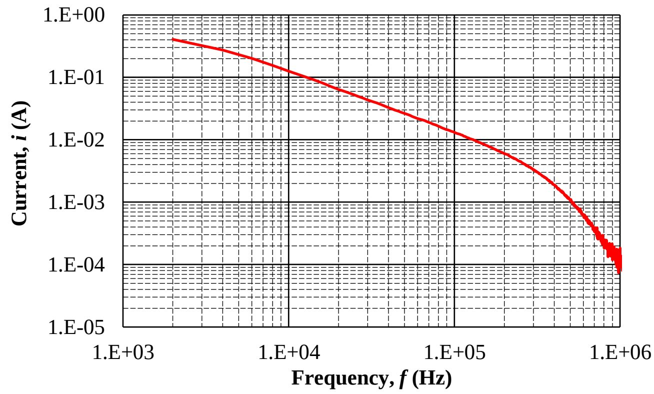
IV. Impedance Analysis of the Test Electrode Based on the Transient Response

A. *FFT analysis of the impulse response*

The raw signals of the voltage and current impulses were initially transformed to frequency domain using the FFT function in Origin 9 waveform analysis software. The resulting voltage and current spectra in frequency domain are shown in Figs 4-a and 4-b, respectively.



(a) voltage frequency spectrum



(b) current frequency spectrum

Fig 4 Frequency spectra of measured V and I impulse impulses

The calculated FFT spectra of the voltage and current signals show increasing variation at frequencies about 400 kHz. This is due to the presence of high frequency noise. The effect of noise may be even greater in practical grounding systems, e.g. HV substations. [15].

The frequency response of the test electrode can be calculated based on the harmonic components of the voltage and current signals in frequency domain [10]:

$$Z_j(\omega) = \frac{V_j(\omega)}{I_j(\omega)} \qquad j = 0, 1, 2, \ldots . n \qquad (3)$$

where V_j (ω) and I_j (ω) are voltage and current phasors at harmonic frequency ω_j, and Z_j (ω) is the harmonic impedance corresponding to the harmonic components of V_j (ω) and I_j (ω). n is the maximum frequency component in the frequency spectrum, which is determined based on the sampling frequency of the data acquisition system [20]. The harmonic impedance of the test electrode at each frequency was calculated based on (3), and the results accompanied by those obtained from the variable frequency test are shown in Fig 5.

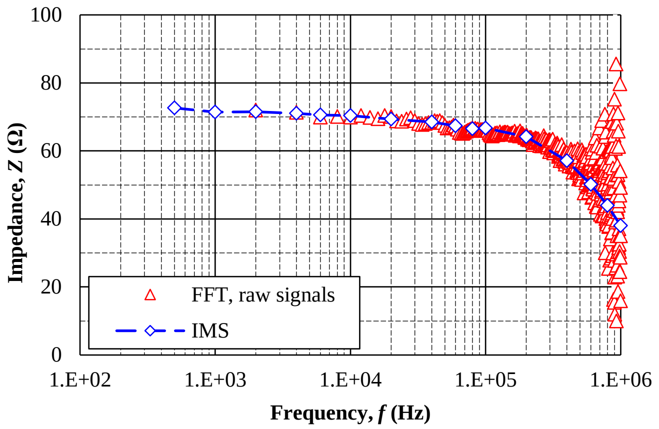


Fig 5 Frequency spectrum of grounding impedance of the test electrode obtained from the raw impulse signals

Over the frequency range from 2 kHz up to about 400 kHz, Fig 5 shows a close agreement between the harmonic impedance determined by the FFT approach and that obtained by the direct injection of ac variable frequency current. At higher frequencies, however, variation in the grounding impedance obtained by the FFT approach is significant, which was found to be a result of the high frequency noises in both voltage and current signals.

B. Technique for filtering high frequency noise in the impulse response

A practical technique was proposed by the authors to characterise high frequency performance of the grounding systems, or any other test object, based on the impulse response [24]. This technique requires a high sampling frequency in the acquisition system to obtain a high resolution in the acquired signals. High frequency noise can be eliminated by replacing the tail of the voltage and current signal waves with a smooth fitted exponential curve.

Based on the proposed method a portion of the tail of the signals, shown in Fig 3, was selected over a time interval of 5 μs ≤ t ≤ 200 μs. The exponential function of this signal was obtained using the polynomial solver of Excel. The raw signals were then enhanced from the peaks of the signals using the so-determined corresponding fitted exponential functions. The processed voltage and current impulse impulses were acquired within a time frame duration of *TF*=500 μs, as shown in Figs 6. These signals were then transformed into the frequency domain; and the corresponding new voltage and current spectra for the exponentially-fitted impulses are shown in Figs 7.

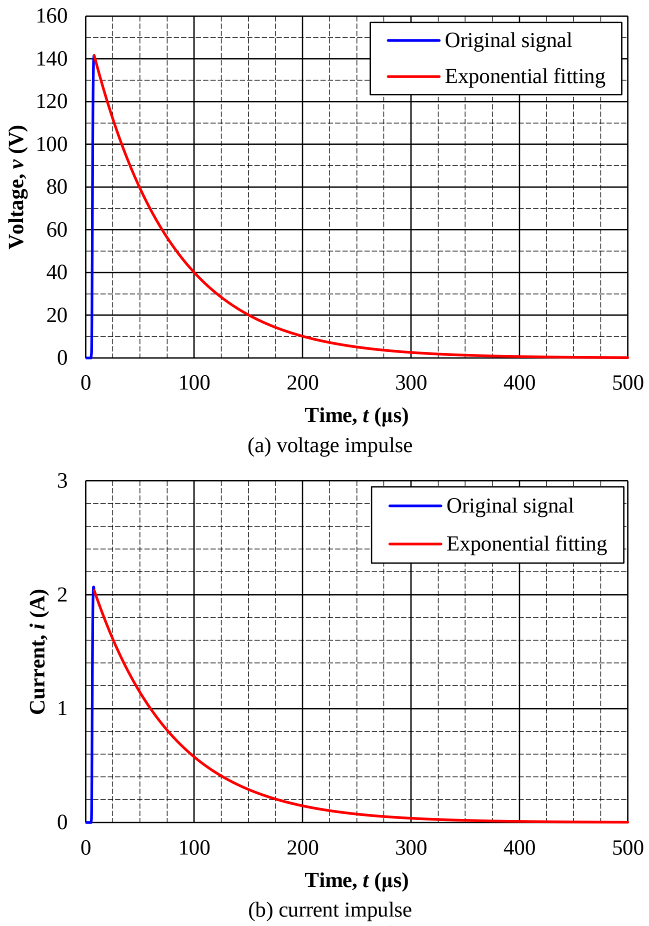
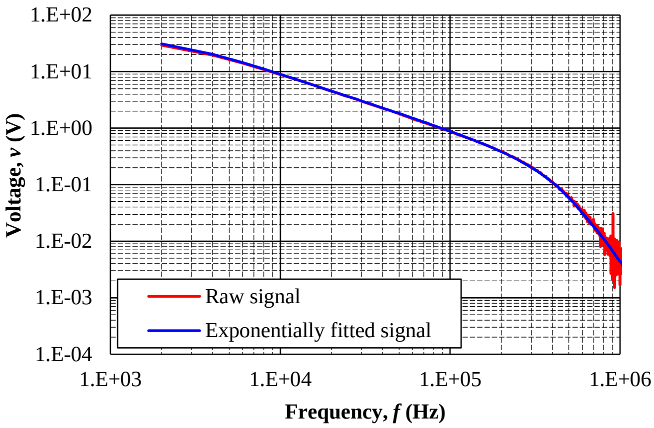


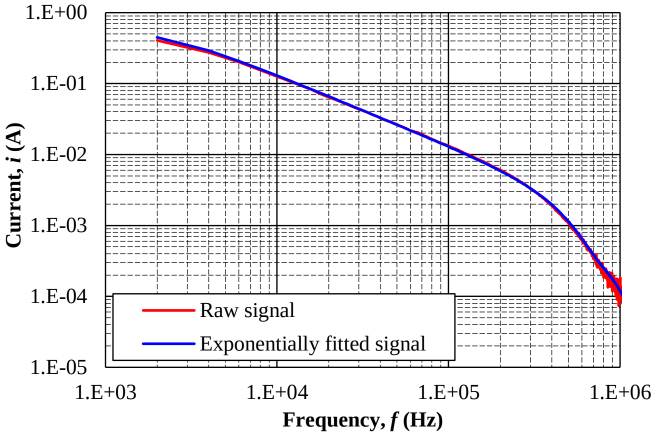
Fig 6 Fitted exponential smoothing of impulse measurements

As can be seen on Fig 7, the high frequency harmonic noise in both voltage and current signals are eliminated using the proposed approach of exponential fitting of the impulse tail. This helps to detect the actual frequency components of the signals. Furthermore, the implemented approach does not affect the frequency spectrum of the signals at low frequencies. As a result, this technique is capable to process the transient response of the grounding systems for frequency analysis purposes. Finally, based on (3), the harmonic impedance $Z(\omega)$ corresponding to each harmonic component of the new voltage $V(\omega)$ and current $I(\omega)$ was calculated. The so-calculated impedance spectrum is compared with the directly measured frequency dependence of the impedance using the ac variable frequency test technique using the IMS, as can be seen in Fig 8.

Fig 8 shows a close agreement over the whole frequency range considered in this work, with a maximum difference of about 2 %, between the direct variable frequency impedance measurements and the grounding impedance spectrum obtained using the FFT approach when enhanced with exponential fitting.



(a) current frequency spectrum



(b) voltage frequency spectrum

Fig 7 Frequency spectra of measured impulses and impulses with expenentially-fitted impulse tails

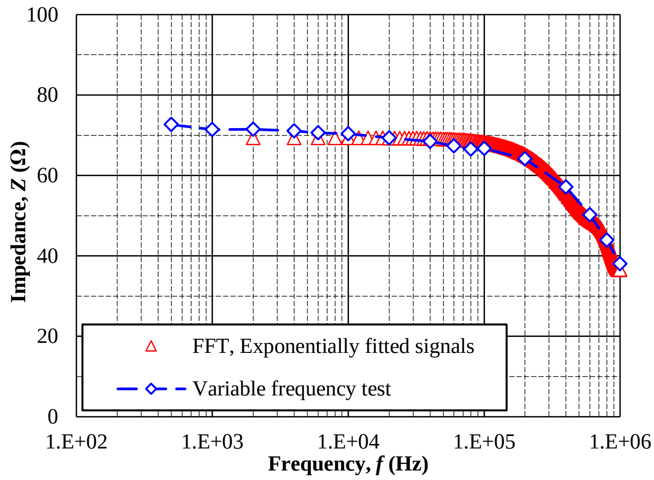


Fig 8 Frequency spectrum of grounding rod electrode impedance using direct variable frequency measurements and FFT derived spectrum with enhanced expenential fitting.

Compared to the variable frequency test, the transient-based test technique provides a quicker way to evaluate the high frequency behaviour of the grounding system, saving a considerable amount of test time and required equipment.

Conclusion

Fast Fourier Transform (FFT) is known as a powerful analytical tool to characterise dynamic performance of the time-dependant signals. However in many practical applications, the acquired signals suffer from high frequency noise, which might have significant influence on the evaluation of the performance of the system at high frequencies. In this paper, the high frequency performance of a rod electrode was investigated based on the impulse response. A fitting-technique was implemented to filter the voltage and current signal waves, mainly to eliminate high frequency noise. A variable frequency test facility was used to evaluate and compare the results.

The results proved that the implemented technique is capable of eliminating the high frequency noise and, hence, determining the high frequency components of the voltage and current signals. Furthermore, it does not affect the actual performance of the test circuit over the whole frequency range.

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