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RESEARCH ARTICLE

Earth Integrity Test–Complexity of and Insight Into the Interpretation of Field Test Results

PERUMAL VELMURUGAN[1], **(Member, IEEE), AND ADHIR BARAN CHATTOPADHAYAY**[2]

[1]Twinvey Electric Consultancy, Dubai, United Arab Emirates
[2]Budge Budge Institute of Technology, Kolkata 700137, India

Corresponding author: Perumal Velmurugan (pv_1227@yahoo.com)

ABSTRACT The purpose of an earth integrity test, as described in IEEE 81-2012, is to assess the healthiness of earth connections through the measurement of the resistance or impedance of the connection path. Undertaking such a measurement is laborious and requires skill, good instruments and current injection equipment. In this paper, field experiences in conducting such tests using both DC and AC currents are shared in detail. The test results from two different sites are analyzed, and the calculated circuit parameter is included in an equivalent circuit diagram. A resistance network is modeled in EMTP software for a sample earth grid to find the equivalent resistances across various nodes. The importance of carefully measuring low resistance values and the complexities of interpreting the test results are highlighted. Reference values for resistance measurement based on different standards are summarized and analyzed. This paper includes observations for improvement on test reference values stated in the relevant IEEE Std. 81-2012 and BS 7430:2011. Despite the earth integrity test is widely used for the primarily testing of joints of earth grid installations in the United Arab Emirates, interpretation of test results is a challenge to field engineers.

INDEX TERMS Earth riser, earth integrity, electric field, earth grid, resistance network, node, low resistance.

NOMENCLATURE

S	Cross-section area of the conductor.
Cu	Copper.
A_1, A_2	Current terminals of the test kit.
E_1, E_2	Exothermic welding joint of Riser 1 & 2 with buried earth grid.
Hz	Frequency in (Hertz).
kΩ	kilo-Ohm.
mΩ	Milli-Ohm.
$\mu\Omega$	Micro-Ohm.
MΩ	Mega-Ohm.
Ω	Ohm.
ρ	Resistivity.
R_L, X_L	Resistance, reactance of test lead.
R_1, X_1	Resistance, reactance of riser 1.
R_2, X_2	Resistance, reactance of riser 2.
R_E, X_E	Resistance, reactance of earth grid at E_1, E_2.
C_1, C_2	Terminal of Riser 1 and Riser 2.
C_3	Test lead joint.
R_T, X_T	Total resistance, reactance across terminals C_1 and C_2.
Rr, Xr	Total resistance, reactance across terminals C_2 and C_3.
V_1, V_2	Voltage terminals of the test kit.

ABBREVIATION

A	Ampere
AC	Alternating Current
DC	Direct current
E	Electric field
HV	High Voltage
I_s	Source current
L	Length of the conductor
m	Length in meters
PVC	Polyvinyl chloride
pf	Power factor
V	Volt
V_s	Supply voltage

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I. INTRODUCTION

The integrity of earth risers' connections with an earth grid is important since it provides a direct path to pass the fault current from faulted equipment to ground. Therefore, testing the integrity of the earth connection is considered essential. Out of several test methods available for resistance measurement [1], [2], [3], [4], [5], [6], [7], only ammeter-voltmeter based four-wire method is recommended for low resistance measurement.

A relevant standard for earth integrity test is IEEE Std. 81-2012. This standard suggests two ways of conducting such four-wire method, one way is to inject high current, typically 10 A to 300 A, to measure the voltage drop across any two risers and another way is to inject a relatively low alternating current, typically 25 A to 30 A, to measure the impedance and power factor and calculate the resistance across any two risers. Although both ways seem simple, carrying out these tests at a site is not easy and requires substantial effort due to moving the test equipment and power cables and making test connections at many locations. Sites under construction require considerably more effort due to the constraints of accessing test locations and the frequent movement from one location to another. Tapping electricity from the construction power supply for the test is another task requiring careful attention to safety. Commissioned sites require many formalities and methods to obtain work permits.

A literature survey indicates the limited number of papers on this subject. One paper on an investigation into grounding grid integrity based on the current injection method [8] discusses a laboratory experiment in which an injection of a square wave with high frequency (500 Hz) and a current of 10 amperes into a grid to find an open circuit within the earth grid.

This paper also discusses the use of magnetic field measurements. It concludes that this method should be further verified by field experiments. The effective use of continuity testing to assess grounding system integrity is discussed in another paper [9]. Obstacles to performing accurate measurements of resistance in the noisy environment of a power substation are discussed in relation to the establishment of measurement targets and specific instances of poor integrity. The paper concludes that the most effective method to perform continuity testing is the four-probe test method with polarity switching.

A study on high-voltage substation ground grid integrity measurement is given in a paper [10] that mainly focuses on the practical feasibility of the method recommended in IEEE Std 81-2012. It concludes that the statistical reliability of the criteria in a substation environment is comparatively low, but a reasonable conclusion is made regarding accessing certain bad earth risers.

A report on grounding grid integrity [11] mainly focuses on suggesting ways of detecting inconsistencies in grounding grids (earthing grids). It refers to the earth riser integrity test guideline of 1.5 V/15 m and points out that it is an acceptable guideline [12] without qualifying its use at a site.

A paper on ground grid integrity testing is presented by Moore of Virginia Power [13] and provides some practical guidelines for evaluating substation ground grid continuity by a DC high current test method. The maximum voltage drop across the grid per 100 feet of straight-line distance should not exceed 0.75 Volts DC at 300 A DC current for a 4/0 (120 mm^2) copper grounding system.

This paper also provides limited information on the voltage drop. Regarding advancements in integrity testing, Safearth consulting [14] discusses the use of relatively small test currents (e.g., one ampere) and the use of precision measurement electronics to achieve the required measurement resolution to distinguish between a good bond and a poor bond. Thus, these literature reports suggest that a clear guideline is yet to be established for the assessment of the measured low resistance values of earth grid risers in a practical system. A reference value of 1.5 V/15 meter for 300 A for integrity testing is given in the IEEE standards [15], [16]. With this single reference value, a direct comparison with field test results is not possible due to variations in earth grids in practical sites.

This paper is divided into 6 sections including the above introductory section.

Section II discusses earth integrity test using AC and DC currents and provides a comparison of these two methods. Section III details field experiences in conducting these tests at two different sites. Section IV includes a survey of reference values for the tests with a remark on the BS Std. Section V includes an analysis of the reference value of 1.5 V/15 m, as sated in IEEE Std. 81-2012, and provides reference value guidance for integrity testing. The conclusions given in Section VI briefly summarize the field experience, as well as the importance and complexity involved in conducting integrity tests.

A useful future work in this area would be the establishment of reference values for AC and DC current testing of different types of earth grids with an aim to provide a table to search for reference values to compare with site test results.

II. EARTH GRID INTEGRITY TEST

This test is simple but requires considerable effort to carry out at a site mainly due to the need for high current injection. The handling of test equipment and connection cables at testing site requires proper resources. The integrity test is applied for the testing of the earth risers' connections integrity with the earth grid in both new and old installations. The integrity test should be performed for all earth risers in new installations, and the results can be used for future reference. The test current can be any value in the range [15], [16] of 10 A to 300 A. In new installations, the use of high current (100 amperes and above) cannot be a restriction / objectionable. In operating installations, the use of such high currents requires careful considerations from the viewpoint of protecting relay current transformer secondary circuits, so obtaining work permits for earth integrity testing with small currents (10 A to 30 A)

TABLE 1. Comparison of test methods.

Comparison Basis	Earth Grid Integrity Testing	
	AC Current	**DC Current**
Measuring quantities	Voltage, current and phase angle or power factor	Voltage and current
Test kit	A test kit with: • Variable voltage • Variable current • Measuring power factor with enough sensitivity for low voltage input	A test kit with: • Variable voltage • Variable current • Micro-ohm measurement set with connection leads
Test kit weight with connection leads	Approx. 130 kg	Approx. 50 kg
Test current range	10 to 300 A	10 to 300 A
Integrity Testing Time	Time consuming	Relatively less time consuming
Labour and skill	Laborious. Highly skilled staff necessary.	Relatively less laborious. Skilled staff necessary.
Precautions	Use of twisted pair connection leads for voltage measurement or adequately separate the current and voltage connection leads.	Not applicable.
Influence on results due to: Ambient temperature	Change in resistance cannot be easily observed probably due to the effects of variation in X/R ratio.	Change in resistance can be easily observed being direct reading.
Measured voltage drops being small	Care needed on accurate phase angle or power factor measurement. [a]	Instruments read directly micro-ohm or milli-ohm.
Interpretation of individual test results	• Interpretation of test results is not easy. • Identification of the test risers that have abnormally high impedance values. Results can be analysed only subjectively as stated in IEEE Std. 81-2012.	• Interpretation of test results is relatively easy. • Identification of the test risers that have abnormally high resistance values. Results can be analysed only subjectively.
Acceptable readings for Resistance measurement or voltage drop measurement	Acceptable values to be ascertained and defined on a case-by-case basis.	Acceptable values to be ascertained and defined on a case-by-case basis.
Complexity in testing, having a reference value	Relatively complex, depends on the earth grid.	Relatively less complex or simple, depends on the earth grid.
Standards	IEEE Std. 81-2012 IEEE Std. 80-2013	IEEE Std. 81.2-1991 BS Std. 7430:2011

[a] A test kit with built-in phase angle measurement will save time. The test kit should have the latest modern instruments capable of accurately measuring the phase angle between very low voltage and high current inputs.

is generally accepted. The permit-issuing authorities restrict the use of high currents and require detailed discussions of the test methods, and generally higher-level authorization is sought if high currents are to be used. The earth integrity test thus has limited use in existing installations in the United Arab Emirates.

Regarding the application of AC or DC currents, the previous IEEE Std., 81.2-1991, accepts the use of a

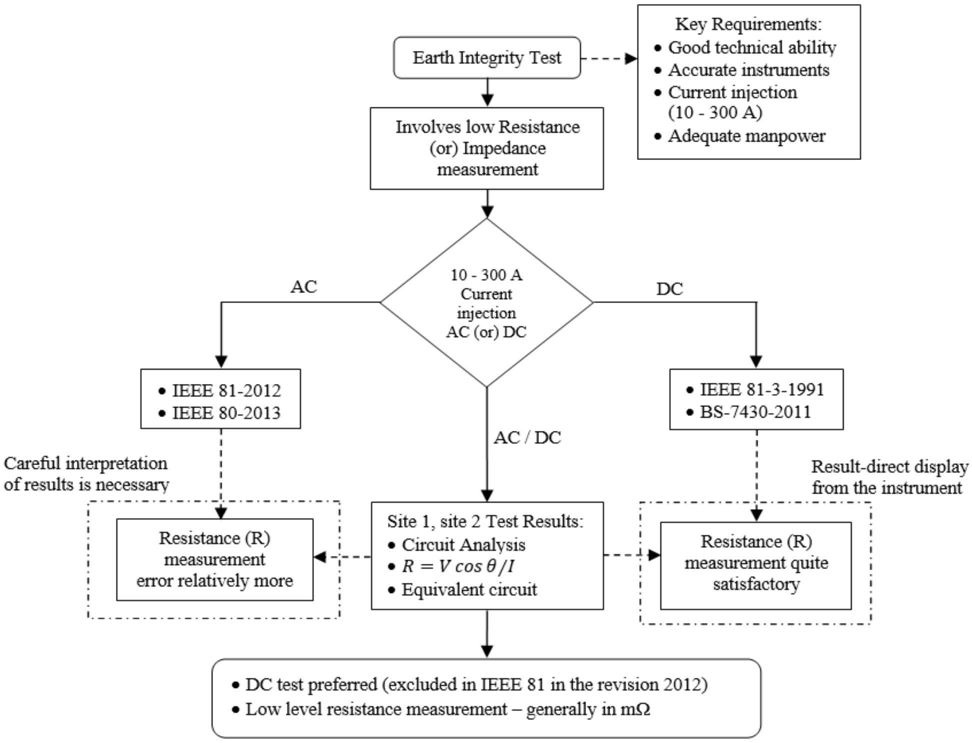


FIGURE 1. Flowchart for earth integrity test.

TABLE 2. Comparison of the methods for DC and AC measurements for resistance.

Comparison Basis	DC Measurement [a]			AC Measurement [b]
Measurement Range [1], [2]	Low resistance (1 Ω or less)	Medium resistance (1 Ω to 100 kΩ)	High resistance (100 kΩ or more)	Resistance (Ohms to 100 MΩ or more)
Measurement methods [1-7]	• Four-wire method [c] (ammeter-voltmeter) • Potentiometer • Kelvin Double bridge	• Two-wire [d] (ammeter-voltmeter) • Substitution • Differential galvanometer • Wheatstone bridge	• Price Guard-Wire • Loss of charge • Megaohm bridge • Megger	• Digital multimeter • Null methods using bridges • Deflection methods • Four terminal resistance • Mueller bridge

[a] Resistance measurement.
[b] High resistance, inductance & capacitance measurements are done using AC current method. Not common for low resistance measurement [7].
[c] Suitable for low resistance measurement (such as high current joints and connections, earthing joints and connections, bus bar joints, bus ducts, motor and transformer windings, etc.).
[d] Not suitable for earth integrity test due to low accuracy.

micro-ohmmeter to inject a dc test current of 10 A to 100 A to measure micro-volt or milli-volt drops.

The present IEEE Std., 81-2012, neither explicitly objects to dc current use nor takes a direct reference to dc current use; however, it details AC current use. Based on the field experience of the author[1] in integrity testing using DC and AC currents, the DC current test method appears to be more appropriate. In support of this assertion, a comparison of the two methods on various bases is given in Table 1, which is quite self-explanatory.

For better clarity a flowchart is given in Fig. 1. The author's field experience indicates that the integrity test can easily reveal poor earth connections that might not be revealed by low values at the field step and the touch potential measurements by the fall of potential method [17].

III. FIELD EXPERIENCE AND CIRCUIT ANALYSIS

A. COMPARISON OF TESTING METHODS

The Table 2 given above provides a comparison of methods for DC and AC measurements for mainly resistance measurements.

The ammeter-Voltmeter based four-wire method is well suited for low resistance measurement [1], [2], [3], [4],

[5], [6], [7]. Modern test kits provide high accurate measurements [1], [21].

B. TEST ARRANGEMENT

A schematic diagram of a test is shown in Fig. 2 and its equivalent circuit diagram given in Fig. 3. They are brought forward to emphasis the importance of this test and understanding of data at two different sites, which are given below in Table 3 and Table 4.

Test measurements with both AC and DC currents are made using four wire connections meant to accurately measure voltage drops [18], [19].

In Fig. 2, four standard test leads supplied by the test kit manufacturer is used to connect the terminals 'C_1' and 'C_2' such a way that the measurement eliminates contact resistance of 'C_1' and 'C_2'.

Since the test kit is placed nearer to Riser cable-2, an additional test lead of '25 m' is used to connect to another Riser cable-1 at terminal 'C_3' (bolted connection).

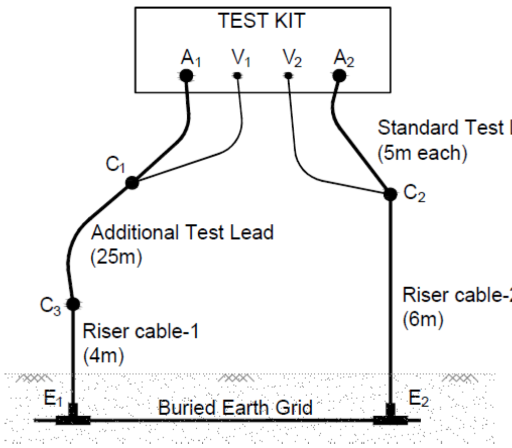


FIGURE 2. Test kit and schematic diagram.

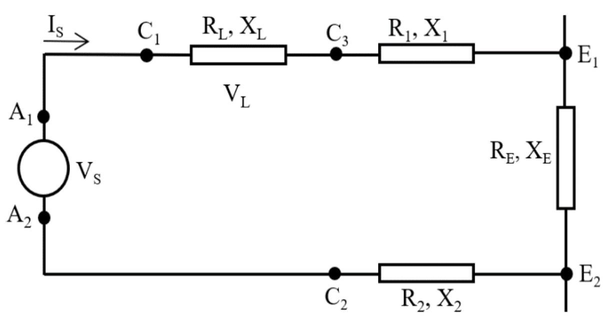


FIGURE 3. Electrical equivalent of the test circuit for resistance measurement across C_1 and C_3. Note: Riser cable resistance R_r (across C_2 and C_3) = $R_1 + R_E + R_2$. Riser cable reactance X_r (across C_2 and C_3) = $X_1 + X_E + X_2$.

The measured contact resistance of the test lead bolted joint 'C_3' was 30 $\mu\Omega$, an acceptable value given in BS Std. 7430:2011 (referred in other context in Table 10). This contact resistance is being relatively insignificant in the resistance or impedance of the connection path; hence it is omitted in the analysis.

This schematic diagram in Fig. 2 and its equivalent circuit in Fig. 3 should be read in conjunction with the two sets of site data given in Table 3 and Table 4 for understanding of the parameters analyzed in section 'III-C' and 'III-D'.

TABLE 3. Site 1 data.

Parameters	Size	Length (m)
Test lead -Rubber insulated	1C x 70 mm^2, Cu conductor	25
Riser cable-1 (E_1, C_3)-PVC	1C x 300 mm^2, Cu conductor	4
Riser cable-2 (E_2, C_2)-PVC		6
Buried earth grid: Bare, 300 mm^2	50 m x 50 m Cu conductor	-
Test riser spacing (E_1, E_2)	-	10
Mesh size	10 m x 10 m	-
Buried depth of earth grid	-	2

TABLE 4. Site 2 data.

Parameters	Size	Length (m)
Test lead -Rubber insulated	1C x 70 mm^2, Cu conductor	25
Riser cable-1 (E_1, C_3)-PVC	1C x 240 mm^2, Cu conductor	4
Riser cable-2 (E_2, C_2)-PVC		6
Buried earth grid: Bare, 240 mm^2	330 m x 230 m Cu conductor	-
Test riser spacing (E_1, E_2)	-	15
Test Area (refer Fig. 8)	23 m x 32 m	-
Mesh size	varies	-
Buried depth of earth grid	-	1

C. MEASUREMENT AT SITE 1 AND SITE 2 USING DC AND AC CURRENTS

During the integrity test in a larger grid, the focus is on conducting the tests with both AC and DC currents at risers C_2 and C_3. The voltage to inject an AC current of 100 amperes is approximately 1.5 V, which includes a voltage drop of approximately 50% across the test cable.

The site measured values and calculated values of circuit parameters are recorded in Table 5 and Table 6. The tests are carried out separately in two steps. The first step is to measure only the test lead parameter (no schematic or circuit diagram is given), and then the next step is to measure the test lead and riser parameter together as shown in Fig. 2 and Fig. 3.

a) DC current test:
   Step 1: Measured parameters: I_s and R_L.
   Step 2: Measured parameters: I_s and R_T.
   Calculated parameter: $R_r = R_T - R_L$.
b) AC current test:
   Step 1: Measured parameters: V_s, I_s, pf_1 or pf_3.

TABLE 5. Site 1 measured data and calculated values of circuit parameters.

	Supply		Test Lead Parameters					Riser Parameters	
DC/AC	V_S Volt	I_S Amp	V_L Volt	R_T mΩ	X_T mΩ	R_L mΩ	X_L mΩ	R_r mΩ	X_r mΩ
DC	-	100.0	-	7.95	-	7.03	-	0.92	-
AC	1.756	100.4	0.98	8.13	15.48	7.03	6.78	1.10 [a]	8.7
	$pf_1 = 0.465$		$pf_2 = 0.724$	$pf_1 = 0.465$		$pf_2 = 0.724$		-	

[a] AC measurement reading shows a 25% higher value compared to that of the DC measurement. 'C_3' is a bolted joint for which the measured contact resistance was 30 μΩ, hence it is neglected.

TABLE 6. Site 2 measured data and calculated values of circuit parameters.

	Supply		Test Lead Parameters					Riser Parameters	
DC/AC	V_S Volt	I_S Amp	V_L Volt	R_T mΩ	X_T mΩ	R_L mΩ	X_L mΩ	R_r mΩ	X_r mΩ
DC	-	100.0	-	8.21	-	7.03	-	1.18	-
AC	1.58	100.0	0.98	8.51	13.31	7.03	6.78	1.48 [a]	6.53
	$pf_3 = 0.539$		$pf_4 = 0.724$	$pf_3 = 0.539$		$pf_4 = 0.724$		-	

[a] AC measurement reading shows a 25% higher value compared to that of the DC measurement. 'C_3' is a bolted joint for which the measured contact resistance was 30 μΩ, hence it is neglected.

Step 2: Measured parameters: V_s, I_s, V_L, pf_2 or pf_4.
Calculated parameters: R_L, X_L, R_r, X_r.

It is noted that the riser resistance, 'R_r', calculated value is slightly higher in the ac current test, as shown in the Table 5 and Table 6, which could be due to measurement error or the proximity of the test circuit cables.

Due to space restrictions at site the measuring leads cannot be much separated.

There is an impact on the inductive reactance 'X_L' of the test lead and that could be the possible reason for 25% higher value in the measurement readings in Table 5 and Table 6 compared to that of the dc measurement.

Overall, as analyzed in section-III-D, a careful interpretation of the AC current test results is always required when compared to those of the dc current test. The dc test kit provides a micro-ohm reading directly as given in section-III-E.

Two sample measurement photographs taken from a site under construction are given in Fig. 4 for dc current test and Fig. 6 for AC current test.

Test measurements with both AC and DC currents are made using four wire connections meant to accurately measure voltage drops [18], [19].

DC current test is done using Microhmmeter type MOM200A, made by Programma [19] [21]. The schematics for DC current test is shown in Fig. 5 and for AC current test in Fig. 7.

The test connections in Fig. 4 show two clamp connections to an earth riser, one connection is thick for current connection and another is thin for voltage connection. The other two clamp connections to a reference riser are not visible in the picture.

Due to site constraints, the pictures show crowded low voltage supply cables and connections.

FIGURE 4. DC current test at site.

Details of operation of the test kit can be found from the relevant literatures [21].

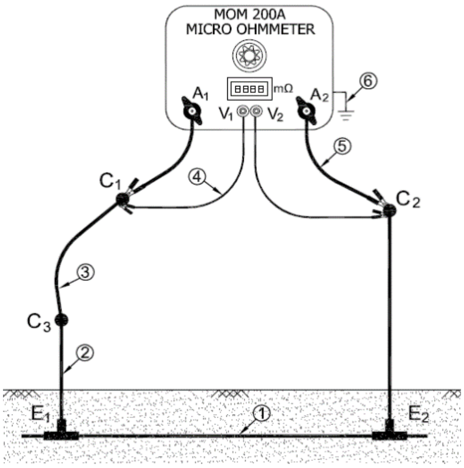
At the same location, AC current test is done using a dedicated current injection Omicron CPC 100 test kit [22] and digital multimeter (Fluke 435) Power Quality Analyzer (PQA) for measuring voltage, current and power factor shown in Fig. 6. The test connections are similar to DC current test but not visible in the picture.

D. CIRCUIT ANALYSIS OF SITE 1 AND SITE 2 MEASURED DATA BY AC CURRENT TEST

The resistance is calculated based on the measured values of voltage, current and power factor using (1) as defined in IEEE Std 81-2012. The total resistance across the test risers' path is as follows:

$$R_{path} = \frac{V\cos\theta}{I} \tag{1}$$

Based on (1), the calculations for site 1 are given below.



1 - Buried earth grid
2 - Riser cable
3 - Additional test lead
4 - Voltage connection with voltage clamp
5 - Current connection with current clamp
6 - Instrument safety earth

FIGURE 5. DC current test schematic. Note: The Microhmmeter instrument provides Ohmic value (ratio of mV/A).

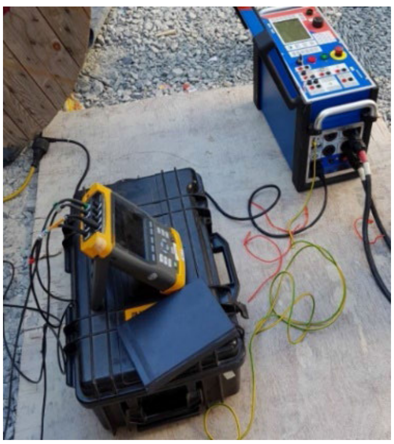


FIGURE 6. AC current test at site.

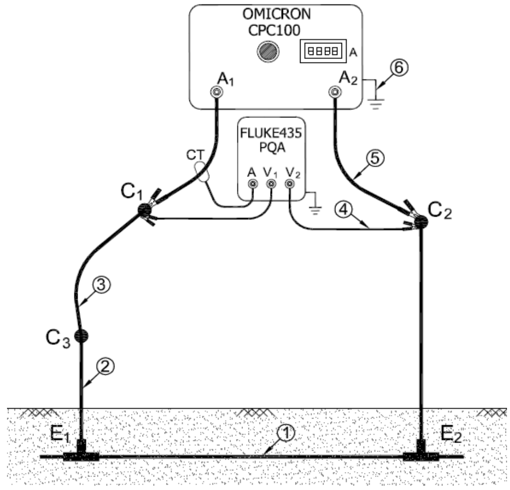
To calculate the 'R_T' value, the voltage, current and power factors values are taken from Table 5. Substituting values of 'V_s' (1.756 V), 'I_s' (100.4 A) and pf_1 (0.465) yields an 'R_T' value of 8.13 mΩ as follows:

$$R_T = \frac{V_s}{I_s} \times pf_1$$
$$R_T = 8.13 \text{ m}\Omega$$

Similarly, to calculate 'R_L', the values are taken from Table 5. Substituting values 'V_L' (0.98 V), 'I_s' (100.4 A) and pf_2 (0.724) yields an 'R_L' value of 7.03 mΩ as follows:

$$R_L = \frac{V_L}{I_s} \times pf_2$$
$$R_L = 7.03 \text{ m}\Omega$$

This value, $R_L = 7.03$ mΩ, is comparable to the value given in the manufacturer's manual [20], that is, 6.7 mΩ derived for



1 - Buried earth grid
2 - Riser cable
3 - Additional test lead
4 - Voltage connection with voltage clamp
5 - Current connection with current clamp
6 - Instrument safety earth
CT - Measuring Current Transformer

FIGURE 7. AC current test schematic. Note: The computation of the ohmic value to be arrived based on the site measurement taken.

a 25 m length of 70 mm^2 copper conductor from the values given in Table 11 in Ω/km. Now the riser resistance, 'R_r', value can be calculated easily as the difference between 'R_T' and 'R_L'. Therefore,

$$R_r = R_T - R_L$$
$$R_r = 1.1 \text{ m}\Omega$$

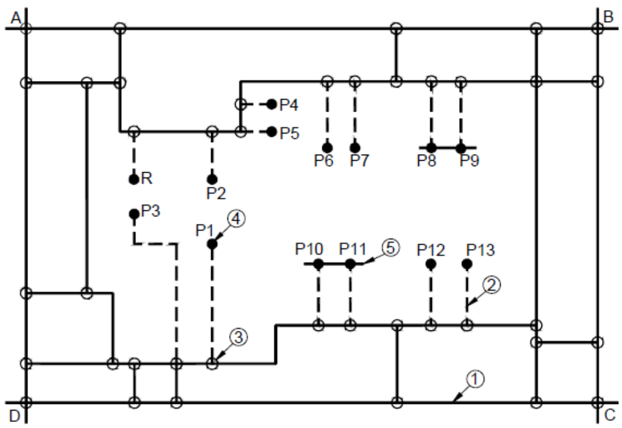
On similar lines, the calculations for 'X_T', 'X_L' and 'X_r' are as follows:

$$X_T = \frac{V_s}{I_s} \times \sin\left(\cos^{-1}(pf_1)\right)$$
$$X_T = 15.48 \text{ m}\Omega$$
$$X_L = \frac{V_L}{I_s} \times \sin\left(\cos^{-1}(pf_2)\right)$$
$$X_L = 6.78 \text{ m}\Omega$$
$$X_r = X_T - X_L$$
$$X_r = 8.70 \text{ m}\Omega$$

Similarly, the values presented in Table 5 are calculated for Site 2. Though the measured values at both sites are similar, the site-2 values are taken for analysis in sections III-E and III-F.

E. MEASUREMENT AT SITE 2 USING DC CURRENT

In a large grounding system (330 m x 230 m) with many meshes, a dc current test was carried out for a limited test area of 23 m x 32 m for several risers using a test kit, Microhmmeter type MOM200A, made by Programma [19], [21]. The DC current applied was 100 A. This test kit provides a micro-ohm reading directly. No interpretations are required. The test risers' locations 'P' including the reference riser



1 - Buried earthing grid conductor
2 - PVC insulated riser conductor
3 - Exothermic welding joint
4 - Bolted connection to the equipment within area-A, B, C & D
5 - Bolted connection to the earth bar
R - Reference riser
P - Measurement point

FIGURE 8. Test area of 23 m x 32 m with riser locations (part of a large 330 m x 230 m grounding system).

TABLE 7. Riser resistance (R_r) values using the DC current test.

Measurement points	Resistance (mΩ)		
	Measured Value (R_T)	Lead Resistance (R_L)	Calculated Value ($R_r = R_T - R_L$)
P1	13.41	12.17	1.24
P2	13.32	12.17	1.15
P3	13.90	12.17	1.73
P4	13.25	12.17	1.08
P5	13.34	12.17	1.17
P6	13.47	12.17	1.30
P7	13.26	12.17	1.09
P8	13.43	12.17	1.26
P9	12.35	12.17	1.18
P10	13.54	12.17	1.37
P11	12.52	12.17	1.35
P12	13.54	12.17	1.37
P13	13.50	12.17	1.33

location 'R' in the test area are shown in Fig. 8, and the results are given in Table 7.

When 'P1' is tested with respect to 'R', P2, P3…P13 remain connected to equipment, and such connections provide additional parallel paths. Similarly, other risers are tested. The lead resistance is measured and recorded once a day prior to the commencement of the tests because frequent checks would severely hinder the measurement progress.

The minimum riser resistance, 'R_r', value from Table 7 is 1.08 mΩ, and the maximum value is 1.73 mΩ. On site, the riser 'P3' is longer and hence the value is more although the riser is not far from the reference riser. The maximum value depends also on the riser length and therefore should be carefully accounted in the analysis. It should be noted that the routing of the riser cables to the equipment earthing is entirely dependent on the site conditions and that the measured values cannot be correlated with physical distances of the measurement points (P1, P2, P3, …P13), as shown in Fig. 8.

During the test, all other risers remain connected to the site equipment earth terminals and thus form more parallel paths. An integrity test should be carried out for all risers, and the results should be kept for future reference purposes. Comparison of these results with future test results will be helpful to arrive at proper conclusions.

F. CIRCUIT ANALYSIS OF SITE 2 MEASURED DATA USING DC CURRENT

To highlight the importance of understanding the resistance per meter length when applied to a mesh system, the following mathematical analyses are useful.

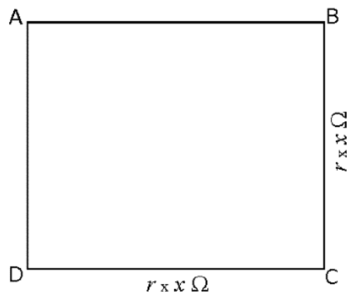


FIGURE 9. Square mesh with side 'x'.

In a square mesh with side 'x' as shown in Fig. 9, with a conductor resistance of 'r' Ω/m, the resistance across the diagonal (of distance equal to $\sqrt{2}$x) is:

$$r \times x\ \Omega \tag{2}$$

For example, the 50 m x 50 m square mesh shown in the solid lines in Fig. 8 having copper conductors of size 300 mm^2 whose resistance is 0.06 mΩ/m.

The resistance across AC (of distance equal to $\sqrt{2}\times 50$ m) is equal to the resistance of a side of distance 50 m which is 3 mΩ.

Therefore, when the resistance measurement taken across a side or diagonal is resulting in the same resistance value. This is an important circuit analysis made to understand the test results. In the case of a rectangular mesh with sides 'x_1' and 'x_2', with a conductor resistance value of 'r' Ω/m, the resistance across the diagonal (of distance equal to $\sqrt{x_1^2 + x_2^2}$) is:

$$\mathrm{r} \times \left(\frac{x_1 + x_2}{2}\right) \tag{3}$$

Applying (3) to the installation Fig. 8 in section III-E, the resistance across the diagonal is calculated by substituting values 'x_1' as 23 m, 'x_2' as 32 m and 'r' as 0.075 mΩ/m for copper conductor of size 240 mm^2 of site 2.

$$\text{Resistance across the diagonal} = 0.075 \times 10^{-3} \times \left(\frac{23 + 32}{2}\right)\ \Omega$$

$$\text{Resistance across the diagonal} = 2.06\ \text{m}\Omega$$

It can be observed that the site 2 measured values given in Table 7 are less than the resistance across the diagonal of an approximate rectangle of 23 m x 32 m.

Thus, the DC resistance measured values are easy to interpret and analyze while the AC current test data are to be interpreted and analyzed as detailed in section III-D.

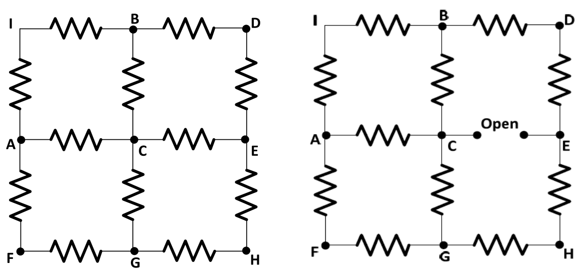
G. ANALYSIS OF RESISTANCE ACROSS NODES OF AN EARTH GRID (50m X 50m AND 100m X 100m)

Analyzing the resistance network using delta-star transformation technique manually will be very cumbersome process. So, the analysis is conducted using EMTP software to calculate the resistance across various nodes of the resistance network, as shown in Fig. 10 and in a simple flowchart in Fig. 11.

Two sample copper earth grids of size 50 m x 50 m and 100 m x 100 m are considered for four study cases, namely, Case 1A, Case 1B, Case 2A and Case 2B.

The riser connections are not made, and hence no more parallel resistance of the network is simulated.

a) Case 1A: The earth grid has four meshes of each 25 m x 25 m. The conductor is of size 300 mm^2 and has a resistance value of 0.060 Ω/km. All nodes are interconnected.
b) Case 1B: This case is the same as Case 1A, but branch 'CE' is open.
c) Case 2A: The earth grid has four meshes of each 50 m x 50 m. The conductor is of size 300 mm^2 and has a resistance value of 0.060 Ω/km. All nodes are interconnected.
d) Case 2B: This case is the same as Case 2A, but branch 'CE' is open.



Case 1A and 2A Case 1B and 2B

FIGURE 10. Resistance network of an earth grid for case-1 and case-2.

Simulation in the EMTP software was conducted by applying a voltage across two nodes and measuring the current. Sample computational results of the resistance across node 'FD' for each of the four case studies are given in Table 8.

The resistance values are summarized in Table 9 for 15 branches of the resistance network shown in Fig. 10. The following points are observed:

a) All values are reported in milli-ohms, indicating the need for the proper measurement of resistance, and thus errors in measurement should be minimized.

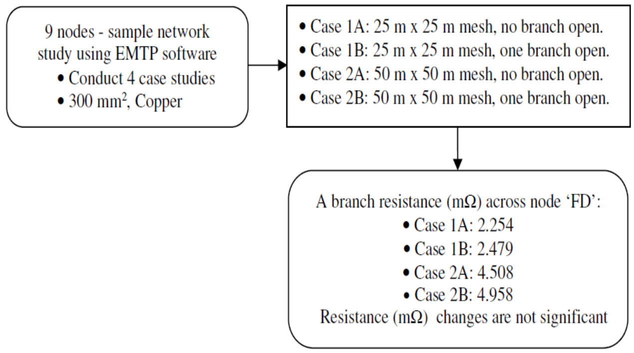


FIGURE 11. Flowchart for EMTP sample network results.

TABLE 8. Computational results for cases 1A, 1B, 2A, and 2B.

Parameters	Case 1A	Case 1B	Case 2A	Case 2B
Applied voltage in (V)	10	10	10	10
Current into node 'D' in (A)	4437	4034	2218	2017
Branch resistance 'FD' in (mΩ)	2.254	2.479	4.508	4.958

b) The resistance of the eight outer branches of the case 1A is 1.064 mΩ for a branch length of 25 m. This value will be lower in the case of reduced mesh size. Also, this is the case if the risers are connected to site equipment earthing terminals.
c) In the case of the two risers taken at 10 m spacing within the branch 'AI', then the resistance of these risers' points on the earth grid is calculated as 0.53 mΩ in study case 1 A, which is less than the resistance of 0.6 mΩ of the 10 m length of conductor 300 mm^2.
d) The values across the open branch, 'CE', reflect a higher resistance. This difference can be noted only in sites under construction and when the risers are not terminated to equipment. In completed sites, the value will be lower still due to a greater number of parallel paths formed by such equipment connections.

Therefore, it is suggested that a set of measured readings should be taken as reference for future test reading comparison purposes.

In the United Arab Emirates, earth grid design is carried out based on IEEE Std. 80-2013, and the values are generally low and less than 0.1 Ω in most sites to ensure safety under heavy earth fault situations [23]. Hence, a dense earth grid is usually applied.

Typically, a 50 m x 50 m earth grid with many meshes (a maximum size of 10 m x 10 m mesh) is used for HV substations.

By presenting the tabulated values, the reader is given an idea of the ohmic value of an earth grid resistance across the branches or nodes.

In constructed sites, as explained earlier, an earth grid is interconnected to many pieces of equipment, such that

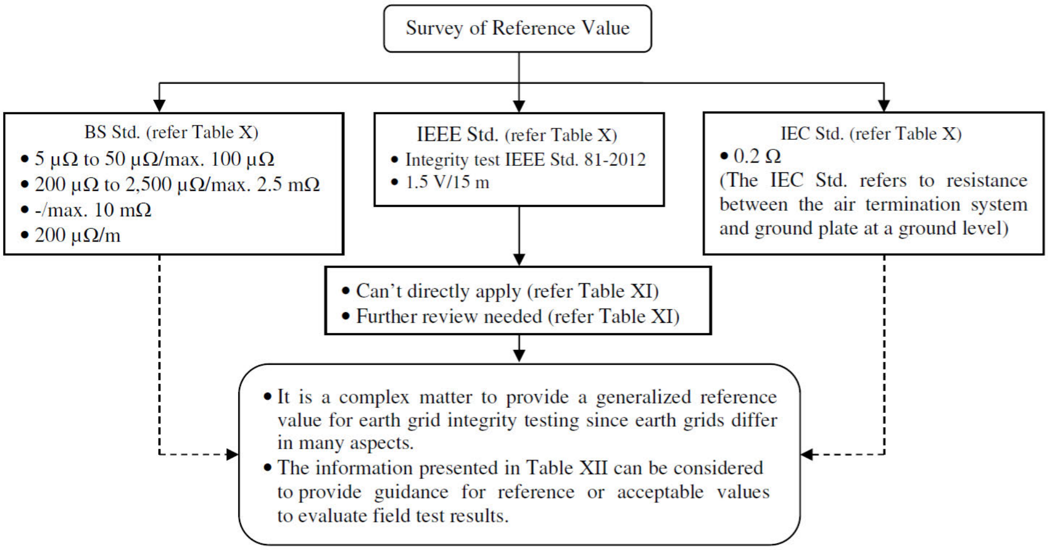


FIGURE 12. Flowchart for EMTP sample network results.

TABLE 9. Summary.

Branch	Branch Resistance (mΩ) [a]			
	Case 1A	Case 1B	Case 2A	Case 2B
AC	0.876	0.902	1.753	1.803
CE	0.876	2.104	1.753	4.207
IB	**1.064**	**1.071**	**2.129**	**2.141**
BD	**1.064**	**1.221**	**2.129**	**2.442**
DE	**1.064**	**1.221**	**2.129**	**2.442**
EH	**1.064**	**1.221**	**2.129**	**2.442**
HG	**1.064**	**1.221**	**2.129**	**2.442**
GF	**1.064**	**1.071**	**2.129**	**2.141**
FA	**1.064**	**1.071**	**2.129**	**2.141**
AI	**1.064**	**1.071**	**2.129**	**2.141**
AB	1.252	1.277	2.504	2.554
GE	1.252	1.878	2.504	3.756
CD	1.315	1.822	2.629	3.644
FC	1.315	1.371	2.629	2.742
FB	1.816	1.822	3.631	3.644
GD	1.816	1.972	3.631	3.944
FD	2.254	2.479	4.508	4.958
HI	2.254	2.479	4.508	4.958

[a] Add 0.06 mΩ for every one-meter riser to ascertain the total resistance across risers connected to the nodes of any branch.

interconnections form another layer of irregular mesh, resulting the overall resistance value across any branch being less than the tabulated value. Risers, if broken or if very poor joints exist in the riser connections, can be easily identified because these two risers are removed from the equipment for the test.

A reference drawing showing the earth grid layout and riser connections should be available. Thus, by this test, either in construction sites or completed sites, the following can be addressed in general.

a) An open circuit or poor joints of connections of risers can be identified.
b) Open circuits in larger earth grids with many meshes cannot be identified or must be identified with great attention and difficulty by an expert engineer.

TABLE 10. Acceptable readings for joints, conductor and riser.

Description	Typical values as per standards		
	BS	IEEE	IEC
Individual Joints [a] (e.g., bolted connection)	5 μΩ to 50 μΩ/max. 100 μΩ	-	-
Between any two items of plant or equipment within 2 m of each other	200 μΩ to 2,500 μΩ/ max. 2.5 mΩ [b]	-	-
Maximum resistance between any items within the whole substation	max. 10 mΩ	-	0.2 Ω [c]
Example resistance of 1 m length of 25 mm x 3 mm copper tape	200 μΩ/m [d]	-	-
Integrity test	-	1.5 V/15 m [e]	-

c) Open circuits in larger earth grids with larger meshes can be identified with careful examination by an expert engineer.
d) Open circuit in smaller earth grids with many smaller meshes cannot be identified.

This test is best used in the United Arab Emirates to test joints in earth grids during installation. This test is currently gaining importance in the testing of risers in existing substations as a part of the health checks of their earthing systems.

IV. EARTH GRID JOINTS, RISER CONDUCTOR AND INTEGRITY TEST-SURVEY OF REFERENCE VALUE

Any reference value to ascertain the test results should generally be simple and easy to compare. Therefore, a literature survey was conducted to obtain source reference values of resistances of joints and conductors from different standards and manufacturer's data. Based on a survey [24],

TABLE 11. Calculated values of V/15 m for various conductors and different currents.

Conductor size (mm^2)	Copper conductor resistance 'R' in (Ω/km) at 20°C [20], [26]	Per unit length (m)	Voltage drop values of DC current in (A) [a]				
			100	200	260	300	373
			Voltage per 15 meters (V/15 m)				
50	0.387	15	0.58	1.16	**1.51**	1.74	2.17
70	0.268	15	0.40	0.80	1.05	1.21	**1.50**
95	0.193	15	0.29	0.58	0.75	0.87	1.08
120	0.153	15	0.23	0.46	0.60	0.69	0.86
150	0.124	15	0.19	0.37	0.48	0.56	0.69
185	0.099	15	0.15	0.30	0.39	0.45	0.55
240	0.075	15	0.11	0.23	0.29	0.34	0.42
300	0.060	15	0.09	0.18	0.23	0.27	0.34

[a] Voltage drop values for AC current can be calculated either using V/A/m (Voltage/Ampere/meter) data or using the *R*, *X* parameters of cable, refer [20].

TABLE 12. Reference value guidance.

Item	Description	Values	Reference
a)	Riser conductor resistance, impedance per meter	Ohmic value as per manufacturer factory test data	[20], [26]
b)	Individual joints (e.g., bolted connection)	5 to 50 μΩ typical, maximum 100 μΩ	[24], Table X
c)	Study case 1 and case 2: earth grid resistance of any branch (specific to a site)	Refer to Table IX	Table IX
d)	As in case 'c' plus risers	Refer to Table IX and the note therein	Table IX
e)	Study case 1 and case 2: earth grid resistance of any two nodes	Refer to Table IX	Table IX
f)	As in case 'e' plus risers	Refer to Table IX and the note therein	Table IX
g)	Specific to an HV substation - Thermo weld joints (earth grid as in study case 1A)	2 to 15 μΩ (Based on real site measured value)	Table X
h)	Study case 1 and case 2: earth grid impedance	As in item (c) to item (e): to be evaluated for AC current test	Table IX, Table X

acceptable readings are given in Table 10 along with a flowchart in Fig. 12.

V. ANALYSIS OF THE REFERENCE VALUE

A. REVIEW OF THE REFERENCE VALUE OF 1.5 V/15 m/300 A

The IEEE Std. 80-2013 states that the reference value for integrity tests is 1.5 V/15 m for 300 A, which equates to a single ohmic reference value of 0.33 mΩ per meter. As a result of this observation, voltage drops across 15 m length of different copper conductors for various currents are calculated and summarized in Table 11. There are only two voltage drop values (highlighted in bold) that match the 1.5 V/15 m criteria, corresponding to currents of 260 A (for the 50 mm^2 conductor) and 373 A (for the 70 mm^2 conductor). Due to variations in conductor sizes, site extents, soil resistivity parameters, touch & step criteria, earth grid resistance, grid current and other factors will lead to designing different earth grids.

Therefore, in practical sites, it is not possible to make a direct comparison between field test results and this single reference value of 0.33 mΩ per meter. Therefore, additional guidance on reference values is discussed further in section V-B.

B. REFERENCE VALUE GUIDANCE FOR AN EARTH GRID INTEGRITY TEST

It is a complex matter to provide a generalized reference values for earth grid integrity testing since earth grids differ in many aspects. The information presented in Table 12 can be considered to provide guidance for reference or acceptable values to evaluate field test results.

VI. CONCLUSION

Integrity tests are generally considered to be simple, but this is not true because they involve measuring very low resistance values. They require skilled personnel and accurate instruments. The use of the DC current method is preferable over the use of the AC current method for integrity tests. This test is primarily used for the testing of thermo welded joints of a buried earth grid in the United Arab Emirates.

However, integrity testing for the evaluation of earth risers has been gaining importance in recent years for health checks of earth connections. This test is well suited to identify open or very poor joints in earth riser connections. As guided by IEEE Std. 81-2012 earth integrity test results can be analyzed only subjectively. The best way is to compare the measured resistance values with each other and identify the test risers that have abnormally high impedance values. Another way is to conduct a comparison with a set of previous test results. Reference values or acceptable readings for earth grid resistance across nodes or branches can be established by computation on a case-by-case basis for DC current testing. However, impedance calculations at a site are difficult in the case of AC current testing. The value of 1.5 V/15 meters for 300 A cannot serve as a reference value since it doesn't account for any specific conductor sizes or earth grid configurations although it points to a single ohmic value of 0.33 mΩ per meter. Therefore, it is advisable to use the manufacturer's recommended Ω/m as a reference for riser conductors. However, it is essential to evaluate and incorporate reference values for earth grid resistance across risers as well. The analyses given in this paper indicate the complexity of interpreting the field test results. Based on the guidance provided in this paper, integrity testing, when properly carried out, can evaluate the health of earth connections. An open circuit in a buried earth grid can be identified only in certain cases. A useful future work in this area would be the establishment of reference values for AC and DC current testing of different types of earth grids with an aim to provide a table to search for reference values to compare with site test results.

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PERUMAL VELMURUGAN (Member, IEEE) was born in Tamil Nadu, India, in 1962. He received the B.E. degree in electrical and electronics engineering from the College of Engineering, Guindy, in 1984, the M.E. degree in power system studies from Annamalai University, Tamil Nadu, in 1990, and the Ph.D. degree from BITS-Pilani, Dubai Campus, India, in 2020. He is currently an Engineering Manager with Twinvey Electric Consultancy, Dubai. He possesses extensive experience of over 33 years in power generation, transmission and distribution, including power system analysis using various software. He is familiar with earthing standards IEEE Std. 80 (design), IEEE Std. 81 (site test), BS Std. 7430, and Lightning Protection Systems IEC 62305. He has hands on experience in earthing grid design using cymgrd/edsa software. He has been involved in testing of over 100 earthing systems in measurement of soil resistivity, ground potential rise, step and touch potentials, and earth integrity test measurements. He was involved in a trail earthing studies in desert regions to evaluate earthing systems performance in different regions of varying soil resistivity. He is a member of the Society of Engineers, UAE, and a fellow of the Institution of Engineers, India.

ADHIR BARAN CHATTOPADHAYAY was born in West Bengal, India, in 1957. He received the B.E. degree in electrical engineering from the Bengal Engineering College, University of Calcutta, India, in 1979, the M.Sc. (Engineering) degree in electrical engineering from the Regional Institute of Technology, Jamshedpur, Ranchi University, India, in 1990, and the Ph.D. degree in electrical engineering from the Indian Institute of Technology, Kharagpur, India, in 1998. He is currently a Professor of electrical engineering and the Former Dean of the Research and Development, Budge Budge Institute of Technology, Kolkata, West Bengal. He possesses both industrial and teaching experience of over 39 years, of which 34 years of teaching was in India and Dubai. His industrial experience as an Electrical Engineer includes the design, modification, and testing of low-tension induction motors and the inspection and industrial testing of raw materials at the incoming stage. His experience in teaching includes supervision of thesis work, research guidance, and publication of books and research papers. He has published many papers in international and national journals and in the proceedings of international and national conferences. He has published one book in the area of power system design (Publisher: New Age International Publishers Private Ltd.; London and New Delhi).