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ELECTRODE RESISTANCE
MEASUREMENT**

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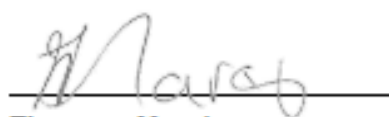
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Compiled by



Theunus Marais

**Chief Engineer –
Substation Engineering**

Date: 10 September 2021

Approved by

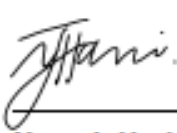


Braam Groenewald

**Corporate Consultant –
Substation Engineering**

Date: 10 September 2021

Authorized by

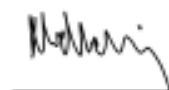


Naresh Hari

**General Manager –
Transmission Engineering**

Date: 2021-09-15

Supported by SCOT/SC



Subhas Maharaj

Substation SC Chairperson

Date: 14/9/2021

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Executive Summary

As described in IEEE Standard 81-2012, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System, connections to earth have complex impedances that include resistive, capacitive, and inductive components, all of which affect their current-carrying capabilities. The resistance of the connection to remote earth is of particular interest to those concerned with power frequencies because it is affected by the resistivity of the earth in the area of the connection assuming the earthing system is small enough that the resistance dominates the overall impedance. The capacitance and inductance values are of interest to those concerned with higher frequencies, such as radio communications and lightning applications, or very large earthing systems when the resistance does not dominate the overall impedance.

A substation earthing system typically consists of buried earth conductors connected to several transmission and distribution structure earths and interconnected by shield and possibly neutral conductors. The interconnected impedance of this type of earthing system will be referred to as the earthing system impedance. Isolated pole earths and most distribution substations with typical soil resistivities are predominately resistive. On the other hand, large earthing systems, especially in low soil resistivity areas, will have a significant reactive component.

The impedance of an earthing system largely depends on the resistivity of the surrounding soil and the extent and configuration of the buried electrode. Earth at a given location can be composed of various combinations of natural materials of widely varying resistivity. The soil can be relatively homogeneous over a large area, or it can be made up out of layers of different materials.

Calculations and experience show that, in a given soil, the effectiveness of an earth grid is dependent largely on the overall size of the earth grid and the resistivity of the soil. The addition of conductors and earth rods within an existing earth grid system can also aid somewhat in reducing the earth grid impedance. This reduction diminishes with the addition of each successive conductor or rod.

After the installation of a substation earth grid, the settling of the soil with annual cyclical weather changes tends to reduce the earth impedance during the first year or two.

The impedance of an earth electrode is usually measured in terms of resistance because the reactance is generally negligible with respect to the resistive component. The reactive component increases with the size of the earth grid and especially when the earth grid is interconnected with earthed neutral and shield wire systems. Determination of the reactive component is necessary when the analysis involves surge or impulse currents. To avoid confusion, the term "resistance" will be used to mean the impedance of an isolated earth electrode.

The resistance will not usually vary greatly from year to year after the first year or two following its installation.

Two measurement methods are proposed for use:

- Tagg slope method for small substations (typically sub-transmission and distribution size), and
- Variable Frequency method for big substations (typically transmission size).

1. Introduction

In order to evaluate the new or existing substation earth electrodes (also referred to as earth mats or earth grids), the earth electrode resistance of the substation needs to be tested. For new substations this is a verification that the substation earth grid as installed complies with the associated design, and for existing substations this gives an indication of the grid condition if measured periodically over time. The result of this test is not a definitive indication of the grid condition, but must be compared to the original design value and/or previously measured values.

2. Supporting clauses

2.1 Scope

This standard details the methodology to be followed in measuring the earth electrode resistance. The principles prescribed in this standard are applicable to conducting electrode resistance testing at new or existing substations as long as cognisance is taken of the factors affecting the measurement accuracy.

2.1.1 Purpose

The purpose of this standard is to provide employees and contractors with a process to be followed in measuring the substation earth electrode resistance of new or existing substations in order to evaluate the earth grid condition.

2.1.2 Applicability

This document shall apply throughout Eskom Holdings Limited Divisions.

2.2 Normative/informative references

Parties using this document shall apply the most recent edition of the documents listed in the following paragraphs.

2.2.1 Normative

- [1] EPRI 1013793, Substation Ground Grid Impedance Measurement, Field Demonstration of Meters
- [2] EPRI TR-106661-V1, Distribution Grounding Volume 1: Handbook.
- [3] IEEE Std 81-2012, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System.
- [4] ISO 9001 Quality Management Systems.
- [5] SANS 10199:2010, South African National Standard, The design and installation of earth electrodes.
- [6] 240-44175132, Eskom Personal Protective Equipment (PPE).

2.2.2 Informative

- [7] DPC 34-227, Pre-Task Planning and Feedback Process
- [8] SANS 725, Guide for Safety in AC Substation Grounding (IEEE Std 80-2000).
- [9] 240-105197930, Variable Frequency Earth Electrode Resistance Measurement Result Sheet
- [10] 240-105197932, Tagg Slope Earth Electrode Resistance Measurement Result Sheet
- [11] 240-134369472, Substation Earth Grid Design Standard

2.3 Definitions

2.3.1 General

Definition	Description
Earth electrode impedance	The vector sum of resistance and reactance between the earth electrode, grid or system and remote earth.
Earth electrode resistance	The impedance, excluding reactance, between the earth electrode, grid or system and remote earth. Note that some sections of this document refer to impedance as resistance if the reactive portion of the impedance is deemed negligible.
Earth electrode/grid/mat	An earth electrode consisting of a large rectangular arrangement of conductors buried in trenches and divided by longitudinal and transverse conductors into a number of smaller rectangles.
Earth grid resistance	Refer to the definition of earth electrode resistance above.
Earthing	The electrical connection between an apparatus and the general mass of earth in such a way that it will ensure a safe discharge of electrical energy at all times.
Earthing system	A system intended to provide at all times, by means of one or more earth electrodes in a specific area, a low impedance path for the immediate discharge of electrical energy, without danger, into the general mass of the earth.
Remote earth	A theoretical concept that refers to an earth electrode of zero impedance placed an infinite distance away from the earth electrode under test. In practice, remote earth is approached when the mutual resistance between the earth electrode under test and the test electrode becomes negligible. Remote earth is normally considered to be at zero potential.
Stake	Firm stick or post sharpened at one end and driven into the ground as a support, boundary mark, etc.

2.3.2 Disclosure classification

Controlled disclosure: controlled disclosure to external parties (either enforced by law, or discretionary).

2.4 Abbreviations

Abbreviation	Description
Dx	Distribution
I	Current, measured in amp (A)
NECRT	Combined three-phase neutral electromagnetic couplers with neutral earthing resistors and auxiliary transformers
PPE	Personal Protective Equipment
R	Resistance, measure in ohm (Ω)
s/s	Substation
Tx	Transmission
V	Voltage, measured in volt (V)

2.5 Roles and responsibilities

All designers shall utilise and implement this standard during the substation earth grid design or evaluation process. This is applicable to all new as well as existing substations.

2.6 Process for monitoring

The following should review the correct application of the guide as and when applicable:

- 1) Substation Design Engineers.
- 2) Substation Design Senior Engineers.
- 3) Substation Chief Engineers.

2.7 Related/supporting documents

This document can be read in conjunction with [3] and [5] listed in 2.2.1 above.

3. Conducting earth electrode resistance tests

It must be noted that there is no generic resistance value that a grid must comply with, but the measured result must favourably compare to the specific grid's design value.

The two methods supported for use are:

- Distribution size grids: Tagg Slope method
- Transmission size grids: Variable Frequency method

3.1 Background

The purpose of this document is to give guidance on the acceptable methods to be used for substation earth electrode resistance testing.

There are a number of documents available indicating how the earth electrode resistance should be measured. The concern however is that most of these documents are generic in their proposed application, i.e. measuring equipment manufacturer manuals or application guides. Unfortunately these documents are not directly applicable to measurements associated to transmission, sub-transmission or distribution substation applications and as a result omit important practical requirements to be adhered to when conducting these measurements.

Irrespective of the test method used, it is always important to gather sufficient data to plot the actual resistance/impedance curve, and to use this curve as visual confirmation of the test result integrity while still on site.

3.2 Measurement frequency

Test intervals are dependent on specific requirements, but should as a minimum be done when:

- New earth grid installation has been completed to verify compliance to the design,
- Whenever the earth grid is modified or extended to verify compliance to the design,
- There is a concern about the continued performance of the earthing system.

3.3 Measurement method comparison

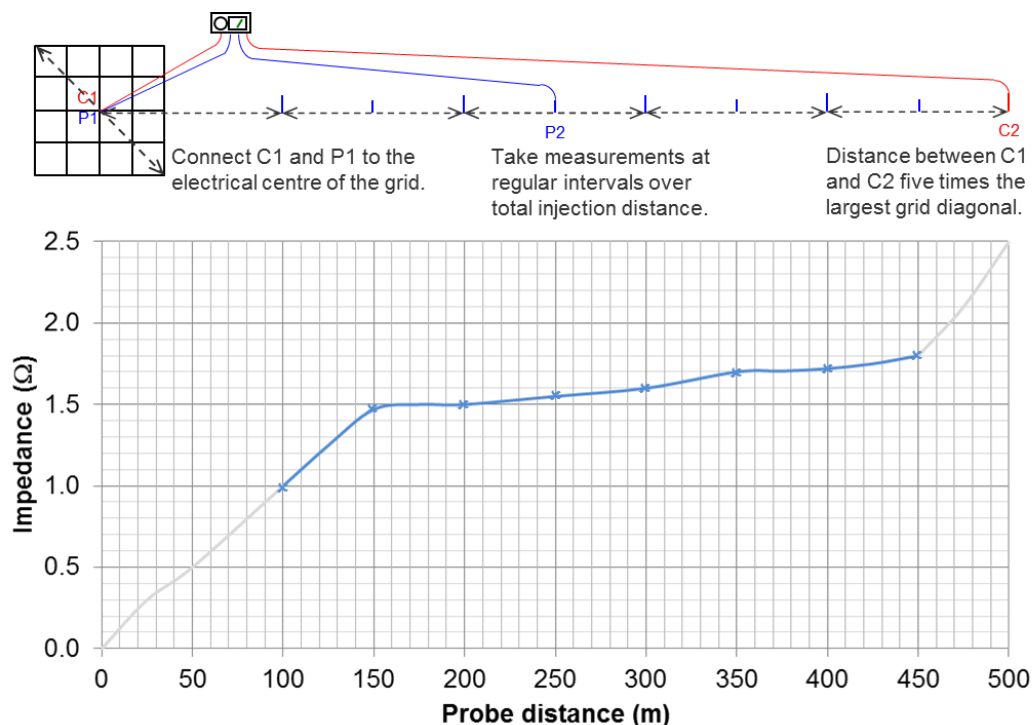
There are various methods that can be used, and all of them have certain advantages and disadvantages. Listed in Table 1 are the various methods considered with their main advantages and disadvantages.

Table 1: Comparison of the various test methods

Method	Description	Advantages	Disadvantages
Fall-of-potential (refer to Figure 1) (Typically for small installations)	Inject a current between the grid electrical centre and a remote current probe at least <u>five times the grid largest diagonal</u> away. Take resistance measurements between the grid electrical centre and the current probe at distances varying from 10% - 90% of current probe distance. Plot resistance values versus distance. Earthing system resistance is represented by the area where the curve flattens. The non-linear slope is as a result of the varying soil structure.	Simple to carry out. Requires a minimal amount of calculations to obtain a result. Same test-set can be used as for soil resistivity testing.	Only suitable for complex systems only if the full resistance curve is plotted, otherwise suitable for small earth electrodes only. Applicable to uniform soil. Electrical centre of the earth electrode must be known. Current should be injected over a distance 5 times the largest diagonal of the earth electrode to minimise inter-electrode influences.
61.8% (refer to Figure 2) (Typically for small installations)	This is an adaptation of the fall-of-potential method. Inject a current between the grid electrical centre and a remote current probe at least <u>five times the grid largest diagonal</u> away. Take 3 resistance measurements between the grid electrical centre and 60%; 62.5% and 65% of the current probe distance. Plot resistance values versus distance. If these values correlate well then it can be used as the earthing system resistance. This point might vary based on the soil structure.	Simple to carry out. Requires a minimal amount of calculations to obtain a result. Same test-set can be used as for soil resistivity testing.	Suitable for small earth electrodes only, not applicable for distribution or transmission size stations. Applicable to uniform soil. Electrical centre of the earth electrode must be known. Current should be injected over a distance 5 times the largest diagonal of the earth electrode to minimise inter-electrode influences.
Tagg Slope (refer to Figure 3) (Typically for Dx sized substations)	Inject a current between the grid edge and a remote current probe preferably <u>three to four times the grid largest diagonal</u> away. Take resistance measurements between the grid and the current probe at distances varying from 10% - 70% of current probe distance. Plot resistances values versus distance. The theoretical optimum location at which the electrode resistance should be measured is then determined through a few basic calculations and from tabulated data. Measure the grid resistance at the distance calculated, or determine it from the graph of the measured values.	Suitable for use with larger earthing systems, typically distribution size substations. Electrical centre of the earth electrode is not important. Current should only be injected over a distance 2 - 3 times the largest diagonal of the earth electrode. Same test-set can be used as for soil resistivity testing.	Not as simple to carry out as the fall-of-potential or 61.8% methods. Requires a few calculations to obtain a result.

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Method	Description	Advantages	Disadvantages
Variable Frequency (refer to Figure 4) (Typically for Tx sized substations)	<p>This is a modification of the Tagg Slope method taking the effect of earthing system reactance into consideration and is applicable to especially large earthing systems.</p> <p>Inject a known current (preferably 1A) between the grid edge and a remote current probe preferably <u>three to four times the grid largest diagonal</u> away.</p> <p>Take impedance measurements between the grid and the current probe at distances varying from 10% - 70% of the current probe distance for frequencies ranging from 60Hz to 180Hz excluding multiples of 50Hz at each distance.</p> <p>Plot the impedance values against frequency, the DC (0Hz) resistances is obtained from the extrapolated graph for each measurement distance (10%, 20%, 30%, 40%, 50%, 60% and 70% of current injection distance).</p> <p>Apply the DC resistances to the Tagg Slope method to determine the grid resistance.</p>	<p>Suitable for use with large earthing systems, typically transmission size stations.</p> <p>Electrical centre of the earth electrode is not important.</p>	<p>Specialised test equipment needed.</p> <p>Current injection and voltage measurements must be done over long distances.</p> <p>Requires a number of calculations and graphs to obtain a result.</p> <p>Substantial current needed for injection, preferably 1A, but not less than 0.5A.</p>

**Figure 1: Fall-of-potential method setup with typical measurement results****ESKOM COPYRIGHT PROTECTED**

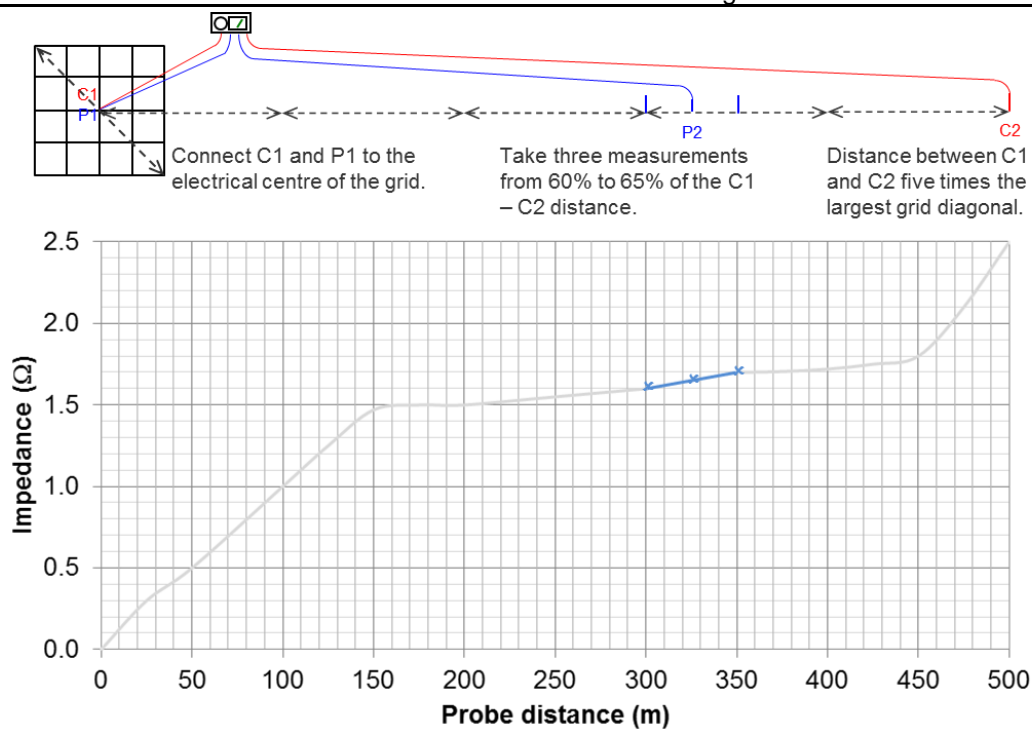


Figure 2: 61.8% method setup with typical measurement results

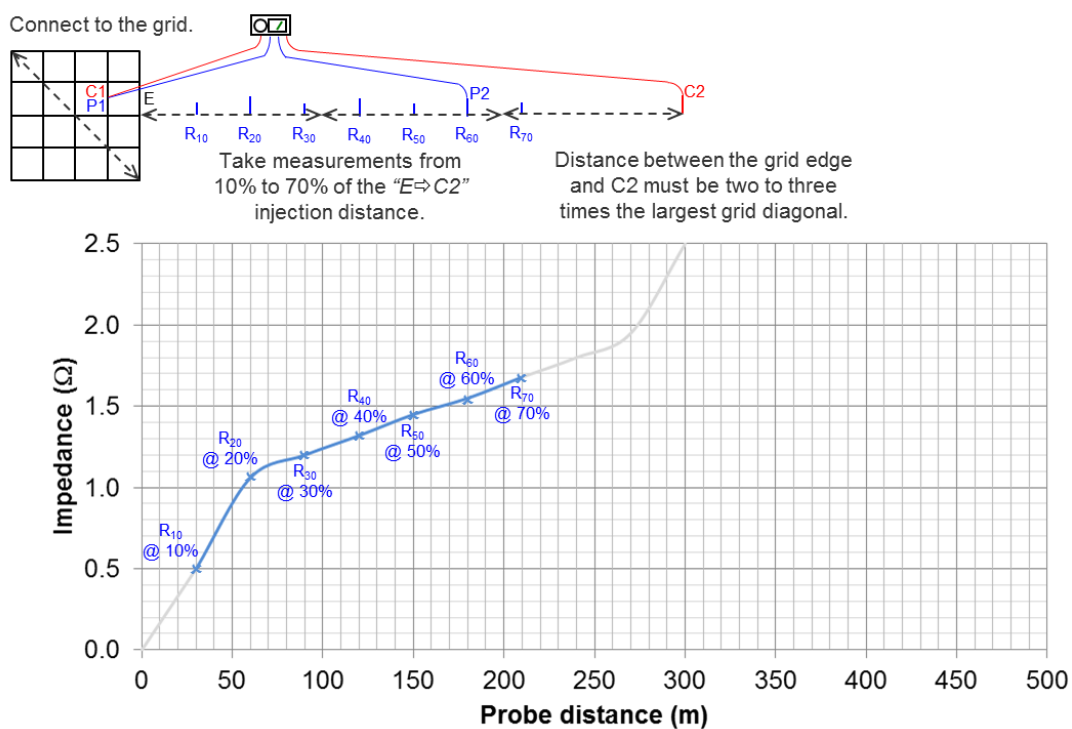


Figure 3: Tagg Slope method setup with typical measurement results

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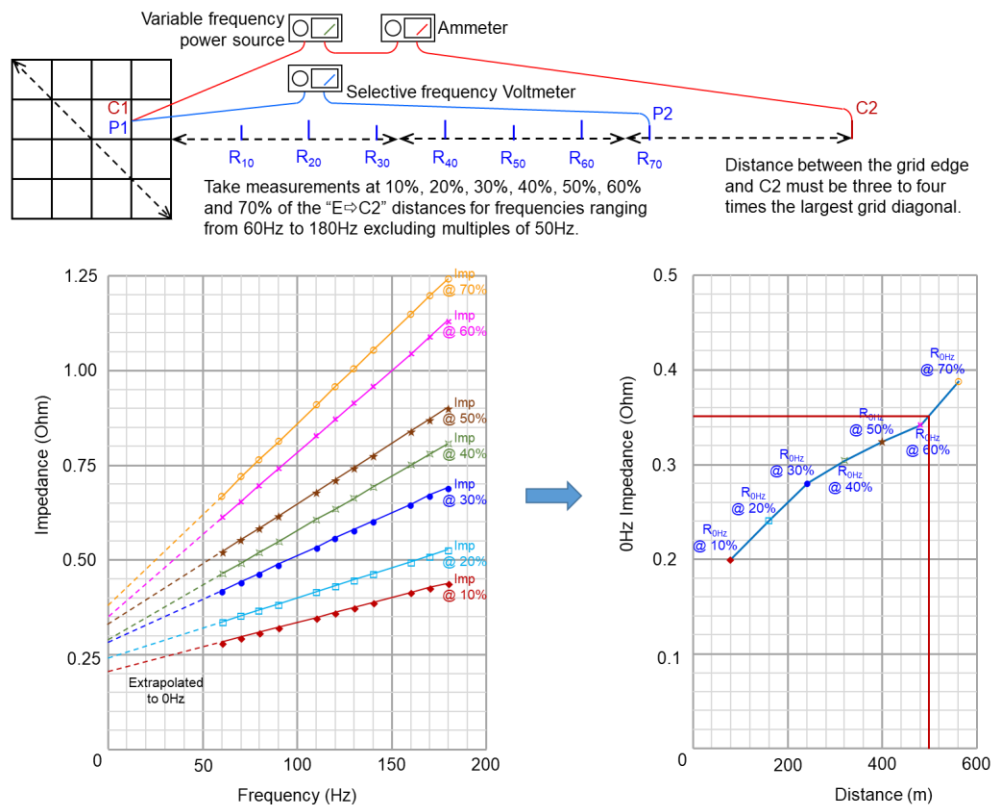


Figure 4: Variable Frequency method setup with typical measurement results

3.4 Factors affecting the accuracy of measured results

The connection of overhead shield wires, buried water pipes, cable sheaths, adjacent railroad tracks, conveyor systems, and so on, can all have an effect on the measurement results and can introduce significant errors. The following factors will affect the accuracy of the results and shall be mitigated when expected to be present during the measurements:

- Existing earth grids: measurements cannot be performed on or in close proximity parallel to existing earth grids as the grid material and layout will create unwanted current return paths and will, as a result, invalidate the measured results. All measurements shall be done away from existing earthing systems.
- Stray alternating currents: mitigated by making use of a high frequency (>100Hz) narrow band filtered test set. This means the current must be injected at a fixed frequency and the potential measured at the same frequency only.
- Metallic structures, fences, power lines with shield wires, etc. shall be avoided in the area where the measurements are performed. These create unwanted current return paths that will invalidate measured results. It is mitigated by performing the measurement perpendicular to any of these present in the test area.
- Unwanted voltages can be induced into test leads running parallel to an energized line for a significant distance. These induced voltages will not only affect the accuracy of measured results but can also be a safety hazard. It is mitigated by performing the measurement perpendicular to any of these present in the test area.
- Test leads must be uncoiled from the reels completely to prevent self-induction that will negatively affect test results.

-
- f) Test lead resistance: if C1 and P1 are connected together at the test set with a jumper and then with a single lead connection to the earth electrode, the resistance of the lead from the test set to the earth electrode adds to the measured results. This is mitigated by connecting C1 and P1 with separate leads to the earth electrode.
- g) Measurement errors or localised inconsistencies in the soil: mitigated by calculation and plotting of the results as the measurements are performed. It is advisable to do a second set of measurements but in a different direction to the first set for result comparison and verification purposes.
- h) Coupling between test leads: mitigated by ensuring all leads are properly uncoiled, crossing each other at 90° only and separated by at least 500mm at all times to prevent self and mutual induction.
- i) Current injection distance: ensure that current is injected over a long enough distance. Refer to Annex D for an indication of the impact when the current injection distance is not sufficient.
- j) C1/P1 connection to earth grid: ensure that this connection is at a point that has been verified by an earth continuity test as connected to the earth grid to ensure a valid test result.

3.5 Determining where measurements should be done

As indicated in paragraph 3.4 above it is important to consider the factors affecting the accuracy when determining where to do measurements. If at all possible, two sets of measurements must be done for each substation to verify the accuracy of the final result.

An area free from interfering services (metallic structures, fences, power lines with shield wires, pipelines, etc.) must be identified. This area shall be equal to or longer than three to four times the largest diagonal of the substation for the Tagg Slope method and three to four times the largest diagonal for the Variable Frequency method. Refer to Figures 5, 6, 9 and 10 for examples on how the injection distance and area of measurement should be determined.

3.6 Safety precautions while doing tests

Since the current and potential electrodes are located at points that represent remote earth, the leads to these electrodes should be treated as though a possible voltage could exist between the test leads and any point on the substation earth grid. The main area of concern involves system faults or lightning strikes, which can cause voltages as high as several thousand volts to occur between the substation earth grid and remote points. One or more test leads that are electrically connected to an earth grid can cause a transfer of potential under these conditions.

The test signal injected into a remote current electrode can also result in significant touch voltages.

The following precautions can reduce these hazards although other precautions might also be necessary:

- Hands or other parts of the body are not allowed to complete the circuit between points of possible high-potential difference. Gloves and dielectrically rated footwear can reduce the hazards associated with handling test leads that extend outside the substation earth grid.
- Workers and the general public shall be kept away from areas around the test probes by either cordoning the area around the test probes off by typically making use of danger-tape or having these areas under continuous observation for as long as it takes to conduct the tests.
- If remote current and potential probes are not within sight of test personnel or if the test leads are located in an area accessible to the public, then these remote points should be under continuous observation for as long as it takes to conduct the test.
- Test signals must be applied for short periods at a time only, and all test leads must be promptly removed after the test is completed.
- If the unearthed ends of test leads run parallel to an energized line for a significant distance, then a hazardous voltage can be induced into the test leads if large currents are flowing in the energized line. Such conditions must be avoided because it is not only unsafe, but will also negatively affect the measurement results (refer to item 3.4 point (d)).

3.7 Tagg Slope method

This method is applicable for use on Distribution size substations with typical maximum earth grid diagonals up to 150m, with current injection distance between the edge of the grid and C2 of up to 300m. This distance is primarily a function of the test set used for current injection, i.e. maximum current that can be injected.

3.7.1 Equipment and accessories needed for the Tagg Slope method

The following minimum equipment is needed:

- Four terminal earth tester (e.g. Megger DET 2/2 Auto Earth Tester):
 - The test instrument needs to inject sufficient current into the test circuit to ensure acceptable test measurements and reliable test results.
 - The test instrument must have a valid calibration certificate.
- 1 x 450m 1.5mm² lead (typically red panel flex cable) with heavy duty welding clamps for current injection. Alternatively multiple shorter leads (3 x 150m) that can be securely connected together to make up this length.
- 1 x 320m 1.5mm² lead (typically black panel flex cable) with heavy duty welding clamp for voltage measurement. Alternatively multiple shorter leads (2 x 160m) that can be securely connected together to make up this length.
- 2 x 30m 1.5mm² leads with heavy duty welding clamps for connecting to the substation earth electrode.
- 2 or more probes. (SAP 0168669, EARTH ROD Cu 1500x16D THREADLESS D3091, cut in three equal lengths)
- 4 x 500mm long 1.5mm² connector leads, two red and two black.
- 3 x 100m measuring tapes.
- 2 x hammers.
- 4 x 1.2m long stakes and 16m danger-tape to cordon current probe C2 off if necessary (refer to bullet 2 of 3.6 (Safety precautions while doing tests)).
- Water for wetting the current probe to reduce probe resistance. (Typically 5 litres)
- Documentation to capture results (refer to Table 1).
- Appropriate PPE in accordance with [6].

3.7.2 Tagg Slope method description

The process below must be followed when preparing for and taking the actual measurements, with reference to Figures 3, 5, 6, 7 and 8 as well as Table 2. Note that two sets of measurements should be taken at all times.

- 1) In preparation before going to site the following have to be done:
 - Determine the maximum earth grid diagonal by making use of the substation earth mat layout drawing or any other aids such as Google Earth or SmallWorld Geoviewer. Note that where a third party substation is connected to an Eskom substation the total combined grid must be considered. Refer to Figure 5.
 - Calculate the distance needed from the edge of the earth grid to point C2 for current injection. This linear distance should preferably be three times or more but not less than twice the largest diagonal of the earth grid.
 - This linear distance from the edge of the earth grid is labelled “E⇌C2”.

-
- Assess the area around the substation by making use of GIS aids such as Google Earth or SmallWorld Geoviewer, identifying infrastructure such as overhead power lines, fences and pipelines around the substation and determine possible areas where the measurements can be done, taking cognisance of the linear distance needed for the measurements. Refer to Figure 6.
 - Considering the information gathered in the previous bullet points and the requirements as stated in section 3.6 (Safety precautions while doing tests), determine the minimum number of people needed to conduct the test.
- 2) At the substation, carefully assess the area where the measurements will be done and do a risk assessment by using [7] as a guideline.
 - 3) Determine the point at the edge of the earth grid where the equipment will be set up and unpack all needed equipment. This point is labelled “E”.
 - 4) Connect current lead C1 and voltage lead P1 to the transformer or NECRT earth connection to ensure a proper connection to the earth grid. In cases where no transformers or NECRTs are available a reference point should be chosen that has been verified to be connected to the earth grid through earth continuity measurements.
 - 5) Roll the measuring tapes out in the direction the measurements will be done up to the distance over which current will be injected. This point is labelled “C2”. Hammer the current probe into the ground at this point.
 - For earth grids with a maximum diagonal length of 150m or less, current should be injected over at least three times this diagonal length (minimum of three times the maximum diagonal length),
 - For earth grids with a maximum diagonal length of more than 150m, current should be injected at least over a distance of 450m (minimum of twice the maximum diagonal length) but preferably more.
 - 6) Roll the leads out in the same directions as the measuring tapes, one for voltage and one for current ensuring a separation distance of at least 500mm between leads.
 - 7) Connect the current lead to current probe C2.
 - 8) Hammer the voltage probe P2 into the ground at a distance 70% “E⇒C2” and connect the voltage lead.
 - 9) Connect all leads to the test equipment by making use of the connectors if necessary.
 - 10) Take the measurement and note the result in the table (refer to Table 2 for an example).
 - 11) Plot the result on the graph paper (refer to Figure 8 for an example).
 - 12) Repeat steps (8) to (11) above for the following distance fractions of “E⇒C2” by moving probe P2: 60%; 50%; 40%; 30%; 20%; 10% (refer to Figure 7).
 - 13) From the graph select three measurement points that are in a straight line and equal distances apart, i.e. from Figure 3 typically R20; R40; R60.
 - It is important that the values selected are in a straight line and equal distances apart.
 - Capture these values as R1; R2; R3 in Table 2.
 - 14) Calculate z , with $z = \frac{R3-R2}{R2-R1}$ and note the value in Table 2.
 - 15) From the calculated z value and the table in Annex 1 determine $L1/("E⇒C2")$:
 - The value of z is given in column 1 for the first two decimal places, the third decimal place being given opposite " z " in columns 2-11.

- Alternatively set R1; R2; R3 equal to R30; R50; R70, recalculate z and verify if this z value is reflected in the table (Annex 1). If this z value is in the table, use it to determine the distance at which the grid resistance must be measure.
 - A value of z not reflected in the table (Annex 1) means that the distance “E⇒C2” must be increased and the measurements redone because the variance between R1; R2; R3 is too big.
- 16) The distance L1 from point E where the actual grid resistance should be measured is given by the value obtained in Annex A multiplied by the current injection distance “E⇒C2”.
 - 17) Measure the resistance at distance L1 and note the value in Table 2 as R_{G1} (in ohm).
 - 18) Repeat steps (5) to (17) for the second test.
 - 19) The results of both tests should correlate reasonably well with each other. Earth electrode resistance is the value associated with the largest injection distance, the additional test is done to verify the applicability of the results obtained.

Refer to Annex B for an example on determining R1; R2; R3; calculating z and L1 and determining R_G.

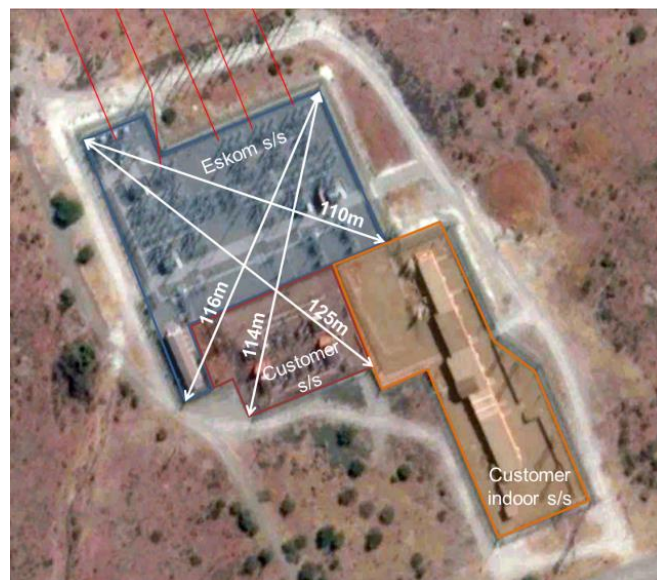


Figure 5: Determining the substation maximum diagonal

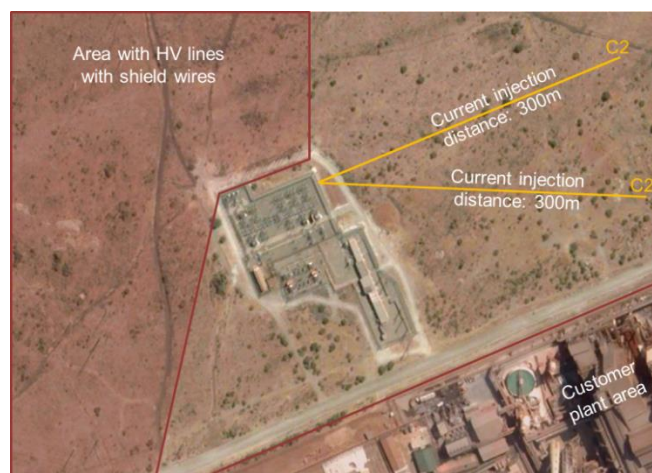


Figure 6: Determining current injection area

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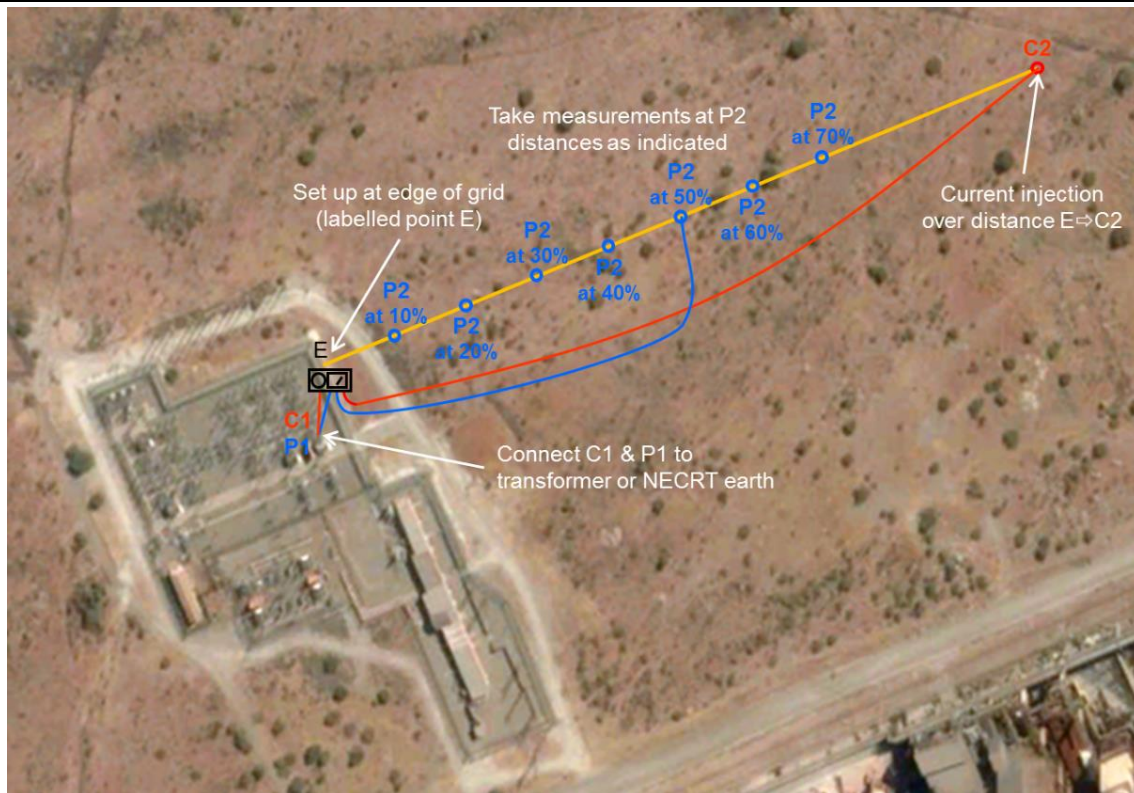


Figure 7: Tagg Slope method setup

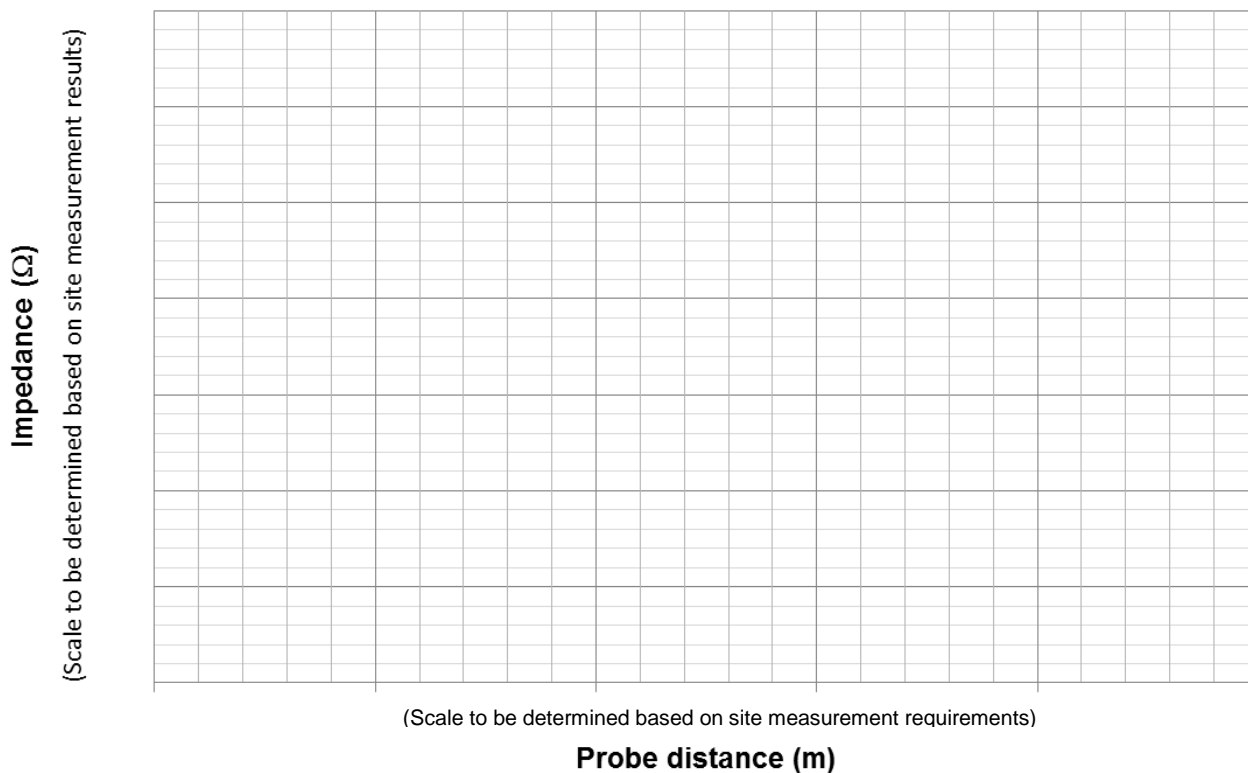


Figure 8: Example of graph paper to be used for the Tagg Slope method

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Table 2: Tagg Slope measurement results

Date:		Measurement set T ₁		Measurement set T ₂	
Time:					
Weather conditions:					
Site conditions:					
Soil conditions:					
Earth electrode largest diagonal (m)					
Distance "E⇨C2" (m)					
Connection point in substation					
Point "E" coordinate:		S	E	S	E
Point "C2" coordinate:		S	E	S	E
		Distance	Resistance	Distance	Resistance
		m	Ω	m	Ω
R ₁₀	10% "E⇨C2"				
R ₂₀	20% "E⇨C2"				
R ₃₀	30% "E⇨C2"				
R ₄₀	40% "E⇨C2"				
R ₅₀	50% "E⇨C2"				
R ₆₀	60% "E⇨C2"				
R ₇₀	70% "E⇨C2"				
Notes / Comments:					
Choose R1; R2; R3 from the measured values above		R1		R1	
		R2		R2	
		R3		R3	
Calculate Z: $z = \frac{R_3 - R_2}{R_2 - R_1}$		Z		z	
From calculated z value and Annexure 1 determine L1/("E⇨C2")		L1/("E⇨C2")		L1/("E⇨C2")	
Distance at which earth electrode resistance must be measured		L1 (m)		L1 (m)	
Measured earth electrode resistance at distance L1		R _{G1} (Ω)		R _{G2} (Ω)	
Earth electrode resistance is the value associated with the largest injection distance, the additional test is done to verify applicability of the results.					

3.8 Variable frequency method

This method is applicable for use on Distribution and Transmission size substations with typical maximum earth grid diagonals more than 150m, with current injection distance between the edge of the grid and C2 of preferably three or more times the largest grid diagonal.

3.8.1 Equipment and accessories needed for the variable frequency method

The following minimum equipment is needed:

- Variable frequency power source:
 - The instruments need to inject preferably not less than 500mA into the test circuit considering the applicable injection distances.
 - The injection frequency must be selectable.
 - The instrument must have a valid calibration certificate.
- Selective frequency voltmeter:
 - The measurement frequency must be selectable,
 - The instrument must be equipped with a selectable narrow band filter.
 - The instrument must have a valid calibration certificate.
- Ammeter
 - The instrument must have a valid calibration certificate.
- Alternatively a single test set that comply with all the above stated requirements can be used.
- 1 x 16mm² lead for current injection, as long as needed with heavy duty welding clamps for connecting to the probes.
- 1 x 16mm² lead for voltage measurement, as long as needed with heavy duty welding clamps for connecting to the probes.
- 2 x 30m 16mm² leads with heavy duty welding clamps for connecting to the substation earth electrode.
- 2 or more probes. (SAP 0168669, EARTH ROD Cu 1500x16D THREADLESS D3091, cut in three equal lengths)
- 4 x 500mm long 16mm² connector leads, two red and two black.
- Additional connectors as needed.
- 2 x hammers.
- 4 x 1.2m long stakes and 16m danger-tape to cordon current probe C2 off if necessary (refer to bullet 2 of 3.6 (Safety precautions while doing tests)).
- Water for wetting the current probe to reduce probe resistance. (Typically 5 litres)
- Documentation to capture results (refer to Table 1).
- Appropriate PPE in accordance with [6].

3.8.2 Variable frequency method description

The process below must be followed when preparing for and taking the actual measurements, with reference to Figures 4, 9, 10, 11 and 8 as well as Table 3. Note that eleven measurements should be taken at each of the predetermined distances.

- 1) In preparation before going to site the following shall be done:

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-
- Determine the maximum earth grid diagonal by making use of the substation earth mat layout drawing or any other aids such as Google Earth or SmallWorld Geoviewer. Refer to Figure 9 for an example. Note that, where a third party substation is connected to an Eskom substation, the total combined grid size must be considered.
 - Calculate the distance needed from the edge of the earth grid to point C2 for current injection. This linear distance should preferably be between three and four times the largest diagonal of the earth grid.
 - This linear distance from the edge of the earth grid is labelled “E⇨C2”.
 - Assess the area around the substation by making use of GIS aids such as Google Earth or SmallWorld Geoviewer, identifying infrastructure such as overhead power lines, fences and pipelines around the substation and determine possible areas where the measurements can be done practically, taking cognisance of the linear distance needed for the measurements. Refer to Figure 10 for an example.
 - Considering the information gathered in the previous bullet points and the requirements as stated in section 3.6 (Safety precautions while doing tests), determine the minimum number of people needed to conduct the test.
- 2) At the substation, carefully assess the area where the measurements will be done and do a risk assessment, refer to [7] as a guideline.
 - 3) Determine the point at the edge of the earth grid where the equipment will be set up and unpack all needed equipment. This point is labelled “E”.
 - 4) Connect current lead C1 and voltage lead P1 to a structure in the substation that is properly bonded to the earth grid to ensure a proper connection to the earth electrode. The integrity of this structure’s bonding to the earth grid must be verified by referencing the substations latest continuity test results.
 - 5) By making use of the measuring wheel determine the positions for “P2” and “C2” based on the predetermined distance over which current will be injected. Hammer the voltage and current probes into the ground at these points.
 - The linear distance “E⇨C2” should be between three and four times the largest diagonal of the earth grid.
 - The linear distance “E⇨P2” should be 70% “E⇨C2”
 - 6) Roll the leads out from point “E” to points “P2” and “C2” ensuring a separation distance of at least 1m between leads.
 - 7) Connect the voltage lead to voltage probe “P2” and the current lead to current probe “C2”.
 - 8) Connect all leads to the test equipment by making use of the connectors if necessary.
 - 9) Take the measurement and note the impedance in the table (refer to Table 3), ensuring that:
 - The variable frequency power source is set to 60Hz,
 - The selective frequency voltmeter is set to 60Hz,
 - The current injected is 0.5A (preferably).
 - 10) Calculate the impedance and plot the result on the graph paper (refer to Figure 11 for an example).
 - 11) Repeat steps (9) and (10) above for the following frequencies as well:
 - 70Hz; 80Hz; 90Hz; 110Hz; 120Hz; 130Hz; 140Hz; 160Hz; 170Hz and 180Hz.
 - 12) On the graph, extrapolate the measured result to intercept the 0Hz axis and note this impedance (resistance) value in Table 3.
 - 13) Repeat steps (9) to (12) for voltage probe “E⇨P2” distances 60%, 50%, 40%, 30%, 20% and 10% of the “E⇨C2” distance.

- 14) Transfer the 0Hz values obtained to Table 3 for “E⇒P2” distances 70% 60%, 50%, 40%, 30%, 20% and 10%.
- 15) Follow the steps 11, 13 – 16 described in section 3.7.2 (Tagg Slope method) to determine the distance at which the grid resistance should be determined.
- 16) At the distance calculated determine the grid resistance from the Tagg Slope graph.

Refer to Annex C for an example on applying the Variable Frequency method and determining R_G .

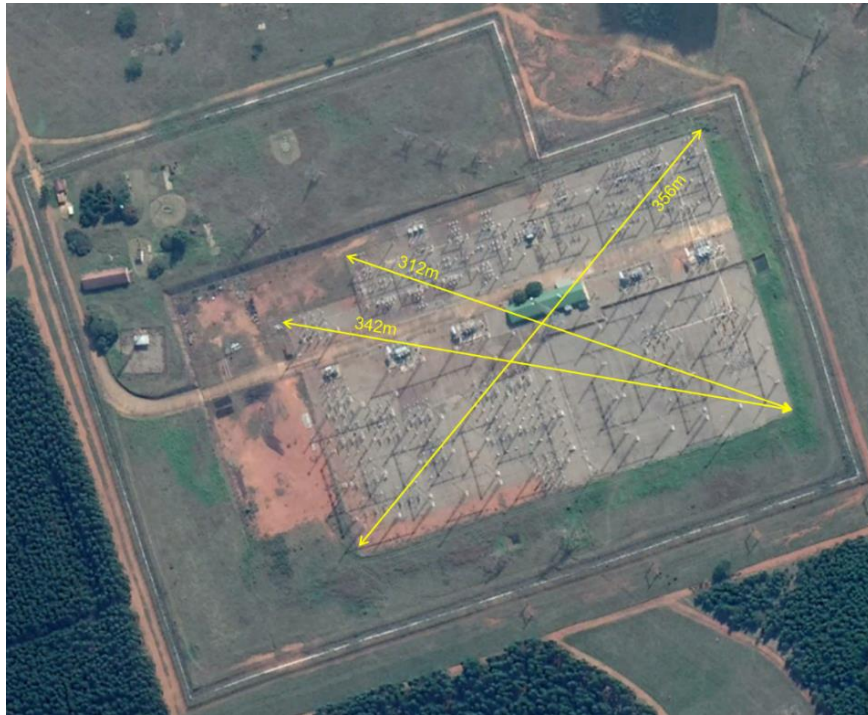


Figure 9: Determining substation diagonal for current injection distance



Figure 10: Determining current injection distance and direction

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Table 3: Variable Frequency measurement results

Substation Name							
Date:				Time:			
Weather conditions:							
Site conditions:							
Soil conditions:							
Earth electrode largest diagonal (m)				Distance "E⇨C2" (m)			
"C1" and "P1" connection point in substation							
Point "E" coordinate:	S			E			
Point "C2" coordinate:	S			E			
Distance "E⇨P2" (%)	10%	20%	30%	40%	50%	60%	70%
Distance "E⇨P2" (m)							
	Impedance (Ω)						
60Hz							
70Hz							
80Hz							
90Hz							
110Hz							
120Hz							
130Hz							
140Hz							
160Hz							
170Hz							
180Hz							
0Hz resistance from graph							
Choose R1; R2; R3 from the 0Hz values above	R1 =		R2 =		R3 =		
Calculate $z = \frac{R3-R2}{R2-R1} =$	From calculated z value and Annexure 1 determine L1/("E⇨C2") from the table				L1/("E⇨C2") =		
Distance at which earth electrode resistance must be measured	L1 =		0Hz earth electrode resistance at distance L1			R _G =	
Notes / Comments:							

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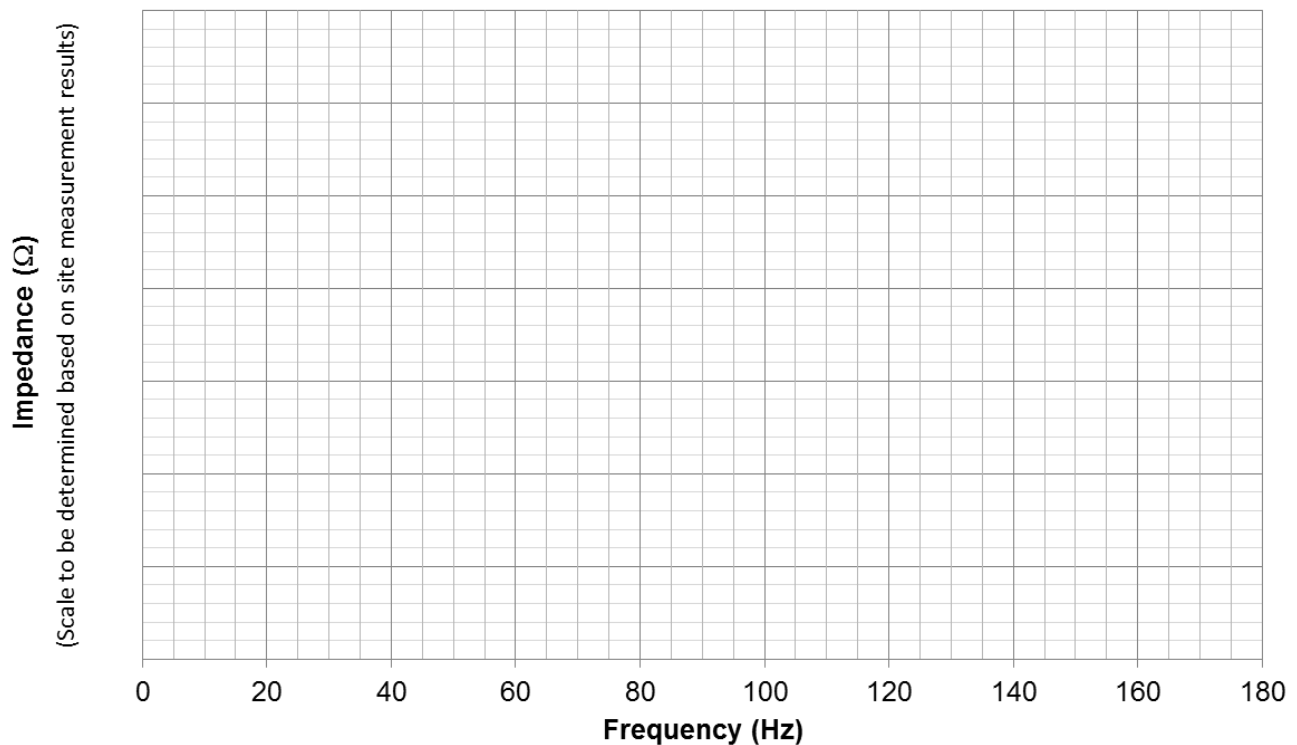


Figure 11: Example of graph paper to be used for the variable frequency measurements

3.9 Final report

It is important that the process followed and results obtained are documented properly for future reference when additional work at the applicable substation needs to be done. The following minimum information should be captured in the report:

- Detail on the four terminal earth tester used, including a copy of the valid calibration certificate.
- Information on the site and location where the measurements were conducted, including site drawing (or google map) indicating the numbered measurement traverses (as per Figures 7 and 10).
- All details and measurement results as per Tables 2 and 3 as applicable.
- All measurement and calculation results must be provided in table and graph format. Refer to Tables 2 and 3, Figures 7 and 10 as well as Annex B and C for examples of what should be in the report.

4. Authorization

This document has been seen and accepted by:

Name and surname	Designation
Alex Ndlela	Senior Manager, Engineering, Dx
Braam Groenewald	Corporate Specialist, Tx, Substation Engineering
Andile Madikizela	Senior Technician, Dx, Network Engineering & Design, Eastern Cape OU
Christy Thomas	Senior Engineer, Tx, Substation Engineering
Fannie Masango	Senior Advisor, Dx, Network Engineering & Design, North West OU
Jayant Raghubir	Senior Engineer, Dx, Network Engineering & Design, KwaZulu Natal OU

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Name and surname	Designation
Kabelo Molapise	Engineer, Dx, Network Engineering & Design, Dx, Mpumalanga OU
Mark Pepper	Chief Engineer, Tx, Substation Engineering
Modiri Seate	Senior Engineer, Dx, Network Planning, Free State OU
Nkululeko Mazibuko	Engineer, Tx, Substation Engineering
Sydney Mukhawane	Senior Technologist, Dx, Network Engineering & Design, Northern Cape OU
Vusi Cele	Senior Engineer, Dx, Network Engineering & Design, Gauteng OU

5. Revisions

Date	Rev	Compiler	Remarks
Sept 2021	2	TJ Marais	Table 1 Variable Frequency description updated. Figure 4 updated. Section 3.4 (d) and (j) added. Section 3.7.1 updated. Section 3.7.2 (4) updated. Section 3.8.1 updated. Section 3.8.2 points (13)-(15) updated and (16) added. Figure 9 replaced. Figure 10 replaced. Table 3 updated. Annex C updated.
Dec 2015	1	TJ Marais	First issue

6. Development team

The following people were involved in the development of this document:

- Theunus Marais

7. Acknowledgements

Not applicable

Annex A – Values of $L1/(E(C2))$ for various values of z

As per table F.1, Annex F in SANS 10199:2010

The value of z is given in column 1 for the first two decimal places, the third decimal place being given opposite " z " in columns 2-11.

1	2	3	4	5	6	7	8	9	10	11
Values of $L1/(E \Rightarrow C2)$										
z	0	1	2	3	4	5	6	7	8	9
0.40	0.6432	0.6431	0.6429	0.6428	0.6426	0.6425	0.6425	0.6422	0.6420	0.6419
0.41	0.6418	0.6416	0.6415	0.6413	0.6412	0.6410	0.6410	0.6408	0.6406	0.6405
0.42	0.6403	0.6402	0.6400	0.6399	0.6397	0.6396	0.6395	0.6393	0.6392	0.6390
0.43	0.6389	0.6387	0.6386	0.6384	0.6383	0.6382	0.6380	0.6379	0.6377	0.6376
0.44	0.6374	0.6373	0.6372	0.6370	0.6369	0.6367	0.6366	0.6364	0.6363	0.6361
0.45	0.6360	0.6359	0.6357	0.6356	0.6354	0.6353	0.6351	0.6350	0.6348	0.6347
0.46	0.6346	0.6344	0.6343	0.6341	0.6340	0.6338	0.6337	0.6336	0.6334	0.6333
0.47	0.6331	0.6330	0.6328	0.6327	0.6325	0.6324	0.6323	0.6321	0.6320	0.6318
0.48	0.6317	0.6315	0.6314	0.6312	0.6311	0.6310	0.6308	0.6307	0.6305	0.6304
0.49	0.6302	0.6301	0.6300	0.6298	0.6297	0.6295	0.6294	0.6292	0.6291	0.6289
0.50	0.6288	0.6286	0.6285	0.6283	0.6282	0.6280	0.6279	0.6277	0.6276	0.6274
0.51	0.6273	0.6271	0.6270	0.6268	0.6267	0.6265	0.6264	0.6262	0.6261	0.6259
0.52	0.6258	0.6256	0.6255	0.6253	0.6252	0.6252	0.6248	0.6247	0.6245	0.6244
0.53	0.6242	0.6241	0.6239	0.6238	0.6236	0.6235	0.6233	0.6232	0.6230	0.6229
0.54	0.6227	0.6226	0.6224	0.6223	0.6221	0.6220	0.6218	0.6217	0.6215	0.6214
0.55	0.6212	0.6210	0.6209	0.6207	0.6206	0.6204	0.6203	0.6201	0.6200	0.6198
0.56	0.6197	0.6195	0.6194	0.6192	0.6191	0.6189	0.6188	0.6186	0.6185	0.6183
0.57	0.6182	0.6180	0.6179	0.6177	0.6176	0.6174	0.6172	0.6171	0.6169	0.6168
0.58	0.6166	0.6165	0.6163	0.6162	0.6160	0.6159	0.6157	0.6156	0.6154	0.6153
0.59	0.6151	0.6150	0.6148	0.6147	0.6145	0.6144	0.6142	0.6141	0.6139	0.6138
0.60	0.6136	0.6134	0.6133	0.6131	0.6130	0.6128	0.6126	0.6125	0.6123	0.6121
0.61	0.6120	0.6118	0.6117	0.6115	0.6113	0.6112	0.6110	0.6108	0.6107	0.6105
0.62	0.6104	0.6102	0.6100	0.6099	0.6097	0.6096	0.6094	0.6092	0.6091	0.6089
0.63	0.6087	0.6086	0.6084	0.6083	0.6081	0.6079	0.6076	0.6076	0.6074	0.6073
0.64	0.6071	0.6070	0.6068	0.6066	0.6063	0.6063	0.6061	0.6060	0.6058	0.6057
0.65	0.6055	0.6053	0.6052	0.6050	0.6047	0.6047	0.6045	0.6044	0.6042	0.6040
0.66	0.6039	0.6037	0.6036	0.6034	0.6031	0.6031	0.6029	0.6027	0.6026	0.6024
0.67	0.6023	0.6021	0.6019	0.6018	0.6015	0.6015	0.6013	0.6011	0.6010	0.6008
0.68	0.6006	0.6005	0.6003	0.6002	0.5998	0.5998	0.5997	0.5995	0.5993	0.5992
0.69	0.5990	0.5989	0.5987	0.5985	0.5982	0.5982	0.5980	0.5979	0.5977	0.5976
0.70	0.5974	0.5973	0.5971	0.5969	0.5965	0.5965	0.5964	0.5962	0.5960	0.5959
0.71	0.5957	0.5955	0.5953	0.5952	0.5948	0.5948	0.5947	0.5945	0.5943	0.5942

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The value of z is given in column 1 for the first two decimal places, the third decimal place being given opposite "z" in columns 2-11.

1	2	3	4	5	6	7	8	9	10	11
Values of L1/(E⇒C2)										
z	0	1	2	3	4	5	6	7	8	9
0.72	0.5940	0.5938	0.5936	0.5935	0.5931	0.5931	0.5930	0.5928	0.5926	0.5924
0.73	0.5923	0.5921	0.5920	0.5918	0.5914	0.5914	0.5912	0.5911	0.5909	0.5907
0.74	0.5906	0.5904	0.5902	0.5900	0.5897	0.5897	0.5895	0.5894	0.5892	0.5890
0.75	0.5889	0.5887	0.5885	0.5883	0.5880	0.5880	0.5878	0.5877	0.5875	0.5873
0.76	0.5871	0.5870	0.5868	0.5866	0.5863	0.5863	0.5861	0.5859	0.5858	0.5856
0.77	0.5854	0.5853	0.5851	0.5849	0.5846	0.5846	0.5844	0.5842	0.5841	0.5839
0.78	0.5837	0.5835	0.5834	0.5832	0.5829	0.5829	0.5827	0.5825	0.5824	0.5822
0.79	0.5820	0.5818	0.5817	0.5815	0.5812	0.5812	0.5810	0.5808	0.5806	0.5805
0.80	0.5803	0.5801	0.5799	0.5797	0.5794	0.5794	0.5792	0.5790	0.5788	0.5786
0.81	0.5785	0.5783	0.5781	0.5779	0.5775	0.5775	0.5773	0.5772	0.5770	0.5768
0.82	0.5766	0.5764	0.5762	0.5760	0.5757	0.5757	0.5755	0.5753	0.5751	0.5749
0.83	0.5748	0.5746	0.5744	0.5742	0.5738	0.5738	0.5736	0.5735	0.5733	0.5731
0.84	0.5729	0.5727	0.5725	0.5723	0.5720	0.5720	0.5718	0.5716	0.5714	0.5712
0.85	0.5711	0.5709	0.5707	0.5705	0.5701	0.5701	0.5699	0.5698	0.5696	0.5694
0.86	0.5692	0.5690	0.5688	0.5686	0.5683	0.5683	0.5681	0.5679	0.5677	0.5675
0.87	0.5674	0.5672	0.5670	0.5668	0.5664	0.5664	0.5662	0.5661	0.5659	0.5657
0.88	0.5655	0.5653	0.5651	0.5650	0.5646	0.5646	0.5644	0.5642	0.5640	0.5638
0.89	0.5637	0.5635	0.5633	0.5631	0.5627	0.5627	0.5625	0.5624	0.5622	0.5620
0.90	0.5618	0.5616	0.5614	0.5612	0.5608	0.5608	0.5606	0.5604	0.5602	0.5600
0.91	0.5598	0.5596	0.5594	0.5592	0.5590	0.5588	0.5586	0.5584	0.5582	0.5580
0.92	0.5578	0.5576	0.5574	0.5572	0.5570	0.5568	0.5565	0.4463	0.5561	0.5559
0.93	0.5557	0.5555	0.5553	0.5551	0.5549	0.5547	0.5545	0.5543	0.5541	0.5539
0.94	0.5537	0.5535	0.5533	0.5531	0.5529	0.5527	0.5525	0.5523	0.5521	0.5519
0.95	0.5517	0.5515	0.5513	0.5511	0.5509	0.5507	0.5505	0.5503	0.5501	0.5499
0.96	0.5497	0.5495	0.5493	0.5491	0.5489	0.5487	0.5485	0.5483	0.5481	0.5479
0.97	0.5477	0.5475	0.5473	0.5471	0.5469	0.5467	0.5464	0.5462	0.5460	0.5458
0.98	0.5456	0.5454	0.5452	0.5450	0.5448	0.5446	0.5444	0.5442	0.5440	0.5438
0.99	0.5436	0.5434	0.5432	0.5430	0.5428	0.5426	0.5424	0.5422	0.5420	0.5418
1.00	0.5416	0.5414	0.5412	0.5409	0.5407	0.5405	0.5403	0.5400	0.5398	0.5396
1.01	0.5394	0.5391	0.5389	0.5387	0.5385	0.5383	0.5380	0.5378	0.5376	0.5374
1.02	0.5371	0.5369	0.5367	0.5365	0.5362	0.5360	0.5358	0.5356	0.5354	0.5351
1.03	0.5349	0.5347	0.5345	0.5342	0.5340	0.5338	0.5336	0.5333	0.5331	0.5329
1.04	0.5327	0.5325	0.5322	0.5320	0.5318	0.5316	0.5313	0.5311	0.5309	0.5307
1.05	0.5305	0.5302	0.5300	0.5298	0.5296	0.5293	0.5291	0.5289	0.5287	0.5284

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The value of z is given in column 1 for the first two decimal places, the third decimal place being given opposite "z" in columns 2-11.

1	2	3	4	5	6	7	8	9	10	11
Values of L1/(E⇒C2)										
z	0	1	2	3	4	5	6	7	8	9
1.06	0.5282	0.5280	0.5278	0.5276	0.5273	0.5271	0.5269	0.5267	0.5264	0.5262
1.07	0.5260	0.5258	0.5255	0.5253	0.5251	0.5249	0.5247	0.5244	0.5242	0.5240
1.08	0.5238	0.5235	0.5233	0.5231	0.5229	0.5226	0.5224	0.5222	0.5219	0.5217
1.09	0.5215	0.5213	0.5211	0.5209	0.5206	0.5204	0.5202	0.5200	0.5197	0.5195
1.10	0.5193	0.5190	0.5188	0.5185	0.5183	0.5180	0.5178	0.5175	0.5173	0.5170
1.11	0.5168	0.5165	0.5163	0.5160	0.5158	0.5155	0.5153	0.5150	0.5148	0.5145
1.12	0.5143	0.5140	0.5137	0.5135	0.5132	0.5130	0.5127	0.5125	0.5122	0.5120
1.13	0.5118	0.5115	0.5113	0.5110	0.5108	0.5105	0.5103	0.5100	0.5098	0.5095
1.14	0.5093	0.5090	0.5088	0.5085	0.5083	0.5080	0.5078	0.5075	0.5073	0.5070
1.15	0.5068	0.5065	0.5062	0.5060	0.5057	0.5055	0.5052	0.5050	0.5047	0.5045
1.16	0.5042	0.5040	0.5037	0.5035	0.5032	0.5030	0.5027	0.5025	0.5022	0.5020
1.17	0.5017	0.5015	0.5012	0.5010	0.5007	0.5005	0.5002	0.5000	0.4997	0.4995
1.18	0.4992	0.4990	0.4987	0.4985	0.4982	0.4980	0.4977	0.4975	0.4972	0.4970
1.19	0.4967	0.4965	0.4962	0.4960	0.4957	0.4955	0.4952	0.4950	0.4947	0.4945
1.20	0.4942	0.4939	0.4936	0.4933	0.4930	0.4928	0.4925	0.4922	0.4919	0.4916
1.21	0.4913	0.4910	0.4907	0.4904	0.4901	0.4899	0.4896	0.4893	0.4890	0.4887
1.22	0.4884	0.4881	0.4878	0.4875	0.4872	0.4870	0.4867	0.4864	0.4861	0.4858
1.23	0.4855	0.4852	0.4849	0.4846	0.4843	0.4841	0.4838	0.4835	0.4832	0.4829
1.24	0.4826	0.4823	0.4820	0.4817	0.4814	0.4812	0.4809	0.4806	0.4803	0.4800
1.25	0.4797	0.4794	0.4791	0.4788	0.4785	0.4783	0.4780	0.4777	0.4774	0.4771
1.26	0.4768	0.4765	0.4762	0.4759	0.4756	0.4754	0.4751	0.4748	0.4745	0.4742
1.27	0.4739	0.4736	0.4733	0.4730	0.4727	0.4725	0.4722	0.4719	0.4716	0.4713
1.28	0.4710	0.4707	0.4704	0.4701	0.4698	0.4696	0.4693	0.4690	0.4687	0.4684
1.29	0.4681	0.4678	0.4675	0.4672	0.4669	0.4667	0.4664	0.4661	0.4658	0.4655
1.30	0.4652	0.4649	0.4645	0.4642	0.4638	0.4635	0.4631	0.4628	0.4625	0.4621
1.31	0.4618	0.4614	0.4611	0.4607	0.4604	0.4601	0.4597	0.4594	0.4590	0.4586
1.32	0.4583	0.4580	0.4577	0.4573	0.4570	0.4566	0.4563	0.4559	0.4556	0.4553
1.33	0.4549	0.4546	0.4542	0.4539	0.4539	0.4532	0.4529	0.4525	0.4522	0.4518
1.34	0.4515	0.4511	0.4508	0.4505	0.4501	0.4498	0.4494	0.4491	0.4487	0.4484
1.35	0.4481	0.4477	0.4474	0.4470	0.4467	0.4463	0.4460	0.4457	0.4453	0.4450
1.36	0.4446	0.4443	0.4439	0.4436	0.4432	0.4429	0.4426	0.4422	0.4419	0.4415
1.37	0.4412	0.4408	0.4405	0.4402	0.4398	0.4395	0.4391	0.4388	0.4384	0.4381
1.38	0.4378	0.4374	0.4371	0.4367	0.4364	0.4360	0.4357	0.4354	0.4350	0.4347
1.39	0.4343	0.4340	0.4333	0.4333	0.4330	0.4326	0.4323	0.4319	0.4316	0.4312

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The value of z is given in column 1 for the first two decimal places, the third decimal place being given opposite "z" in columns 2-11.

1	2	3	4	5	6	7	8	9	10	11
Values of L1/(E⇒C2)										
z	0	1	2	3	4	5	6	7	8	9
1.40	0.4309	0.4305	0.4301	0.4296	0.4292	0.4288	0.4284	0.4280	0.4275	0.4271
1.41	0.4267	0.4263	0.4258	0.4254	0.4250	0.4246	0.4242	0.4237	0.4233	0.4229
1.42	0.4225	0.4221	0.4216	0.4212	0.4208	0.4204	0.4200	0.4195	0.4191	0.4187
1.43	0.4183	0.4178	0.4174	0.4170	0.4166	0.4162	0.4157	0.4153	0.4149	0.4145
1.44	0.4141	0.4136	0.4132	0.4128	0.4124	0.4120	0.4115	0.4111	0.4107	0.4103
1.45	0.4099	0.4094	0.4090	0.4086	0.4082	0.4077	0.4073	0.4069	0.4065	0.4061
1.46	0.4056	0.4052	0.4048	0.4044	0.4040	0.4035	0.4031	0.4027	0.4023	0.4018
1.47	0.4014	0.4010	0.4006	0.4001	0.3997	0.3993	0.3989	0.3985	0.3980	0.3976
1.48	0.3972	0.3968	0.3964	0.3959	0.3955	0.3951	0.3947	0.3943	0.3938	0.3934
1.49	0.3930	0.3926	0.3921	0.3917	0.3913	0.3909	0.3905	0.3900	0.3896	0.3892
1.50	0.3888	0.3883	0.3878	0.3874	0.3869	0.3864	0.3859	0.3854	0.3850	0.3845
1.51	0.3840	0.3835	0.3830	0.3825	0.3820	0.3816	0.3811	0.3806	0.3801	0.3796
1.52	0.3791	0.3786	0.3781	0.3776	0.3771	0.3766	0.3760	0.3755	0.3750	0.3745
1.53	0.3740	0.3735	0.3730	0.3724	0.3719	0.3714	0.3709	0.3704	0.3698	0.3693
1.54	0.3688	0.3683	0.3677	0.3672	0.3667	0.3662	0.3656	0.3651	0.3646	0.3640
1.55	0.3635	0.3630	0.3624	0.3619	0.3613	0.3608	0.3602	0.3597	0.3591	0.3586
1.56	0.3580	0.3574	0.3569	0.3563	0.3557	0.3552	0.3546	0.3540	0.3534	0.3528
1.57	0.3523	0.3517	0.3511	0.3506	0.3500	0.3494	0.3488	0.3482	0.3477	0.3471
1.58	0.3465	0.3459	0.3453	0.3447	0.3441	0.3435	0.3429	0.3423	0.3417	0.3411
1.59	0.3405	0.3399	0.3393	0.3386	0.3380	0.3374	0.3368	0.3362	0.3355	0.3349

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Annex B – Tagg Slope method example

Two sets of measurements taken in two different directions from the substation.

		Measurement set T ₁		Measurement set T ₂	
Distance “E⇨C2” (m)		300		250	
		Distance	Resistance	Distance	Resistance
		m	Ω	m	Ω
R ₁₀	10% “E⇨C2”	30	0.50	25	0.46
R ₂₀	20% “E⇨C2”	60	1.06	50	0.92
R ₃₀	30% “E⇨C2”	90	1.20	75	1.25
R ₄₀	40% “E⇨C2”	120	1.32	100	1.35
R ₅₀	50% “E⇨C2”	150	1.45	125	1.44
R ₆₀	60% “E⇨C2”	180	1.55	150	1.52
R ₇₀	70% “E⇨C2”	210	1.68	175	1.62
Choose R ₁ ; R ₂ ; R ₃ from the measured values above		R ₁	1.06	R ₁	1.25
		R ₂	1.32	R ₂	1.44
		R ₃	1.55	R ₃	1.62
Calculate $z = \frac{R_3 - R_2}{R_2 - R_1}$		Z	0.885	z	0.947
From calculated z value and Annex 1 determine L1/ (“E⇨C2”)		L1/ (“E⇨C2”)	0.5646	L1/ (“E⇨C2”)	0.5523
Distance at which earth electrode resistance must be measured		L1 (m)	169.4	L1 (m)	138.1
Measured earth electrode resistance at distance L1		R _{G1} (Ω)	1.51	R _{G2} (Ω)	1.48

For measurement set T₁: R₁; R₂; R₃ is selected equal to R₂₀; R₄₀; R₆₀ because these are the standard selection and they are in a straight line.
For measurement set T₂: R₁; R₂; R₃ is selected equal to R₃₀; R₅₀; R₇₀ because although these are not the standard selection they are equal distances apart and in a straight line.

For measurement set T₁ the following is applicable:

From z and the table in Annex A determine L1/ (“E⇨C2”):
The value of z is given in column 1 for the first two decimal places, the third decimal place being given opposite “z” in columns 2-11.

For measurement set T₁: L1/ (“E⇨C2”) = 0.5646
Thus L1 = (“E⇨C2”) • 0.5646 = 300 • 0.5646 = 169.4m

Measurements are done at calculated distances L1. Earth electrode resistance is the value associated with the largest injection distance, i.e. R_{G1} therefor R_G = 1.51Ω. Measurement set T₂ is used as a check / verification.

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Annex C – Variable Frequency method example

Earth electrode largest diagonal = 356m			Distance “E⇒C2” (m) = 800m					Method 1) Determine the earth electrode’s largest diagonal. 2) Determine the distance over which current must be injected. 3) Determine the area where the measurements can be done. 4) Do the measurements as described in section 3.8.2: 5) Note the measured results in the table for each frequency per distance. 6) Plot the impedance values against frequency for each measurement distance, refer to Figure C1. 7) Extrapolate the curves to intercept the 0Hz axis. 8) Note the 0Hz values for each “E⇒P2” distance in the table. 9) Plot the 0Hz values against distance on the graph, refer to Figure C2. 10) Select R1, R2 and R3 equal to the “E⇒P2” 20%, 40% and 60% distances. 11) Calculate Z. 12) Determine L1/(E⇒C2) from the table in Annex 1. 13) Calculate the distance L1 at which the grid resistance must be measured. 14) At distance L1 measure the impedance for all frequencies and plot it on the graph. 15) Extrapolate the curve to incept the 0Hz axis. 16) This 0Hz value is the grid resistance. alternatively 14) From the Tagg Slope graph at distance L1 determine the grid resistance as indicated in Figure C2.
“C1” and “P1” connection point in substation			Line reactor earth connection					
Distance “E⇒P2” (%)	10%	20%	30%	40%	50%	60%	70%	
Distance “E⇒P2” (m)	80	160	240	320	400	480	560	
	Resistance (Ω)							
60Hz	0.267	0.343	0.406	0.476	0.519	0.633	0.697	
70Hz	0.278	0.355	0.449	0.503	0.548	0.640	0.718	
80Hz	0.284	0.368	0.467	0.524	0.579	0.679	0.757	
90Hz	0.297	0.379	0.486	0.548	0.621	0.718	0.798	
110Hz	0.312	0.407	0.527	0.600	0.679	0.802	0.890	
120Hz	0.324	0.423	0.548	0.628	0.711	0.848	0.958	
130Hz	0.343	0.440	0.569	0.657	0.736	0.894	0.995	
140Hz	0.349	0.461	0.588	0.677	0.771	0.945	1.040	
160Hz	0.371	0.494	0.644	0.728	0.847	1.026	1.123	
170Hz	0.387	0.504	0.663	0.774	0.874	1.082	1.198	
180Hz	0.389	0.521	0.689	0.808	0.899	1.130	1.250	
0Hz resistance from graph	0.2011	0.2461	0.2819	0.3074	0.3251	0.3424	0.3892	
Choose R1; R2; R3 from the 0Hz values above			R1 = 0.2461		R2 = 0.3074		R3 = 0.3424	
Calculate Z: $z = \frac{R3-R2}{R2-R1} = 0.571$		From calculated z value and Annexure 1 determine L1/(E⇒C2) from the table				L1/(E⇒C2) = 0.618		
Distance at which earth electrode resistance must be measured		L1 = 494.4m		Earth electrode resistance at distance L1		R _G = 0.352		

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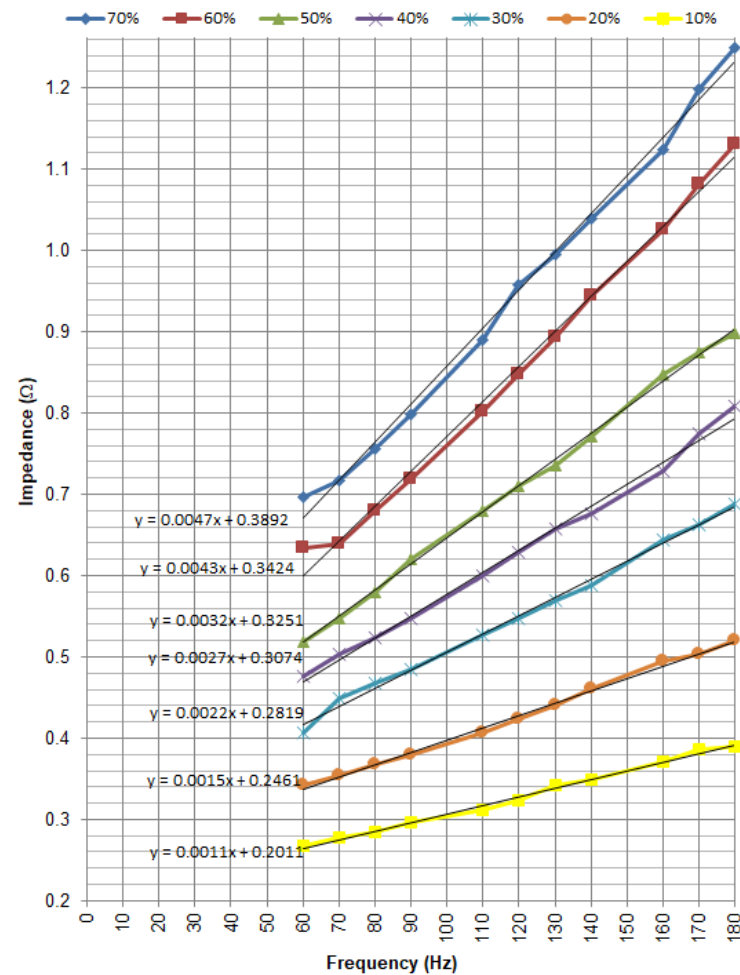


Figure C1: Measured Impedances plotted against frequency

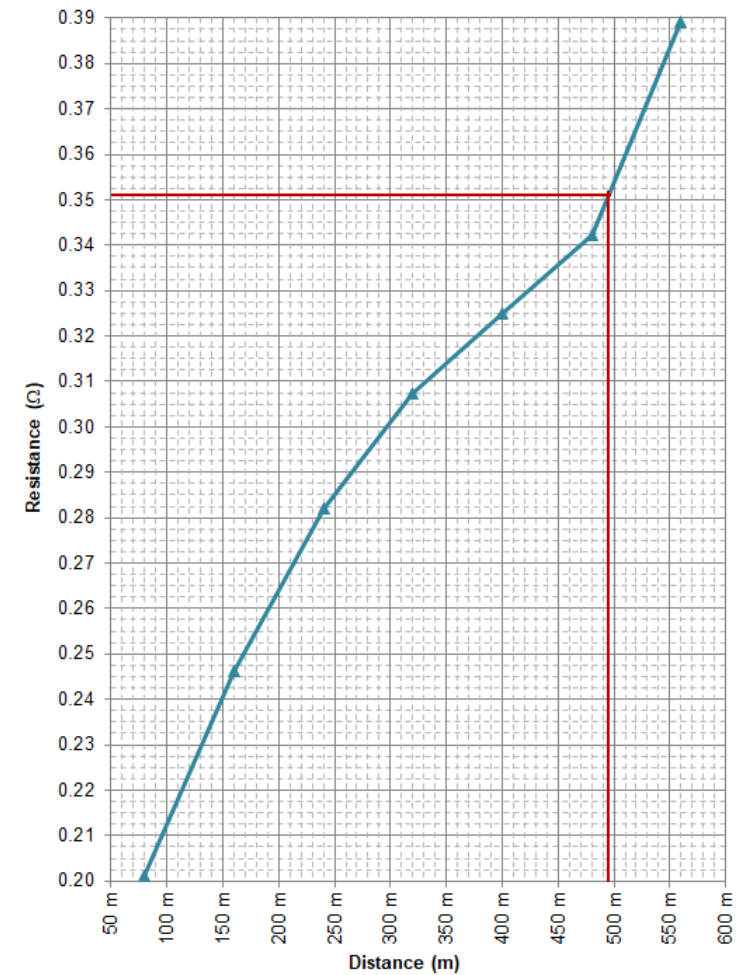


Figure C2: 0Hz Impedance plot against distance

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Annex D – Impact of chosen distance “E⇌C2” on test results

The accuracy of the measured results can be verified by carrying out additional tests at varying distance of “E⇌C2” and comparing the results from the different tests with each other. This is applicable to both the Tagg-Slope or Variable Frequency methods.

- Perform the test according to the Tagg Slope or Variable Frequency methods for varying distances of “E⇌C2”, or in different direction away from the substation.
- From the results obtained for the various test at the different distances for “E⇌C2”, a graph should be plotted as indicated below. The graph will show that as the distance for “E⇌C2” increases the associated measured resistance decreases asymptotically.
- It can be seen from this curve that “E⇌C2” distances chosen for tests 1 and 2 were insufficient because the measured resistance is still reducing substantially as the distance increases, while those distances chosen for tests 4 and 5 yielded the more correct “stabilised” results.
- It is unreasonable to expect an accuracy of readings better than 5% because of various external impacts such as soil non-homogeneity and seasonal soil moisture variations. If the current injection distance “E⇌C2” is sufficient, realistic measured result accuracies will typically be around 10%.

The best guarantee of a satisfactory measurement result is to apply the guidelines with regards to the proposed minimum current injection distances for “E⇌C2”. That is:

- Tagg Slope method: At least 2 – 4 times the maximum earth grid diagonal distance.
- Variable Frequency method: At least 3 – 4 times the maximum earth grid diagonal distance.

