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FOR SUBSTATION
APPLICATIONS**

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Compiled by



Theunus Marais
**Chief Engineer –
Operations Support**

Date: 2020/08/03


Approved by



Braam Groenewald
**Corporate Specialist –
Substation Engineering**

Date: 05/08/2020

Authorized by



Bheki Ntshangase
**Senior Manager –
Substation Engineering**

Date: 5 August 2020

Supported by SCOT/SC



Bheki Ntshangase
Substation SC Chairperson

Date: 5 August 2020

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1. Introduction

In order to evaluate the safety parameters (step and touch potentials) of new or existing substation earth electrodes (also referred to as earth mats or earth grids), the electrical soil characteristics applicable to the substation yard is needed. This will form an input into the substation earth grid design process which can be done by hand from first principles, or by making use of a software package like CDEGS.

2. Supporting clauses

2.1 Scope

This standard details the methodology to be followed in measuring the electrical soil parameters of the site to be used for substation earth grid design.

The principles prescribed in this standard are applicable to conducting soil resistivity 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 substation designers with a process to be followed in measuring the substation yard soil electrical properties applicable to the existing/future substation yard in order to design/evaluate the substation earth grid.

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] DISASAAT8, Standard for Selection, Use and Maintenance of Personal Protective Equipment.
- [2] ISO 9001 Quality Management Systems.
- [3] NST 39-54, Standard for Selection, Use and Maintenance of Personal Protective Equipment.
- [4] SANS 10199:2010, South African National Standard, The design and installation of earth electrodes.
- [5] 240-44175132, Eskom Personal Protective Equipment (PPE).
- [6] 240-76624513, Standard for the Calibration of Test Instruments Used by Field Staff
- [7] 240-134369472, Substation Earth Grid Design Standard

2.2.2 Informative

- [8] SANS 725, Guide for Safety in AC Substation Grounding (IEEE Std 80-2000).
- [9] 240-105221530, Soil Resistivity Measurement Result Sheet

2.3 Definitions

2.3.1 General

Definition	Description
Apparent soil resistivity	The equivalent, overall resistivity of a volume of soil with varying properties, expressed in ohm meter.
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis software package developed by SES Technologies.
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.
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, a low impedance path for the immediate discharge of electrical energy, without danger, into the general mass of the earth.
Potential gradient	Potential difference per unit length (usually expressed in volts per metre, V/m), measured in the direction in which the potential difference is at a maximum
Soil resistivity	The resistance between opposite faces of a cube of soil having sides of length 1 m. This value is expressed in ohm meter.
Step potential	Part of the earth electrode potential gradient that could be bridged by a person from foot to foot, normally calculated over a distance of 1m.
Touch potential	Part of the earth electrode potential gradient that could be bridged by a person from a hand in contact with a structure, through the body to the feet.

2.3.2 Disclosure classification

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

2.4 Abbreviations

Abbreviation	Description
ρ	Resistivity, depicted in ohm meter (Ωm)
a	Probe spacing, measured in meter (m)
I	Current, measured in amp (A)
PPE	Personal Protective Equipment
R	Resistance, measure in ohm (Ω)
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 Design Group Leaders.

2.7 Related/supporting documents

This document must be read in conjunction with [4].

3. Conducting soil resistivity tests

3.1 Background

There are a number of documents available indicating how soil resistivity testing should be done in general. 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 tests.

The purpose of this document is to give guidance on how the soil resistivity measurements for use in substation designs should be done.

3.2 Equipment and accessories

The following minimum equipment is needed:

- Four terminal earth tester (e.g. Megger DET 2/2 Auto earth Tester):
 - Test instruments need sufficient current flowing in the test circuit to obtain accurate test measurements and reliable test results.
 - The test instrument must have a valid calibration certificate, refer to [6].
- 2 x 80m leads with heavy duty welding clamps.
- 2 x 30m leads with welding clamps.
- 4 electrodes.
- 4 x connectors.
- 2 x 100m measuring tapes.
- 2 x hammers.
- Documentation to capture results (refer to table 1).
- PPE in accordance with [1], [3] and [5] as applicable.



(a) Equipment



(b) Accessories

Figure 1: Example of equipment needed

3.3 Measurement method description

A practical method to determine the soil resistivity distribution of the earth for the purpose of designing an earth electrode system is the four-electrode Wenner method as indicated in figure 2. Current is passed through the earth between two current electrodes C_1 and C_2 , and the resulting potential drop over a given distance is measured between two potential electrodes P_1 and P_2 . All probes are in a straight line and equal distances apart. It is therefore necessary to move all four electrodes for each measurement.

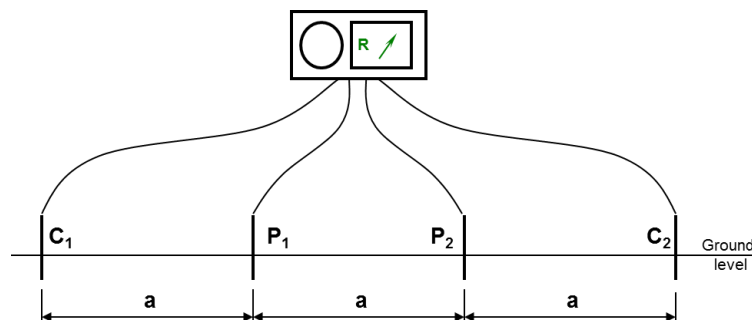


Figure 2: Four electrode Wenner method

If the current electrode spacing is increased, then current will penetrate deeper into the earth and the potential measured at the surface should reflect changes in resistivity as the depth increases. Because the relation between the current electrode spacing and depth of investigation in a multi-layered soil is a very complex one, it is not sufficient to carry out a single measurement, but instead a series of measurements with progressively larger electrode spacing is required. The measured resistance values must be converted to resistivity by making use of the equation

$$\rho = R2\pi a$$

where ρ is the soil resistivity, in ohm metres (Ωm),

R is the measured resistance, in ohms (Ω),

a is the probe separation distance, in meters (m).

The calculated resistivities must then be plotted against electrode spacing on bi-logarithmic graph paper. The resulting curve is used to obtain an estimation of the thickness and resistivities of the different soil layers. In other words, this curve is used to derive the soil model to be used for earth grid design / evaluation purposes.

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 must be mitigated when expected to be present during the measurements:

- Existing earth grids: soil resistivity measurements cannot be performed on or 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 must be done away from existing earthing systems.
- To ensure the measurement results are applicable to the area under investigation the meter must be set up in the centre of the 150m traverse and all four probes moved for each measurement (refer to annex G).
- Metallic structures, fences, HV lines with shield wires, etc. must 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.
- Coupling between test leads: mitigated by ensuring all leads are properly uncoiled, crossing each other at 90° and separated by at least 200mm at all times to prevent self and mutual induction.
- Probe depth: The soil apparent resistivity is a function of the probe depth, especially in the range 0.5m to 2m. If the probes are driven to a depth not exceeding 0.1 times the probe separation distance (a) then the approximate apparent soil resistivity is representative at a depth equal to the probe separation distance (a).
- 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. Interference might be manifested by the measurement not stabilising, in which case it will be necessary to activate the narrow-band-filter on the test set.
- 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 in the same area but in a different direction to the first set for result comparison and verification purposes.

3.5 Determining where measurements should be done

As indicated in paragraph 3.4, it is important to consider the factors affecting the accuracy of the measurements when determining where to do the measurements. It is strongly advised that probe spacings of up to 50m are used to ensure that representative soil electrical parameters are obtained, resulting in the total distance over which the measurements must be done to be 150m.

Two sets of measurements must be done for each area chosen as indicated in figure 3. A set of measurements include measurements associated with all the probe spacings referred to in paragraph 3.6 and listed in table 1.

The philosophy applied in determining where the measurements should be done will differ between existing substations and new (to be constructed) substations.

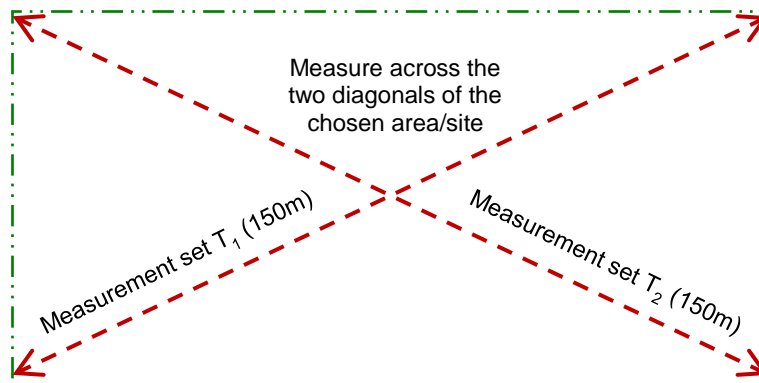


Figure 3: Indication of where measurements should be done in chosen area

The metering equipment must be set up in the centre of the proposed traverse and all four probes moved for each probe spacing.

Although not strictly necessary, it is advisable to do the measurements on the virgin site before the design is done (or before construction is started) to get an indication of the original soil properties in order to do the initial earth grid design. After the terrace has been completed and before the earth grid is installed or the foundations cast, the soil resistivity should be measured again. The results from this second set of measurements must be used for final earth grid design purposes and retained for future verification or design amendments as might be necessary.

Most distribution substations range from small (MV/MV: 30m x 30m) to large (HV/HV: 110m x 150m) in size compared to transmission substations (500m x 500m), and this will determine the number of measurements needed per site.

3.5.1 New distribution substations

Figures 4 and 5 below indicate where measurement should be done in relation to the proposed substation earth grid, and not necessarily in relation to the site. It is proposed that the measurement alignments should be through the diagonals of the proposed substations, or aligned in such a way to cover the biggest portion of the proposed substation. As indicated, for smaller substations two set of measurements should be adequate, while bigger stations require four sets (figure 5).

It is important to calculate and plot the resistivity results concurrently while the measurements are done (i.e. on the fly) to ensure that discrepancies are identified while doing the tests and reasons for it can be investigated while busy with the tests, or retested if necessary. Refer to Annex D, E and F for examples.

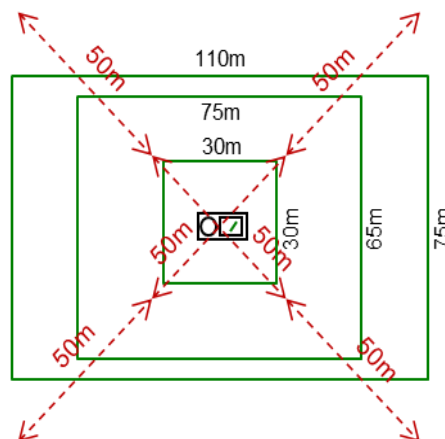


Figure 4: Proposed measurements associated with small to medium size distribution substations

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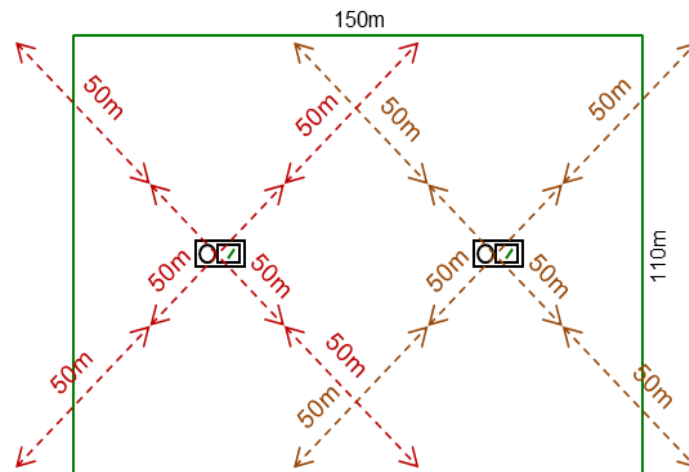


Figure 5: Proposed measurements associated with large distribution substations

3.5.2 New transmission substations

For transmission sites that are magnitudes bigger than distribution sites it is necessary to divide the site into equal blocks of 150m x 150m and then conduct the measurements on a representative sample of these blocks. Refer to figure 6 for an example of the minimum number of measurements to be done on a typical 500m x 500m site. It can be seen that at least ten sets of measurements should be done.

It is important to calculate and plot the resistivity results concurrently while the measurements are done (i.e. on the fly) to ensure that discrepancies are identified while doing the tests and reasons for it can be investigated while busy with the tests, or retested if necessary. Refer to Annex D, E and F for examples.

If marked differences between measurement results of different blocks are observed it will be necessary to do tests on the additional blocks previously omitted. For instance, if there is not an acceptable correlation between the results from blocks 5, 7 and 9, it will be necessary to also test block 8 to get a better indication (or understanding) of the soil characteristics transition over this portion of the site.

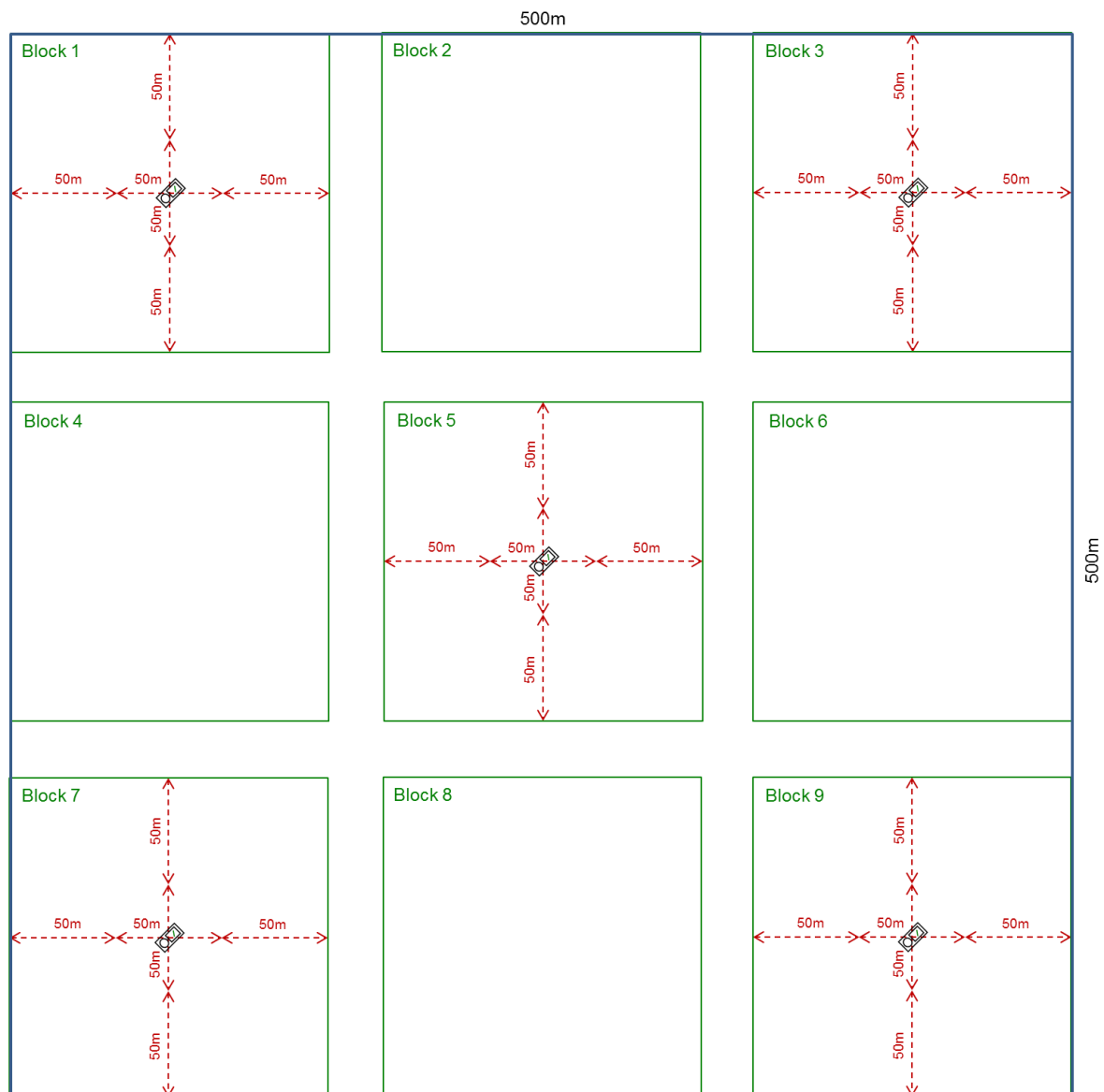


Figure 6: Proposed measurements associated with a 500m x 500m transmission site

3.5.3 Existing substations

At existing substations it is more challenging to find an area representative of the substation terrace to do the measurements on, even more so in urban or built up areas. The substation and surrounding area must be investigated carefully to identify the best position where the measurements should be done taking into consideration the factors highlighted in paragraph 3.4, Factors affecting the accuracy of measured result.

Refer to the examples given in Annex A, B and C for guidance in choosing the areas where measurements should be done for existing substations.

Where there is no space to perform the Wenner method it is possible to take soil samples and have these tested in a laboratory. Obtaining a useful approximation of apparent soil resistivity from resistivity measurements on samples is difficult, and in some cases impossible. This is due to the difficulty of obtaining representative homogeneous soil samples and in duplicating the original soil compaction and moisture content in the test cell. If this is the only option available it is advisable to take a number of samples at various depths, properly labelled.

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It is important to calculate and plot the resistivity results concurrently while the measurements are done (i.e. on the fly) to ensure that discrepancies are identified while doing the tests and reasons for it can be investigated while busy with the tests, or retested if necessary. Refer to Annex D, E and F for examples.

3.6 Taking the measurements

The process below must be followed when taking the actual measurements, with reference to figures 2 – 6:

- a) Identify the area where the tests must be done (refer to 3.4 bullet 1).
- b) Carefully assess the area and do a risk assessment. Take the necessary precautions to mitigate each identified risk.
- c) Determine the centre of the area where the specific measurements should be done, unpack and position the test equipment (refer to 3.4 bullet 2 and annex G).
- d) Roll measuring tapes out in opposite directions in a straight line, taking cognisance of other structures, services, fences etc. in the area (refer to 3.4 bullet 3).
- e) Roll the leads out in the same directions as the measuring tapes, one for voltage and one for current in each direction ensuring a separation distance of at least 200mm (refer to 3.4 bullet 4).
- f) Hammer probes into ground and connect the leads to it (refer to 3.4 bullet 5).
- g) Connect the leads to test equipment, make use of the connectors if necessary.
- h) Take the measurement and note the results in the table (refer to table 1):
 - On the meter ensure the narrow band filter is switched on (refer to 3.4 bullet 6),
 - If available on the meter, select the high current setting to increase the voltage over the sample to be measured.
- i) Calculate the resistivity and plot the results on bi-logarithmic graph paper (refer to Annex I for bi-logarithmic graph paper and Annex D, E and F for examples).
- j) Repeat the above steps for at least the following probe spacings (a), irrespective of the substation size: 0.5m; 1m; 2m; 3m; 4m; 5m; 10m; 15m; 20m; 30m; 40m; 50m. by moving all four probes (refer to 3.4 bullet 6).
- k) Repeat steps (d) to (j) above for the second diagonal (refer to figures 3; 4; 5; 6).
- l) Compare the results for Measurement set T_1 to the results for Measurement set T_2 for consistency and repeat any measurements where there is a discrepancy.
- m) Repeat steps (c) to (l) above for the additional areas identified where tests have to be conducted (refer to figures 5; 6).

Table 1: Measurement result

Date:		Measurement set T ₁		Measurement set T ₂	
Time:					
Site conditions:					
Soil conditions:					
Traverse end 1 coordinate		S	E	S	E
Traverse end 2 coordinate		S	E	S	E
Probe Spacing (a)	Geometric Factor (K = 2 π a)	Tester Reading (R)	Resistivity (RK)	Tester Reading (R)	Resistivity (RK)
m	m	Ω	Ω m	Ω	Ω m
0.5	3.14				
1	6.28				
2	12.57				
3	18.85				
4	25.13				
5	31.42				
10	62.83				
15	94.25				
20	125.66				
30	188.50				
40	251.33				
50	314.16				
Note / Comment:					

3.7 Interpreting the measured results

The ultimate purpose of these measurements is to derive an electrical soil model to be used as input for earth grid design or verification purposes.

The interpretation of the results obtained in the field is considered the most difficult part of the whole process because the earth resistivity variation can be large and complex as a result of the inherent makeup of the earth. Except for very few cases, it is essential to establish a simple equivalent model of the earth structure. This accuracy of the equivalent model depends mainly on the following factors:

- The accuracy and extent of the measurements.
- The method used.
- The complexity of the mathematics involved.
- The purpose of the measurements or model.

The results from these measurements also give high level geology information, i.e. a rapid increase in resistivity may indicate the presence of rock at the depth associated with the measurement depth.

For applications in power engineering, the two-layer equivalent model is accurate enough in most cases without being mathematically too involved. This two-layer equivalent model can be determined manually as described in [7] Annex A, or by making use of a computer program such as CDEGS. To ensure consistency, the computer program method for determining the equivalent soil model is advised.

The equivalent two-layer or multilayer soil model is depicted by two or more apparent resistivity values with associated specific layer thickness.

3.8 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 Annex A, B and C).
- The site conditions must be listed, including the date, times, weather and basic soil conditions.
- All the measurement results must be provided in table and graph format (as per Annex D, E and F).

The following reports can be referred to for examples:

- 240-93720886 Report on Soil Resistivity Measurements Done for Tutuka Power Station HV Yard
- 240-93720888 Report on Soil Resistivity Measurements Done for Arnot Power Station HV Yard
- 240-93720890 Report on Soil Resistivity Measurements Done for Duvha Power Station HV Yard

4. Authorization

This document has been seen and accepted by:

Name and surname	Designation
Andile Madikizela	Senior Technician, Dx, Network Engineering & Design, Eastern Cape OU
Christy Thomas	Senior Engineer, Tx, Substation Engineering
Dorcas Rakgalakane	Senior Engineer, Dx, Network Engineering & Design, Limpopo OU
Enderani Naicker	Chief Engineer, Tx, Substation Engineering
Fannie Masango	Senior Advisor, Dx, Network Engineering & Design, North West OU
Gavin Strelec	Chief Engineer, RT&D
Jayant Raghubir	Senior Engineer, Dx, Network Engineering & Design, KwaZulu Natal OU
Johan Mostert	Senior Technologist, Dx, Network Engineering & Design, Western Cape OU
Kabelo Molapise	Engineer, Dx, Network Engineering & Design, Dx, Mpumalanga OU
Krishna Naidoo	Senior 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
Aug 2020	3	TJ Marais	Updated 2.2 Normative/informative References Updated 3.4 Factors affecting the accuracy of measured results, bullet 5: included 0.5m Updated 3.6 Taking the measurements (j): included 0.5m Updated Table 1 Measurement result: included 0.5m Removed Figure 7 Bi-logarithmic graph paper to scale added as Annex I. Updated Annex A, B, C, G and H: included 0.5m Annex D and F: included measurements at 0.5m Annex E Example 2 replaced Annex I added.
Aug 2015	2	TJ Marais	Converted to a standard with the same number. Updated: 3.4 Factors affecting the accuracy of measured results Added: 3.5.3 Existing substations Updated table 1 Renumbered existing Annex A, B and C to D, E and F Added new Annex A, B, C, G, H
June 2015	1	TJ Marais	First issue (as a guideline)

6. Development team

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

- Krishna Naidoo
- Mohammad Nabbie
- Theunus Marais

7. Acknowledgements

Everybody that took the time to comment on the draft document.

Annex A – Test area example 1: Generation HV yard



If at all possible measurements must be done on the existing substation/power station terrace while giving special consideration to overhead lines, fences, pipe lines and other infrastructure in the area.

Taking the above as well as the existing power substation layout into considerations, the various measurement options are indicated as options 1 and 2.

Option 1 is very close to the HV yard with associated maximum probe spacings of only 45m (135m / 3). To verify the accuracy of these measurements it is proposed to also do measurements as per option 2. Considering the size of the HV yard and the associated earth electrode it is preferable to make use of probe spacings up to 50m if at all possible.

In this case four sets of measurements should be done:

two for option 1, and

two for option 2,

The results from option 1 must then be compared to the results from option 2 to determine the impact of the fences on the results of the option 1 measurements.

The following probe spacings should be used per option:

Option 1: 0.5m, 1m, 2m, 3m, 4m, 5m, 10m, 15m, 20m, 30m, 40m, 45m.

Option 2: 0.5m, 1m, 2m, 3m, 4m, 5m, 10m, 15m, 20m, 30m, 40m, 50m.

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Annex B – Test area example 2: Transmission station



If at all possible measurements must be done on the existing substation terrace while giving special consideration to overhead lines and fences in the area.

Taking the above as well as the existing substation layout into considerations, the various measurement options are indicated as options 1, 2, 3 and 4.

Options 1 and 3 are perpendicular to the fences in their immediate vicinities and far enough from possible interfering parallel fences. The downside of these two traverses is that their associated maximum probe spacings are only 34m (102m / 3) and 32m (96m / 3) respectively. Considering the size of the substation and the associated earth electrode it is preferable to make use of probe spacings up to 50m if at all possible.

The only way to achieve this is to also consider the traverses presented as options 2 and 4 that will give a maximum probe spacing of 50m each.

In this case six sets of measurements should be done,

one for option 1,
two for option 2,
one for option 3, and
two for option 4.

The results from option 1 must then be compared to the two sets of results from option 2 to determine the impact of the fences on the results of the option 2 measurements. The same is applicable to the results from the measurements for options 3 and 4.

The following probe spacings should be used per option:

Option 1: 0.5m, 1m, 2m, 3m, 4m, 5m, 10m, 15m, 20m, 30m, 32m.

Option 2 & 4: 0.5m, 1m, 2m, 3m, 4m, 5m, 10m, 15m, 20m, 30m, 40m, 50m.

Option 3: 0.5m, 1m, 2m, 3m, 4m, 5m, 10m, 15m, 20m, 30m, 34m.

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Annex C – Test area example 3: Distribution station



The terraced area is clearly identifiable by the different ground colour around the substation. Considering the existing layout of the substation with special consideration to overhead lines and fences, the various areas where measurements can be done are limited.

There is no place perpendicular to the fences where the measurements can be done on the terrace and it is therefore proposed to do the measurements with the long possible traverses at the biggest possible angle to the substation as indicated as option 1. It is also proposed to measure along the traverse indicated as option 2.

The maximum probe spacing associated with options 1 is only 20m ($60\text{m} / 3$), and for option 2 it is 31m ($93\text{m} / 3$). Considering the size of the substation and the associated earth electrode it is preferable to make use of the largest possible probe spacings.

In this case three sets of measurements should be done, two for option 1, and one for option 2.

The results from option 1 must then be compared to the results from option 2 to determine the impact of the parallel fence on the results of the option 2 measurements.

In determining the impact of a parallel fence to the measurement results, refer to Annex D for an example.

The following probe spacings should be used per option:

Option 1: 0.5m, 1m, 2m, 3m, 4m, 5m, 10m, 15m, 20m.

Option 2: 0.5m, 1m, 2m, 3m, 4m, 5m, 10m, 15m, 20m, 30m.

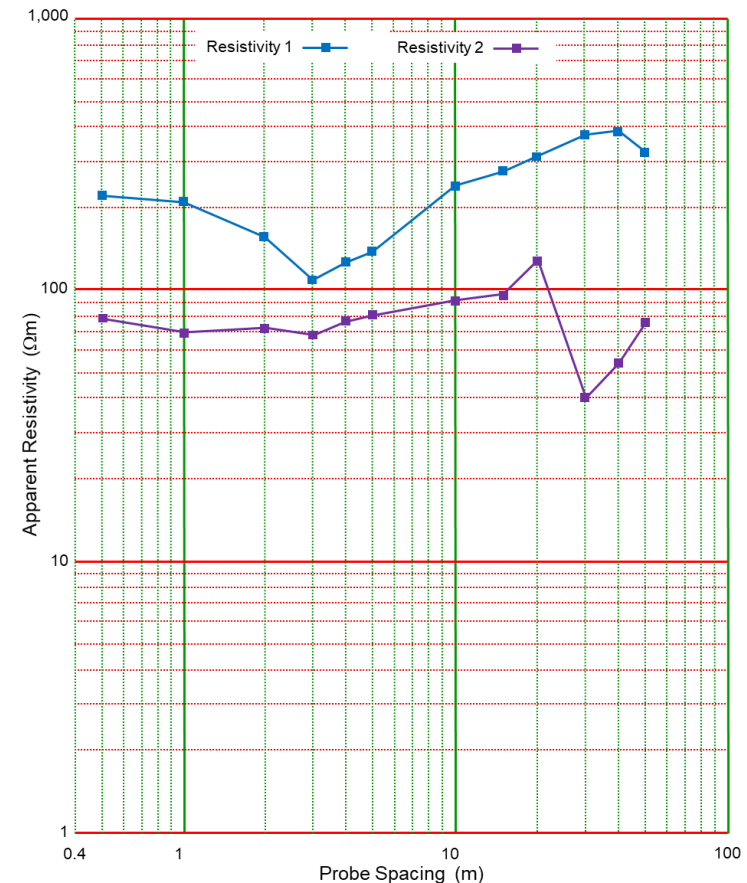
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Annex D – Measurement example 1

Date: 21 Oct '09		Measurement set T ₁		Measurement set T ₂	
Time:		14:00		14:50	
Site conditions:		Undisturbed bush area with grass and vegetation. Traverse perpendicular to fence.		Cleared bush area, vegetation removed close to fence. Traverse parallel to fence, 3m away.	
Soil conditions:		Soil dry, covered with grass and bush.		Soil dry, all vegetation removed.	
Probe Spacing (a)	Geometric Factor (2 πa)	Tester Reading 1 (R)	Resistivity 1 (2 πaR)	Tester Reading 2 (R)	Resistivity 2 (2 πaR)
m		Ω	Ωm	Ω	Ωm
0.5	3.14	70.00	220	25.00	78
1	6.28	33.00	207	10.79	68
2	12.57	12.25	154	5.65	71
3	18.85	5.64	106	3.56	67
4	25.13	4.99	125	3.05	77
5	31.42	4.33	136	2.54	80
10	62.83	3.78	238	1.42	89
15	94.25	2.85	269	1.00	94
20	125.66	2.42	304	1.00	126
30	188.50	1.96	369	0.21	40
40	251.33	1.50	377	0.21	53
50	314.16	0.99	311	0.24	75

NOTE: Both measurements were done in the same area with measurement 1 perpendicular to a game fence and measurement 2 parallel to the same fence, but 3m away. The impact of the fence on the apparent resistivity is clearly visible as it stays relatively unchanged up to 15m.

Measurement 2 is not valid as a result of the influence from the fence on the results.

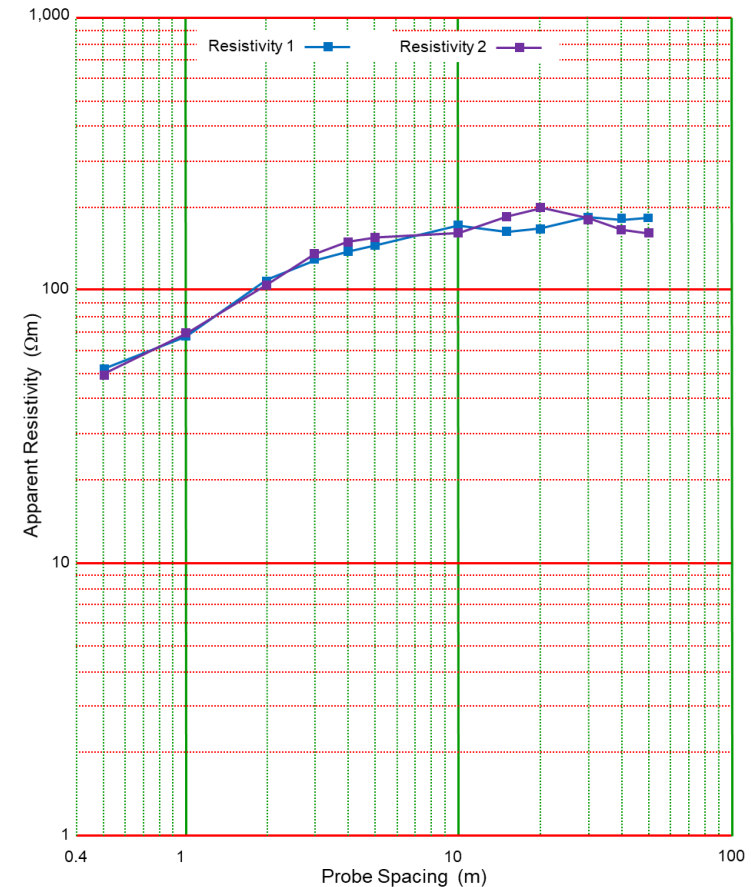


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Annex E – Measurement example 2

Date: 30 Apr '19		Measurement set T ₁		Measurement set T ₂	
Time:		11:40		12:25	
Site conditions:		Flat open area with sparse grass.		Flat open area with sparse grass.	
Soil conditions:		Soil wet on the surface		Soil wet on the surface	
Probe Spacing (a)	Geometric Factor (2 πa)	Tester Reading 1 (R)	Resistivity 1 (2 πaR)	Tester Reading 2 (R)	Resistivity 2 (2 πaR)
m		Ω	Ωm	Ω	Ωm
0.5	3.14	16.18	50.83	15.56	48.88
1	6.28	10.93	68.68	11.02	69.24
2	12.57	8.73	109.70	8.47	106.44
3	18.85	6.99	131.76	7.13	134.40
4	25.13	5.53	138.98	5.99	150.55
5	31.42	4.71	147.97	4.65	146.08
10	62.83	2.77	174.04	2.57	161.48
15	94.25	1.736	163.61	1.978	186.42
20	125.66	1.332	167.38	1.608	202.07
30	188.50	0.982	185.10	0.956	180.20
40	251.33	0.728	182.97	0.667	167.64
50	314.16	0.588	184.73	0.512	160.85

NOTE: The two sets of measurements were done perpendicular to each other in an open veld. The correlation between the two sets of measurements are very good.

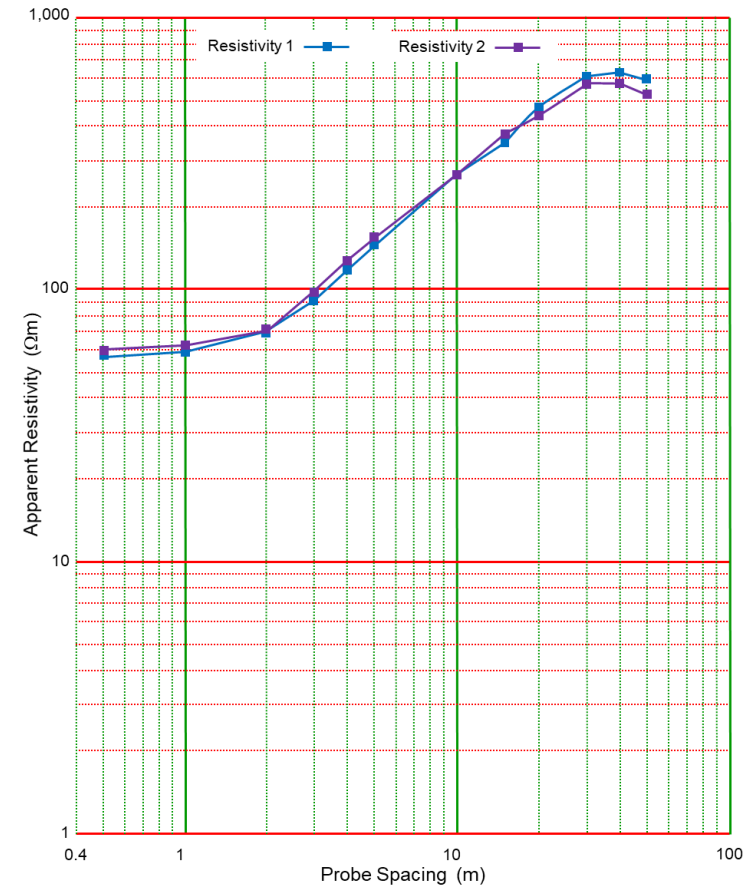


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Annex F – Measurement example 3

Date: 27 Mar '14		Measurement set T ₁		Measurement set T ₂	
Time:		13:30		14:30	
Site conditions:		Level grassed field, poorly drained area		Level grassed field, poorly drained area	
Soil conditions:		Ground covered in grass, moist in places		Ground covered in grass, moist in places	
Probe Spacing (a)	Geometric Factor (2 πa)	Tester Reading 1 (R)	Resistivity 1 (2 πaR)	Tester Reading 2 (R)	Resistivity 2 (2 πaR)
m		Ω	Ωm	Ω	Ωm
0.5	3.14	18.15	57	18.78	59
1	6.28	9.40	59	9.84	62
2	12.57	5.43	68	5.54	70
3	18.85	4.83	91	5.09	96
4	25.13	4.74	119	5.01	126
5	31.42	4.65	146	4.93	155
10	62.83	4.24	266	4.20	264
15	94.25	3.69	348	3.85	363
20	125.66	3.63	456	3.48	437
30	188.50	3.20	603	3.02	569
40	251.33	2.50	628	2.27	571
50	314.16	1.88	590	1.66	521

NOTE: The two sets of measurements were done perpendicular to each other. It is clear from the results that the area has the same electrical properties in both directions and it can be assumed for the whole site under investigation.



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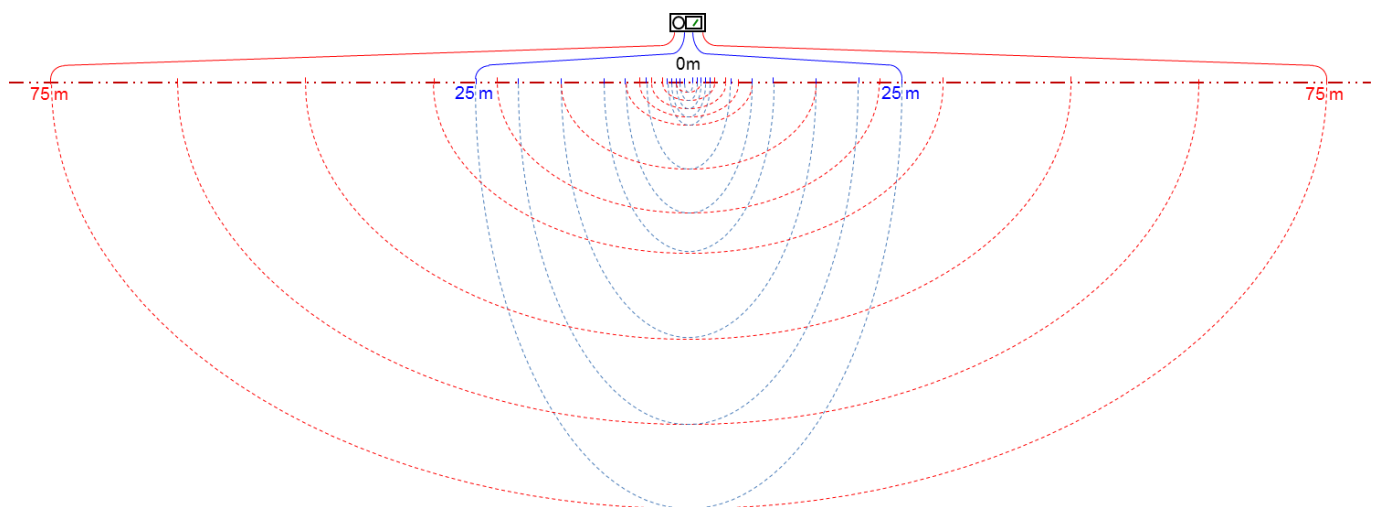
Annex G – Impact of meter positioning on measurement results

There are two basic setup practices each with advantages and disadvantages, which are:

- 1) Set the meter up in the middle of the 150m traverse and move all four probes for each measurement done. This is the accepted method.
- 2) Set the meter up at the one end of the 150m traverse, connect terminal C1 to the probe at this position and move the other three probes only. The C1 probe is kept fixed and not moved during the measurements.

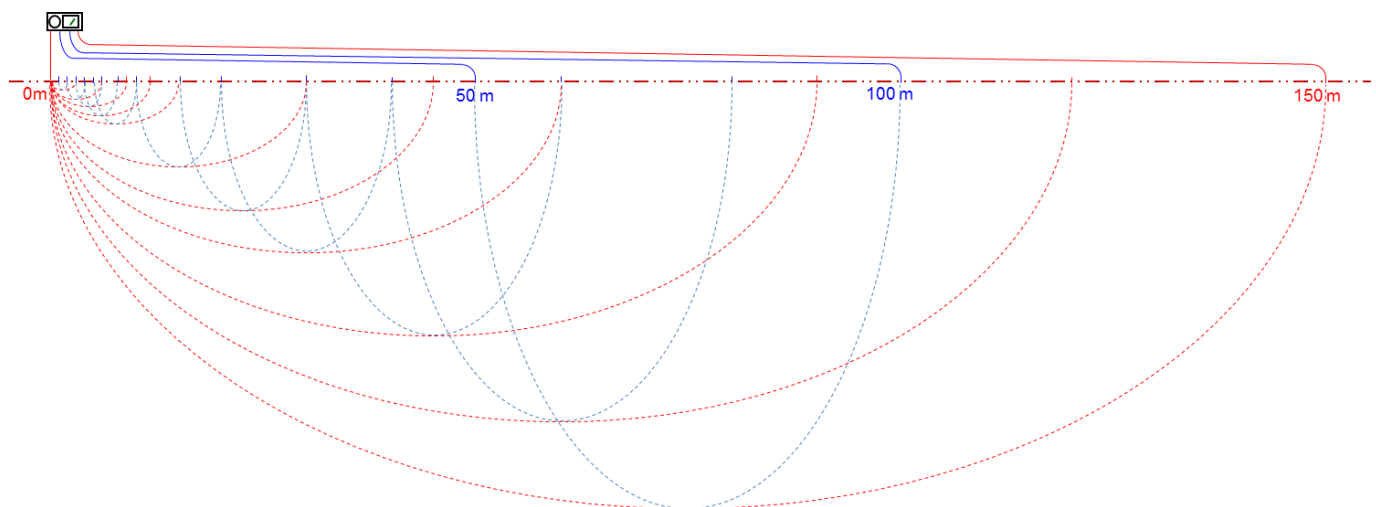
Moving all four probes (accepted method)

When setting the meter up in the middle of the 150m traverse it is necessary to move all four probes to the desired probe separation distances to do the measurements. The measurement results are acceptably representative of the area under investigation as can be seen in the basic representation below.



Keeping probe C1 stationary and moving the other three probes

When setting the meter up at one end of the 150m traverse and keeping probe C1 stationary it is only necessary to move the other three probes (P1; P2; C2) to the desired probe separation distances to do the measurements. As can be seen in the basic representation below, the measurement results for small probe spacings (typically 0.5m – 5m) are applicable to the area where the meter is set up. The results associated with larger probe spacings are typically associated with an area further away from where the meter is set up. Depending on where the meter is setup in relation to the future substation are, the results of tests done in this way will have a low applicability value.



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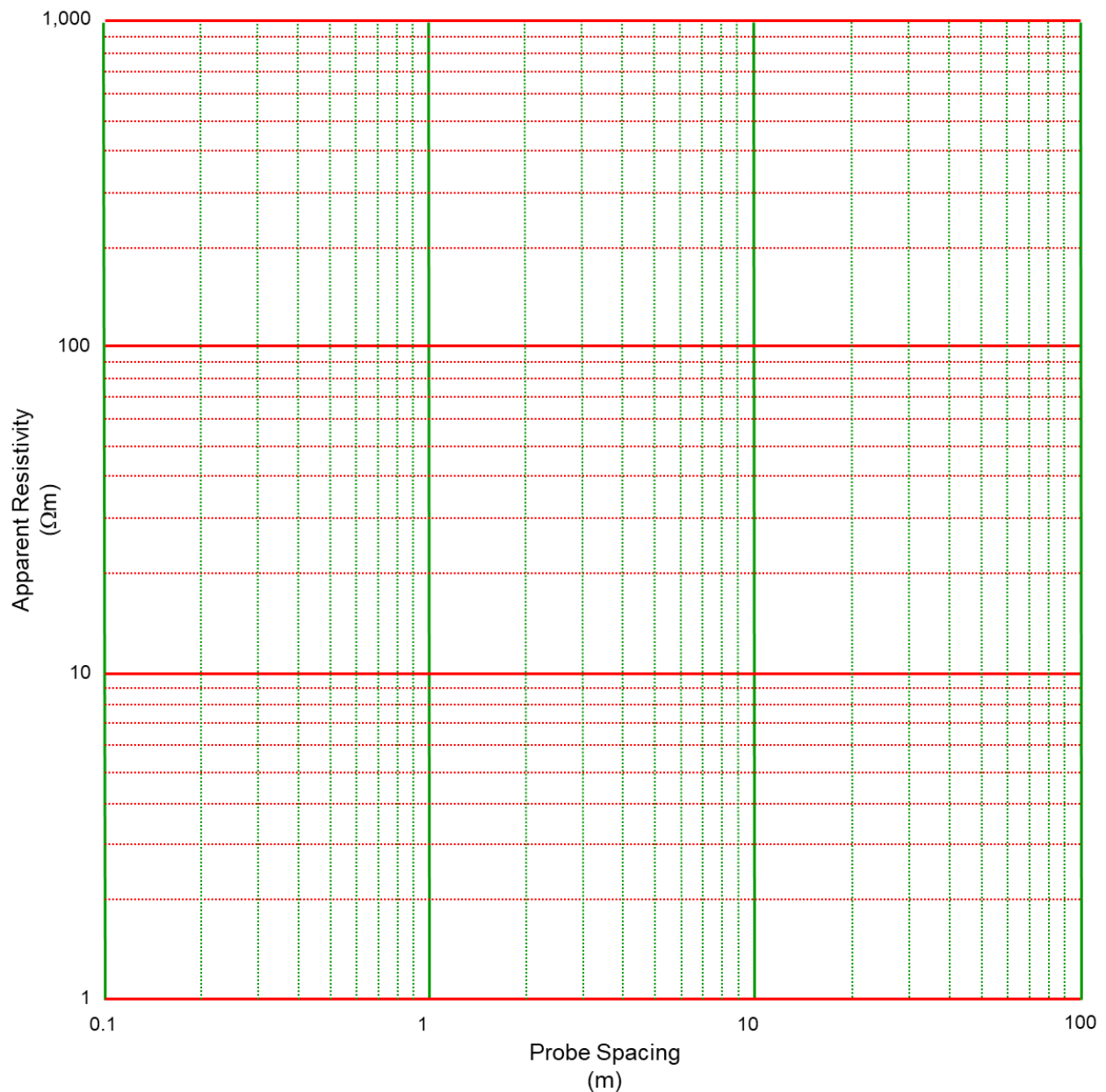
Annex H – Steps to follow for setting up and taking measurements

The process below must be followed when taking the actual measurements:

- 1) Identify the area where the tests must be done:
 - Refer to section 3.4 bullet 1.
- 2) Carefully assess the area and do a risk assessment:
 - Take the necessary precautions to mitigate each identified risk.
- 3) Determine the centre of the area where the specific measurements should be done, unpack and position the test equipment:
 - Refer to section 3.4 bullet 2.
- 4) Roll the measuring tapes out in opposite directions in a straight line taking cognisance of other structures, services, fences etc. in the area:
 - Refer to section 3.4 bullet 3.
- 5) Roll the leads out in the same directions as the measuring tapes, one for voltage and one for current in each direction ensuring a separation distance of at least 200mm:
 - Refer to section 3.4 bullet 4.
- 6) Hammer probes into ground and connect the leads to it:
 - Refer to section 3.4 bullet 5.
- 7) Connect the leads to test equipment, make use of the connectors if necessary.
- 8) Take the measurement and note the results in the table (refer to table 1):
 - On the meter ensure the narrow band filter is switched on (refer to section 3.4 bullet 6),
 - If available on the meter, select the high current setting to increase the voltage over the sample to be measured.
- 9) Calculate the resistivity and plot the results on bi-logarithmic graph paper:
 - Refer to section 3.4 bullet 7.
 - Refer to figure 3 and Annex D, E and F for examples.
- 10) Repeat the above steps for at least the following probe spacings (a), irrespective of the substation size: 0.5, 1m; 2m; 3m; 4m; 5m; 10m; 15m; 20m; 30m; 40m; 50m by moving all four probes:
 - Refer to section 3.4 bullet 2 and annex G.
- 11) Repeat steps (4) to (10) above for the second diagonal:
 - Refer to figures 3; 4; 5; 6.
- 12) Compare the results for Measurement set T1 to the results for Measurement set T2 for consistency and repeat any measurements where there is a discrepancy.
- 13) Repeat points (3) to (12) above for the additional areas identified where tests have to be conducted.
 - Refer to figures 5; 6.

Annex I – Bi-logarithmic graph paper

The bi-logarithmic graph paper below should be used to plot as it is to the same scale as the one given in [7] (240-134369472, Substation Earth Grid Design Standard) Annex A as well as the SANS 10199 two-layer soil model master curves also in Annex A of [7].

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