EARTHING SYSTEM TESTING METHODS - HISTORIC APPROACHES & RECENT DEVELOPMENTS

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ABSTRACT

August 2018 saw the formation of a Cigre Working Group (WG) designated B3.54 with the specific assignment to research, analyse and understand all the information necessary to write a Technical Brochure entitled "Earthing System Testing Methods - historic approaches, recent developments and recommended approaches".

This paper presents pre-work undertaken by the authors in preparation for this WG including an example survey, the survey results and preliminary information of identified developments and improvements of recent times as seen through a review of significant Australian documents.

INTRODUCTION

Historically, the measurement of earthing systems has been difficult, expensive, and in some cases, inaccurate. New testing methods, instruments and analysis methods are being developed which are increasingly being adopted across the industry. In contrast, earthing is becoming more complex due to shrinking substation footprints, closer proximity to other built infrastructure and increased interconnection through the wider use of cabled networks. This has made simple test methods ineffective and led to the broader adoption of more advanced methods.

This context has led many to contemplate what is being done in terms of earthing system testing, by whom, how often and with what justification regarding period and cost. Furthermore, some have wondered, of these commonly applied techniques: what are their strengths and weaknesses, what positives and negatives are evident from each, and how have they been improved or modified, if at all, by others around the world.

The WG will undertake the following key tasks:

1. Survey the different approaches (methods and frequency) used around the world for the testing and monitoring of earthing systems across a range of HV Substations.
2. Examine legal requirements for asset owners and operators to demonstrate due diligence in meeting their duty of care through proving substation earthing systems that are fit for purpose, both initially at commissioning and over the life of the substation.
3. Compare and contrast the range of earthing system test methods available from both a theoretical and practicability stand point.
4. Provide a thorough description of the technical and practical requirements of the various testing methods available.
5. Identify the characteristics that provide reasonable boundaries between different earthing system types.
6. Establish a set of practical recommendations, guidelines and metrics for engineers to use which are technically and economically feasible.
7. Develop recommendations for the inclusion of testing methods descriptions and recommendations in existing Codes and Standards.

As part of team formation and preparation the WG is being asked to research their own country, and/or countries with which they are sufficiently familiar, and determine what focused background reading they can bring to the WG with a focus on:

A. National documents, guidelines, standards or codes providing guidance or obligation with respect to what earthing system testing to do, how to do it and when to do it (possibly with that being a combination of periods or trigger events).
B. Review of existing survey questions and responses from recent years, or other such information that may assist in a first pass determination of what is actually done by earthing system owners, operators and designers and when is it done.

This paper will present pre-work in line with the above, for further assessment by WG members for forthcoming meetings. There are three key sections presented.

i) A review and summary of significant earthing system testing documents from Australia.
ii) A review and summary of earthing system testing related obligations under Australia documents and law.
iii) The presentation of context, questions, results and analysis of a preliminary survey conducted in North America late last year.

AUSTRALIAN EARTHING SYSTEM TESTING RELATED DOCUMENTS

The testing of earthing systems in Australia has been the focus of significant research and development for more the 25 years, and the Safearth entity was effectively born out of that desire to better understand and design earthing systems with a recognised high value in reliable measurement. There have been many published Australian documents that have guidance on earthing systems. Following is a brief outline of the most significant.

ESAA-EG1

The earliest strong publication on earthing systems in Australia was the Substation Earthing Guide, EG1, originally published by ESAA in 1997 [1]. EG1 provided a clear chapter (chapter 5) on soil resistivity testing, interpretation and modelling. Whilst none of this was novel it was a clear statement that measurement should be a key step in the design of earthing systems. EG1 went on to present testing methods in Chapter 11, including a comparison of injection methods in 11.2.4 which were most significant in that time (they have become very familiar within Australia over the 22 years since). Section 10.3.5 of EG1 addressed an old practice of using auxiliary electrodes (or separate or separable electrodes or grids) with several warnings alluding to the safety and inaccuracy issues of the approach. In particular EG1 stated "Routine tests using portable earth testers and "short" current/voltage lead lengths are considered of limited worth, unless the site is small and inductive coupling negligible." Guidance was also provided on when to test in Chapter 12. The comparison of methods, Table 11.1 in EG1, is reproduced following as Table 1.

ENA-EG0

The next big change in earthing management in Australia was led by the ENA document "Power System Earthing Guide, Part 1: Management Principles", known as EG0 and published in May 2010 [2]. This document introduced and recommended the use of Quantified Risk Assessment (QRA) in the management of earthing systems. Rather than the traditional, implicit dependence on likelihood within safety criteria for touch and step voltages, this document presented a quantified method for calculating the probability of fibrillation for a given applied voltage and time, and also the explicit probability of coincidence of the hazardous voltage being present coincident with one or more persons being in a contact situation exposing them to that voltage (potentially as a touch or step voltage, but with many possible configurations).

EG0 provides a clear description of the recommended earthing tests in Chapter 7, "Commissioning and ongoing monitoring". In particular it describes earthing system commissioning activities that are "essential as a validation step for the design and installation", including design inputs. There are six core activities described as normal, but not necessarily all required:

1. Visual inspection
2. Continuity testing
3. Earth resistivity testing
4. Earth potential rise (EPR) measurement
5. Current distribution measurement
6. Transfer, touch and step voltage testing.

Ongoing monitoring including testing is recommended with both scheduled and event based triggers. Consideration of specific circumstances including local conditions and past events is also recommended.

	High Current		Low Current			Comments
	Staged Fault	Low Voltage	Signal Generator	Portable Generator	Portable Meter	
Network reconfiguration required	yes	yes	no (if run own injection cable)	no	no	High current requires large power supply & powerline.
Models actual fault configuration	yes	yes	possibly (if use line)	possibly	no	High current measures directly. Low current indirectly.
Protection Modifications	yes	yes	no	no	no	High current may require protection disabling and installation of temporary backup protection.
Power Frequency Interference	yes	yes (phase reversal)	no (by filtering)	no	no	High current eliminates interference indirectly.
Cost	higher	higher	medium (time <50% cost < 60%)	medium	lower (limited validity & applicability)	
Potential probe effected by mutual coupling	yes	yes	yes can calculate	yes can calculate affect	no	
Measures complex impedance	yes	yes	yes	yes	not usually	External conductors provide large reactive components.
Flexibility of injected frequency	short reading only	usually only short term injection	very if use noise source	fixed frequency range	usually well off 50Hz	Impedance frequency dependence higher on large extended systems.
Safety levels	needs many special precautions		safe (except from external induction)	safe	safe	Low current tests are easier to undertake due to fewer safety hazards.
Effected by resistance voltage dependence	no	no	yes	yes	yes	If circuit voltage dependent, e.g. OHEW corrections.

Table 1. Comparison of earth testing methods from EG1.

Australian Standard AS 2067:2016

The latest document in Australia providing both guidance and obligation on earthing system testing is the Australian Standard AS 2067:2016 "Substations and high voltage installations exceeding 1 kV a.c." [3]. Published in 2016, this edition spoke substantially more about testing than earlier versions. The informative Appendix H "Earthing System Testing" describes assessment categories of commissioning, verification and interface, which includes measurement of interference from or to earthing systems including inductive and conductive coupling. It goes on to explain that the purpose of testing includes "to validate the adequacy of an earthing system to prove compliance with design thresholds" and describes injection testing as such:

Injection testing simulates a power system line to ground fault. To achieve this, a circuit is established between the earthing system under test and a remote injection point. Ideally this circuit should reflect the actual fault return point. Where this is not possible post testing analysis is necessary to reflect the actual fault scenario or scenarios. This may include multiple points of return.

An injection test is typically made sustainable by injecting a small current, commonly between 2 A and 20 A. The effects are made measurable, even on live systems, by injecting at a frequency away from power system frequency and using frequency tunable instrumentation. The test is referred to as a low current, off power frequency *injection test.* AS 2067:2016, Section H5, p207

The basic test circuit is also provide as shown below.

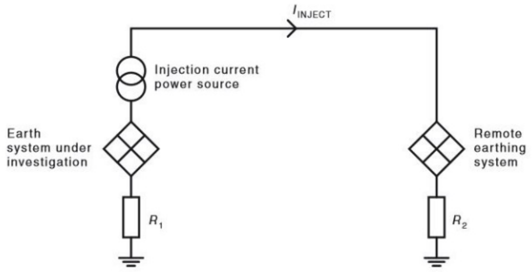

Figure 1. The Basic Test Circuit from AS 2067.

The appendix also covers the need for and benefit of visual inspection, continuity (or integrity) testing, soil electrical resistivity testing and, during injection testing, the direct measurement of Earth Potential Rise (EPR) via Fall Of Potential (FOP) testing, split factor or alternate path performance via direct and indirect measurement of current distributions (or splits), and the direct measurement of transfer, touch and step voltages (whether created through conduction or induction or a combination of both).

In terms of advice on how often testing should occur the appendix suggests typical visual inspection and continuity test intervals of 1 to 3 years and injection testing intervals of 10 to 15 years, but it does state clearly that alternate intervals may be appropriate, based on direct assessment of the reasonably foreseeable failure modes (including likelihood and consequence). Past events including failures and incidents should be considered in this assessment.

AUSTRALIAN EARTHING SYSTEM TESTING RELATED OBLIGATIONS

In Australia, there a range of documents, standards, regulations and codes that require or imply particular earthing system testing requirements. Some are well known and followed, some less so. One example is the legal obligation in the state of Victoria to conduct power station earthing system tests no less frequently than 10 yearly. This was written in law as part of the generator privatisation in the 1990s but has not been broadly understood and, even when performed, the standard of some testing has been questionable.

Other Australian states and territories have varying requirements, including from their regulators, but it was not until the publication of AS 2067:2016 that national obligations became clear. As a brief aside, compliance with AS 2067, or any Australia Standards for that matter, is not mandatory in and of itself, however it does become mandatory through various other legislation, for many entities. It is well argued that under our legal system an adverse event leading to a claim of negligence would see all entities assessed against the standard. Defence therefore requires compliance to the standard or the prior production of a detailed engineered equivalent.

In Section 8.6, AS 2067:2016 makes commissioning of all High Voltage (HV) earthing systems mandatory. What is required to commission a HV earthing system is not prescribed but the requirement is clear to "prove adequacy of the earthing installation (basic material selection, installation quality and as-built drawings), as well as design criteria compliance, and provide the ongoing supervision process with benchmark or baseline figures." It must include visual inspection and proving continuity, whilst tests listed above are listed as 'may be required'. In addition to commissioning obligations, the ongoing supervision and management of earthing systems must include examination or assessment periodically; where the period is based on an appropriate plan and the range of activities could include part or all of the above components.

There is also a mandatory requirement in the normative Appendix B for all "Higher level substations, e.g. 66 kV/22 kV, 132 kV/11 kV, 132 kV/33 kV", that "Testing of the complete earthing installation by current injection shall be undertaken at commissioning and at intervals thereafter." The intervals are not specified in the appendix but must be determined in accordance with Chapter 8 described above.

EARTHING SYSTEM TESTING SURVEY

Part of the WG Terms of Reference is to investigate the common earthing system testing practices in a broad range of countries. Of particular interest is the range of testing methods applied and the spread of what is considered best practice or what is considered necessary and not necessary. There is also evidence throwing into question whether earthing system testing is well enough understood to obtain reliable results. This should also be tested either via survey or otherwise through the experience or expertise of specialists.

The following data was collected at the 2018 CEATI Grounding & Lightning Conference. It was collected by raising and counting of hands during a 30min presentation by the author on Earthing System Testing methods [4]. There were five question areas based on a category of test with the same four sub-questions in each category. Each category was summarised and feedback was sought on the clarity of the category description prior to the show of hands. Following we present the five categories in summary and, following that, the survey results.

Soil Electrical Resistivity Testing

Soil electrical resistivity testing typically involves the injection of current between two electrodes and the measurement of the voltage between two different electrodes. Some or all of the electrodes are reconfigured and/or relocated for each measurement.

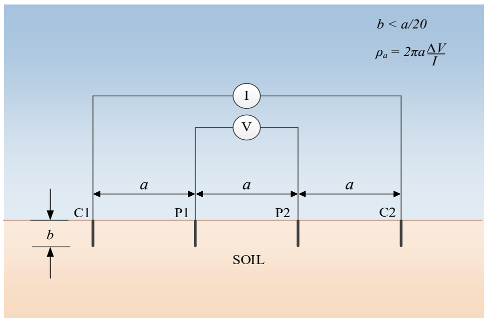

Figure 2. Wenner Soil Electrical Resistivity Test Method

A calculation is made of the 'apparent resistivity' for each spacing and the series of results are compared and analysed to determine an equivalent electrical soil model. Popular methods include Wenner, Schlumberger and deep or driven rod. Tests are commonly performed with temporary leads and a four terminal battery powered instrument. These mostly use a small DC current, polarity reversing at low frequency. Advanced, specialist units are available with higher power that may produce better results in very high resistivity soils.

Q1. Do you routinely/usually conduct soil resistivity tests?

For this and questions 2-5 the question was put for three scenarios as follows.

A. For new substation earthing designs?
B. For review of existing substation earthing systems?
C. Following an event?
D. Never?

Grid Resistance Testing

Grid Resistance Testing typically uses a similar instrument to soil resistivity testing (and small DC current, polarity

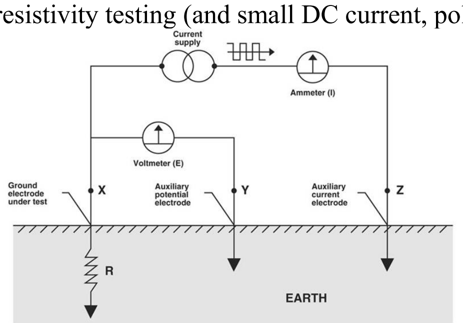

Figure 3. Common Grid Resistance Testing

reversing at low frequency). Common methods include 3 and 4 pin methods, Mutual Earth Resistance (MER) compensation method (62% method), and the Fall of Potential (FoP) method (although there is associated ambiguity with this label). These methods are intended to directly measure the buried grid resistance and requires the disconnection of all other paths.

Q2 - Do you commonly conduct substation grid resistance tests?

Earthing System Impedance Testing

In earthing system impedance testing current is passed through a chosen or temporarily installed circuit to simulate a scaled earth fault. Commonly 2-30A of AC current, at a frequency near but away from the power system is used. This method is often called a Current Injection Test (CIT) however this name also holds ambiguity. A tunable volt meter is used to measure the associated EPR and a tunable ammeter, often with a Rogowski coil, to measure the current through accessible alternate paths (such as shield wires, cable screens and neutral conductors).

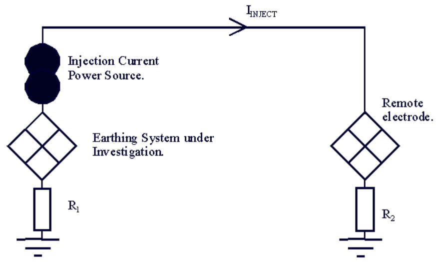

Figure 4. Earthing System Impedance Testing

Q3 - Do you commonly conduct substation earthing system impedance tests?

Earthing System Touch & Step Voltage Testing

This testing allows direct measurement of the simulated touch, step and also transfer voltages. It requires current flowing per the earthing system impedance testing and measurements are made using the tunable volt meter. Scaling these voltages allows comparison against safety criteria. Unlike resistance and impedance measurement this testing is not subject to errors related to estimation of remote earth.

Image 1. Earthing System Step Voltage Testing

Q4 - Do you commonly conduct substation earthing system touch and step voltage tests?

Earthing Integrity or Continuity Testing

The goal of integrity or continuity testing is to prove that everything that should be bonded is appropriately bonded and to prove that everything that should not be bonded is appropriately separated. Some methods allow detection of deteriorating rather than only failed conductors or connectors. Some also identify conductive and soil connections differently. Methods may be 2 or 4 wire, AC or DC current, single or reversing polarity and high or low current (between 1 and 300 Amps). Instruments must have immunity to DC noise and very high AC noise.

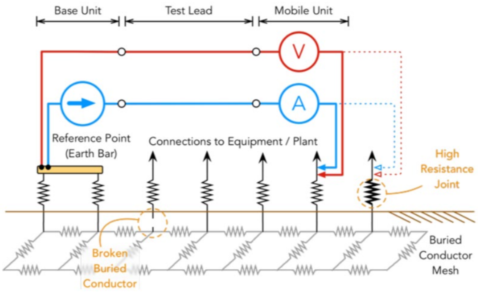

Figure 5. Integrity or Continuity Testing Example

Q5 - Do you commonly conduct substation earthing condition, integrity or continuity tests?

Earthing System Professional Engineer Investigation

Over more than 80 combined years of specialisation in earthing systems it has become clear to the authors that following a script for earthing system testing does not lead to a full understanding of the systems performance and has often led to significant non-conservative errors. Effective testing is more like an investigation than some other electrical tests. Often a measurement finding needs to be properly understood before a good decision can be made about what should be measured next. In the author's experience some technicians and tradespersons can contribute or even lead such testing very well, however, Professional Engineers (PEs) can be incredibly valuable in identifying hidden risks and resolving unexplained failures. In Australia, it is common to have PEs involved in earthing system testing, something we have seen less of in North America.

Q6 - Do you use earthing system PE investigations?

Survey Results

Whilst every effort was made to explain each of the methods, and each question was put to the group clearly and with a mind on each being as simple and clear as possible, participants had very little time to prepare their response. It is possible that some participant bias was involved [5][6]. This recognition and the broader understanding of bias in survey should emphasise the need for great diligence in preparing future survey questions for this research [7]. The results are tabulated in Table 2.

In summary 100% of respondents conduct soil electrical resistivity testing, nearly 100% also conduct resistance tests, and 92% conduct integrity testing. The authors consider the survey results consistent with our experience in North America for utilities that are active in this space. For other utilities, the results would likely be much lower everywhere except the Never column. The low utilisation of the more accurate tests like impedance, touch & step measurement, and the rare use of PEs in assessment or investigations, represent a significant opportunity for better risk and cost management of earthing systems.

	Activity / Test	For New Substation Design	For Substation Review	Following an Event	Never
Q1	Do you routinely/usually conduct soil resistivity tests?	40%	40%	20%	0%
Q2	Do you commonly conduct substation grid resistance tests?	64%	24%	9%	3%
Q3	Do you commonly conduct substation earthing system impedance tests?	26%	22%	4%	48%
Q4	Do you commonly conduct substation earthing system touch and step voltage tests?	16%	37%	11%	37%
Q5	Do you commonly conduct substation earthing condition, integrity or continuity tests?	40%	30%	23%	8%
Q6	Do you use earthing system PE investigations?	30%			70%

Table 2. CEATI Grounding Conference Survey

CONCLUSIONS

This paper has identified and summarised significant earthing system testing related documents from Australia. It has presented and discussed key Australian earthing system testing related obligations and the potential breadth of application. It has presented a brief survey conducted late 2018 in North America. The survey results were presented and the authors have compared them to their own experience based estimation of common practice in North America.

This paper has documented the early work of the authors toward the task set before the Cigre WG B3.54. It provides some insight into the identified historic approaches & recent developments within Australia and provides WG members a starting point from which they can prepare a summary of their country and/or other countries they are suitably familiar with.

REFERENCES

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