MAKING RISK BASED EARTHING DESIGN ACCESSIBLE AND EFFECTIVE

William CARMAN
Bill Carman Consulting – Australia
billcarman2@gmail.com

ABSTRACT

Earthing design requires the synthesis of a number of highly variable parameters, many of which are outside the direct control of the designer. Although probabilistic analysis enables designers to recognise this fact it has rarely been applied to earthing system design. Nevertheless the fundamental need to manage the risk of electric shock is met by quantifying actual risk levels using probabilistic risk analysis techniques.

This paper outlines a quantified risk analysis (QRA) and assessment based methodology that can be used to develop a site-specific earthing design, in order to meet risk targets, optimise expenditure and provide justification to management and auditors. It will also show how it has been used to include realistic operating conditions in a risk analysis of classes of asset in order to justify using design templates (such as <1ohm, or a given touch voltage/time curve), complete with boundary conditions.

1 INTRODUCTION

For many years earthing design engineers have confidently used a single 'safe' touch voltage curve for assets where hundreds of people are exposed to a weekly or fortnightly EPR event, as well as assets where contacts are rare and EPR events are only expected to occur every 50 years. Many have questioned the contradictory logic behind such an approach. Partly in response to this question a new WH&S paradigm is evolving that requires designers to explicitly demonstrate due diligence in managing risk imposed by a design upon staff and the public. In order to demonstrate that a given exposure scenario is tolerable it is necessary firstly to calculate the risk imposed upon a person, and secondly to ascertain if the risk has been reduced to as low as reasonably practicable by the designer.

Some designers might consider that this will be an unreasonable impost, particularly if they have neither the time nor the capability to do the analysis. Others may imagine that risk analysis will lead to an increase in risk to people, or a higher level of uncertainty or variability in the design process. However, based upon over 15 years experience of using and refining the new methodology the author has found that the use of QRA not only provides the answers to the new legislation, but is a very useful and robust earthing system design approach that closely integrates within existing design processes.

2 BACKGROUND TO EARTHING QRA

The need to consider the probabilistic nature of earthing has been clearly acknowledged in a number of forums. IEEE80 [1] clearly acknowledges that a hazardous electric shock will only occur given the coincidence of a number of variable conditions, and then makes the general observation that the relative infrequency of hazardous incidents is due to the low probability of the coincidence of necessary conditions. The standard specifies a tolerable prospective touch voltage design curve based upon Dalziel's [2] fibrillation current withstand curve, that 99.5% of the population can safely withstand assuming a body impedance of 1kohm. Whilst many take the resultant IEEE80 criteria to be inherently safe, if benchmarked against the IEC60479 [3] probabilistic body current withstand and body resistance characteristics it is clear that unless the probability of coincidence is taken into account the risk to a person is well above societally tolerable levels for involuntary risk. Therefore, additional analysis is required to determine when the Dalziel characteristic may be justifiably applied [4].

The international HV installation standard IEC61936 [5] uses selected physiological data from IEC60479 for body impedance (50%), body current withstand (5%), and heart current factor (LH to feet) to generate a permissible prospective touch voltage curve. As was the case for IEEE80, IEC61936 does not overtly incorporate a probabilistic process, however, it does include the following statement: '*It must also be recognized that fault occurrence, fault current magnitude, fault duration and presence of human beings are probabilistic in nature'*. The fact that basic physiological data alone are insufficient in establishing electrical safety requirements is further highlighted in the introduction to IEC 60479 that clearly states that the basic criteria are intended to form part of a synthesis of a number of factors including probability of faults and probability of contact.

Due to the constraints of very high soil resistivity and snow bound conditions for much of the year, Finland adopted a set of earthing voltage requirements in the 1970's as part of the Electrical Safety Code, based upon a probabilistic analysis of the contributing factors [6]. The Finnish work was used as a catalyst for a number of studies in North America that examined individual hazard scenarios in the 1980's [7]. Also a number of the papers at an international symposium in Toronto on electrical shock safety in 1985 [8] concluded that a need existed for the development of probabilistically based safety criteria.

Within Australia probabilistic studies were undertaken in the 1960's [9] in order to determine maximum impressed voltages to allow on telecommunications circuits, yielding 430V, 1000V and 1500V criteria. In the 1980's the power industry undertook probabilistic studies to determine tolerable design criteria for distribution and transmission structures. The latter work generated tolerable prospective touch voltages of 8kV (for clearing times less than 0.2 secs) associated with transmission structures. It is clear that many have seen the need for the use of risk quantification but few countries have put it into practise.

3 EARTHING DESIGN QRA PROCESS

This section gives a brief introduction to the key elements of QRA as applied to earthing system design and outlines one possible design process. The probability of fatality due to indirect contact with a fault voltage may be expressed simply as follows for independent events:

$$P_{fatality} = P_{fibrillation} * P_{coincidence} \qquad \text{(Eqn 1)}$$

Where

$P_{fibrillation} = f(V_{applied}, R_{series}, \text{contact configuration})$

$P_{coincidence} = f(\text{fault and contact frequency and duration})$

The value $P_{fibrillation}$ is the probability that the heart will enter ventricular fibrillation. It is calculated by convolving the applied voltage pdf with the withstand voltage pdf, usually numerically by Monte Carlo simulation [10][11][12][13].

The value $P_{coincidence}$ is the probability that a person will be present and in contact with an item at the same time that the item is affected by a fault. Coincidence probability formulae for both individual and multiple fault/contact event scenarios are required in order to assess individual and societal (multiple fatality) risk exposures. Equation 2 [14] shows a simplified yet robust formulation for the individual coincidence probability.

$$P_{coincidence} = \frac{f_n \times p_n \times (f_d + p_d) \times T}{365 \times 24 \times 60 \times 60} \qquad \text{(Eqn 2)}$$

Where

p_d is the average duration of the average exposure (sec).

f_d is the average duration of the average fault (sec).

p_n is the rate at which exposures occur (presences/year).

f_n is the rate at which faults occur (faults per year).

T is the number of years (exposure duration) = 1 year.

Design process: The following six-step process doesn't greatly differ from existing processes yet provides a designer with a greater understanding of the real threat to life, and the ability to better focus mitigation strategies where they can be most effective in reducing the shock risk.

Step 1: Power system configuration definition. The information required to define the power system configuration includes: earthfault current delivery and return systems for each voltage level, earthing system configuration, soil resistivity, and protection system response characteristics.

Step 2: Human exposure definition. Observation points at which the risk profile will be determined are to be identified. These points are the locations at which staff or public are in contact with metalwork and able to receive an electric shock during earthfault occurrences. Each point is characterized by: contact location, contact voltage (%EPR), contact configuration (eg hand to feet), series impedance (eg footwear), contact frequency and duration.

Step 3: Driving voltage (EPR) definition. Voltage characteristic to which the person(s) will be exposed (magnitude and frequency components) is based upon the driving EPR generated in response to a range of earthfault events.

Step 4: Calculate Cumulative Fatality Probability. The risk to which a person is exposed comprises the accumulation of risk associated with each contact scenario over the course of a year. The cumulative annual fatality probability for all expected fault events, for the exposure scenario under consideration, may be calculated in a number of ways. A simple method that enables each parameter and step of the process to be easily observed, is as follows: for each fault instance, determine the associated incremental fatality probability for the exposure scenario under consideration, and then summate each incremental fatality probability to determine the total annual fatality probability for all expected fault events for the given exposure. Alternatively the analysis may be undertaken using probabilistic distributions for each parameter and using Monte Carlo analysis to derive the final characteristic [10][11].

Step 5: Sensitivity and Criticality Analysis. As for all good design processes the designer should assess the sensitivity of output (fibrillation risk) to changes in the input, and uncertainty in defining critical parameters. Once this is done it is good to do a contingency analysis and ask questions such as: "what could go wrong?", and "what level of redundancy is used?"

Step 6: Risk mitigation assessment and justification. Once the risk profile is defined for each exposure scenario, either as a single number (ie maximum) or probability distribution (say with 90% or 95% confidence limits defined) the decision must be made whether or not additional mitigation measures should be implemented. What constitutes a tolerable risk target is not examined in detail in this paper. For the purposes of the following case study the Individual Risk, being the annual risk of fatality for an exposed individual, will be considered. The risk associated with an individual is usually calculated for a single hypothetical person who is a member of the exposed population. An additional metric concerns 'societal risk' and is usually based upon quantifying the frequency of the simultaneous fatality of more than 1,2,3 or more people. The target ALARP region is then a FN characteristic rather than a simple range [14].

4 CASE STUDY - RESIDENTIAL HOUSING ADJOINING MAJOR SUBSTATION

The gradual encroachment of residential housing upon transmission stations is becoming an increasing problem for power utilities. An EPR event at a transmission station, while being relatively rare, is usually much higher than that for the substation reticulating directly to residential customers. The first step is to start with a basic earthing system layout that meets all 'fundamental' functional requirements (eg equipment bonding redundancy). It is then possible to undertake the risk analysis using a process of stepwise refinement, whereby the initial models are based upon simplified and conservative assumptions (eg fault current magnitude and frequency). If the initial mitigation requirements are overly expensive or difficult to install and/or maintain then the design assumptions may be fine-tuned (eg fault scenarios modeled more closely), more specific mitigation measures implemented, and the risk-cost-benefit analysis revised.

In this example the substation primary has a 132kV bus fed by 2 incoming overhead lines, and secondary 66kV bus feeding 4 lines covering a total of a 100km long 66kV overhead system. The proposed housing development will place houses within 20m of the external fence of the substation. Software modeling indicates that there is likely to be a touch voltage of 25% of EPR associated with the hazard scenario of a person touching taps (shower, laundry) in the nearest house.

In this case study the risk analysis is staged in 2 steps of refinement as follows: Pass I: maximum EPR occurs for all expected earth faults (ie bus fault levels), and Pass II: earth fault levels include line and fault resistance.

As the contact frequency is often seen as being difficult to quantify two options are demonstrated: Option 1 - a value may be reverse engineered to calculate the range of values that meet the ALARP region boundaries (see Section 5), or Option 2 - values determined using engineering judgment and/or risk workshop techniques.

In each instance the fatality probability contributions from the primary and secondary earthfault conditions are quantified and summated to yield an estimate of the expected cumulative risk of fatality for the exposure scenario. At each of the four stages the cumulative risk is also assessed against the 'tolerable risk' guidelines from ENA EG-0 [14] and the Argon [15] software tool is used.

Pass I: 132kV earth fault conditions: EPR (max) = 1200V, V_{touch} (max) = 400V, EPR frequency = 1 fault/10 yrs (bus fault plus upstream line fault cases), EPR duration = 0.2 secs, Series impedance = bare feet, no concrete slab, 50ohmm soil. Average contact duration = 4 secs.

Option I: Contact frequency to yield 10^{-6} individual risk increase = 1500 contacts/yr. Also as 32 people are required to be in simultaneous contact before the societal risk criteria enters the ALARP region, it shall not be considered a significant societal risk.
Option 2: Using the 'typical' figure of 2000 household contacts suggested in ENA EG-0 (no footwear), the annual individual risk increase is $1.3*10^{-6}$. This value is close to being considered a negligible risk increment.

66kV earth fault conditions: EPR (max) = 900V, V_{touch} (max) = 225V, EPR frequency = 5 faults/yr (bus fault plus line fault cases), EPR duration = 0.2 secs, Series impedance = bare feet, no concrete slab, 50ohmm soil. Average contact duration = 4 secs.
Option 1: Contact frequency to yield 10^{-6} individual risk increase = 1500 contacts/yr. As 9 people are required to be in simultaneous contact before the societal risk criteria enters the ALARP region, it shall not be considered a significant risk in the 66kV case.
Option 2: Using the 'typical' figure of 2000 household contacts suggested in ENA EG-0 (no footwear), the annual individual risk increase is $5*10^{-6}$. This value would not be considered a negligible risk increment. Therefore additional mitigation should be undertaken or the analysis more finely tuned.

If the EPR were reduced by 2/3 to around 300V the residual risk would be in the negligible region. However, this is likely to be very costly and impractical, and so would not be considered a reasonable expenditure. Alternatively the analysis may be fine tuned to remove some of the conservatism in the assumptions. In this case either the 66kV fault frequency may be re-examined and fault records used to fine-tune the expected fault frequency (eg remove cases where a line would drop on the earth yielding negligible EPR at the source substation), or the 66kV EPR magnitude may be examined more closely by modeling individual fault scenarios. The latter option will be illustrated.

Pass II: 66kV earth fault conditions: It is found that the 100km of line is associated with some 600 structures and 4 substations, yielding a fault frequency of less than 0.01/yr for each asset. A software model of the 4 lines may be used to calculate current flows and the expected EPR at the source substation (and hence V_{touch}) for each fault case, and the calculated annual individual risk increments aggregated. Using the 'typical' figure of 2000 household contacts suggested in ENA EG-0 (no footwear), the aggregated annual individual risk increase, using actual expected EPR values, is $0.5*10^{-7}$. This value would be considered a negligible risk increase.

Good practice would require a designer to undertake a sensitivity analysis to determine the robustness of the design assumptions, and an assessment of alternative mitigation options. If the risk could be reduced or eliminated by simple or cheap means due diligence would recommend implementing the mitigation measure.

5 STATUTORY REQUIREMENTS

Sitting above the specific physiological safety criteria and standards, most countries mandate WH&S regulations that place a duty of care upon employers and asset owners to demonstrate due diligence and undertake a risk management exercise to identify hazards, assess risks and then eliminate or control risks, where operations or installations may effect staff or the public. The European Union Framework Directive 89/391/EEC [16] requires all member countries to enact such a regulation. The UK has enacted a regulation on the Management of Health and Safety at Work 1999 [17] which states that '*Every employer shall make a suitable and sufficient assessment of ... the risks to the health and safety of persons not in his employment arising out of or in connection with the conduct by him of his undertaking*'.

Within the UK this is clearly embodied in the process described in the HSE document 'Reducing risks, protecting people' [18], and similar processes are used in most countries. The HSE framework for tolerability of risk includes three zones to define the bounds used in the ALARP (as low as reasonably practicable) process, ranging from an unacceptable region (typically seen as greater than a fatality risk increase of 1 in 10000 per year for a member of the public) to broadly tolerable region where the residual risk is extremely small when compared to the background level of risk. A value of one in a million risk increase per year for an individual is often used as a guide to define the boundary for this region.

Within the Australian context WH&S Regulations [19] require an asset owner or business operator to: *(a) to eliminate risks to health and safety so far as is reasonably practicable; and (b) if it is not reasonably practicable to eliminate risks to health and safety, to reduce those risks so far as is reasonably practicable'.*
The determination of what may be considered to be 'reasonably practicable' requires an assessment of the risk profile associated with the hazard scenario.

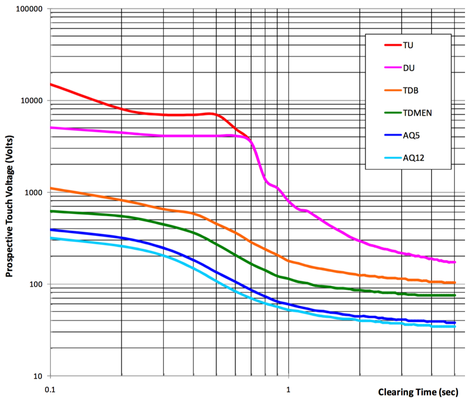
Therefore, it is no longer acceptable to adhere to 'age old' design processes without undertaking an assessment of the residual risk to which people may be exposed through the application of those processes. Such an assessment may confirm the adequacy of the existing processes and safety targets, or it may identify situations in which change is justified. Both the UK and Australia have developed risk quantification processes based upon the IEC60479 physiological data, and incorporated the process within safety standards.

Standards committees and asset owners alike are increasingly being required by Regulators to meet legislative imperatives, and reconsider or redevelop existing standards, policies and processes. Therefore the use of quantified risk analysis and assessment is now becoming mandatory for the management of indirect shock risk in some countries.

UK Experience: The UK has developed an alternative design flowchart in a national annex to the Cenelec earthing standard BS EN50522 [20]. The flowchart has been augmented to allow designers to undertake a quantified risk analysis if normal touch voltage criteria are found to be inadequate (ie too stringent, or unable to take special conditions such as sporting events into consideration). Examples are included based upon the work undertaken at the University of Cardiff [10][11] that incorporates IEC60479 physiological data with system performance information, and uses Monte Carlo analysis to determine risk profiles associated with transmission system assets.

Australian Experience: Under the auspices of the Energy Networks Association a team developed a risk quantification process, based upon the work of the author of this paper [4][12] undertaken in the 1990's. The process has been embedded the within an industry guideline, ENA EG-0 [14]. In addition a software tool was developed to provide users with the ability to assess risk of fatality for a given hazard scenario. The tool entitled Argon [15] was developed within Ausgrid and made available for free download on the ENA website.

Design templates: Standard 'safety' touch voltage withstand curves have long been the means by which designers determine the point at which they stop investing in shock mitigation measures. The use of quantified risk enables touch voltage curves to be generated with clearly defined boundary conditions. Several Australian standards working groups have used the ENA EG-0 (see Fig 1)[14] techniques to redevelop a number of safety standards covering: distribution and transmission assets AS/NZS 7000 [21], metallic pipelines AS4/NZS 4853 [22], and finally HV installations AS2067 [23] (companion to IEC 61936). The latter standard covers all HV plant and includes typical criteria covering a wide range of applications including mining and industrial hazard scenarios.



TU	Transmission urban
DU	Distribution urban
TDB	T&D backyard
TDMEN	T&D MEN
AQ5	Aquatic centre 5months/year
AQ12	Aquatic centre 12 months/year

Figure 1 – Transmission and Distribution asset prospective touch voltage criteria - Case studies [23]

A joint Cigre/Cired working group B3:35 is currently investigating the topic ‘Substation earthing system design optimization through the application of quantified risk analysis’. One of the stated objectives of the project team is to make recommendations for incorporating probabilistic risk analysis in international earthing standards.

6 CONCLUSIONS

Electrocution due to indirect contact with metalwork during earth fault events is a low probability high consequence hazard scenario. A cursory examination of the efficacy of past earthing practices would have difficulty discerning if an adequate level of safety has been achieved for workers and the public. The tolerable level of risk is so low as to be very difficult to identify a statistically significant number of cases, particularly when it is difficult to discern the difference between the result of a coronary heart attack and ventricular fibrillation. Nevertheless new WH&S Act legislation in some countries contain a requirement to demonstrate due diligence in managing the risk imposed upon an individual. In such countries the ability to quantify the risk associated with operating a given power system network asset is now longer an optional activity.

This paper demonstrates how earthing related shock risk quantification aids the design decision process and is able to provide objective yet defensible design criteria and their range of applicability. Thus power utilities and consultants now have the tools to confidently meet the new legislative imperatives, and reconsider or redevelop existing standards, policies and processes. In addition standards bodies in some countries are beginning to provide users with new processes that capitalise on the need for a new decision making framework.

7 REFERENCES

[1] ANSI/IEEE Std 80-2013 ‘IEEE Guide for safety in AC substation earthing’ IEEE, New York, 2010
[2] C.F. Dalziel, 1972, ‘Electric shock hazard’ IEEE Spectrum
[3] IEC/TS 60479-1:2005 ‘Effects of Current on Human Beings and Livestock.’ General Aspects, 2005.
[4] W.D. Carman, 2000, “Probabilistic comparison and application of international electrical safety criteria,” IEEE Powercon, Perth, Australia, 1347–1352.
[5] IEC61936-1 ‘Power installations exceeding 1kV a.c. – Part 1: Common rules’. Ed 2.0, 2010-08
[6] S. Karkkainen, V. Palva, 1974 ,‘Application of probability calculation to the study of the earthing voltage requirements for Electrical Safety Codes’, Sahko, vol. 47, no. 11
[7] B. Sanso, et.al., 1984,‘Total accident probability of a metro system’ IEEE IAS
[8] G. Bridges (ed.) et al., 1983, “Panel meeting on physiology of electric shocks,” Proc. 1st Int. Symposium. Elect. Shock Safety Criteria, Toronto, ON, Canada
[9] C.J. Todd, 1966, ‘Probabilities of personal danger – Low frequency induction and substation potential rise’. Australian Telecommunication Monograph No 3
[10] A. Dimopoulos, et.al. 2012,‘Probability surface distributions for application in earthing safety assessment’, IEEE PWRD, Vol 27. No 4, 1928-1936
[11] A. Dimopoulos, et.al., 2012,‘Proposal for probabilistic risk assessment in earthing systems and its application to transmission substations’, ibid, 2219-2226
[12] W.D. Carman, 2000 “Development of risk profiles associated with electrical power substation earthing systems,” IEEE Powercon, Australia, 2063–2071.
[13] W.D. Carman, 2016, ‘Earthing shock safety design standards’, Down To Earth Conference, IEEE PES, DOI: 10.1109/DTEC.2016.7731280
[14] ENA EG-0 2010, *Power system earthing guide. Part I: Management principles*
[15] Argon safety assessment software, Energy Networks Association (Aust.). www.ena.asn.au
[16] European Union Framework Directive ‘Introduction of measures to encourage improvements in the safety and health of workers at work’. 89/391/EEC 1989
[17] UK SI ‘Management of health and safety at work’ 1999 No. 3242.
[18] ‘Reducing risks, protecting people’ UK HSE, 2001
[19] Work Health and Safety Act 2011, Australian legislation
[20] BS EN 50522:2010 ‘Earthing of Power Installations Exceeding 1 kV a.c.’, CENELEC, 2010.
[21] AS/NZS 7000:2010, *Overhead line design - Detailed procedures*, Standards Australia
[22] AS/NZS 4853:2012, *Electrical hazards on metallic pipelines*, Standards Australia
[23] AS2067:2016, *Power installations over 1kV*, Standards Australia.