EARTHING DESIGN INCORPORATING RISK QUANTIFICATION – AN EXPENSIVE OVERHEAD OR KEY DECISION-MAKING TOOL?

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ABSTRACT

The disparity in a range of traditional and contemporary earthing design approaches and the resultant variation in the cost of implementation has been observed by many and has led to a number of studies since the 1960's, examining the level of risk imposed upon a person by a power system asset in a faulted state. In addition, driven by Work Health & Safety (WH&S) legislation a new safety paradigm is evolving incorporating an explicit requirement to demonstrate due diligence in managing risk imposed upon staff and the public. This paper introduces the findings of the joint Cigre/CIRED working group B3:35 regarding how and why quantified risk analysis (QRA) may be applied to earthing system design.

1 INTRODUCTION

Statistical studies for operational modelling and risk quantification are not new to the electric power industry. The use of such studies is closely linked to the development of strategies for demonstrating due diligence in the management of risk. Given that many of the variables involved in earthing system design are probabilistic in nature, it is logical that similar statistical approaches should be applied.

Earthing systems are safety critical systems in that they are required to operate effectively to protect the lives off the public and utility workers. Traditional designs often use the same 'safety' criteria for sites where people are rarely present and those such as theme parks or swimming pools where many people congregate frequently and ignore the wide variations in fault and contact frequency. A process that is sensitive to the real risk to people created when current is released during a fault event will enable designers to identify the most cost-effective means to mitigate the real risk. Therefore, the goal of earthing system design optimisation using risk quantification is to ensure adequate robustness in the design at the same time as finding a balance between cost, practicality and management of risk.

Cigre and CIRED independently developed plans to form working groups to study 'Substation earthing system design optimisation through the application of quantified risk analysis' and 'Adaptation of earthing systems to reality related requirements' respectively. The intent of both business cases was the same as this extract from the CIRED TOR illustrates, 'An adaptation of the practice of designing earthing systems to a more realistic approach seems reasonable and possible: If one also takes, for example, the fault durations, the presence characteristic of people and the presence of the effectiveness of other protection measures into consideration, this leads to a risk analysis'. A joint working group B3:35 formed and first met in late 2013 with a full group meeting early in 2014. The group consisted of 22 engineers representing some 20 countries. The membership comprised academics and engineers from power utilities and consultancies with many years' experience managing and analysing earthing systems, developing national and international safety standards (IEC, IEEE, Cenelec, national standards, industry standards), and a number with direct experience implementing risk quantification processes.

2 HISTORICAL USE OF QRA IN EARTHING

The working group firstly undertook a survey to determine the where and how risk quantification was or had been used in relation to earthing system design either for use in developing tolerable safety standards (ie touch voltage vs protection clearing time withstand curves), or to assess the risk associated with a specific or class of hazard scenario (ie voltage source and contact exposure mechanism):

- Australia in the 1960's: Risk to telecommunications staff was quantified [1], in order to determine the maximum impressed voltages to allow on telecommunications circuits, resulting in new tolerable safety standards (ie 430V, 1000V and 1500V).
- Finland in 1970's: Finland adopted a set of earthing voltage requirements as part of the Electrical Safety Code [2], based upon a probabilistic analysis of the contributing factors including the physical constraints of very high soil resistivity and reduced exposure due to being snowbound during the winter months.
- IEC479 (1974) [3]: This document published physiological details of human fibrillation current withstand expressed in probabilistic terms. The introduction to the document included the wording: *'There are, however, other aspects to be taken into account, such as probability of faults, probability of contact with live or faulty parts, experience gained, technical feasibilities and economics. These parameters have to be considered carefully when fixing safety requirements, ... for electrical installations.'*
- Germany VDE 0141 [4]: The 1976 edition allowed for networks 110kV or higher to consider a design current of 70% of the maximum fault current. This allowance was based upon the low likelihood of the coincidence of maximum fault current and a person being in the worst-case contact location.
- Australia in 1980's: The power industry undertook probabilistic studies to determine tolerable design criteria for distribution and transmission structures [5][6]. This work generated tolerable prospective touch voltages based upon an annual fibrillation fatality risk increase limit of 1 x 10^{-6}.
- A 1985 Cigre publication [7] stated: '*While a worse-case deterministic assessment may show high values of potential gradients near faulted towers, a more realistic probabilistic assessment often shows that the likelihood of an event is very small and conventional earthing designs*

adequate.'

- IEEE papers in 1980's: A number of papers used QRA to calculate the shock risk for specific assets (e.g. metro system) [8]. At an international symposium held in Toronto in 1985 [9] it was concluded that a need existed for the development of probabilistically based safety criteria.
- IEEE80 [10]: The preconditions for a hazardous electric shock incident are identified and it is observed that the '*relative infrequency of hazardous incidents is due to the low probability of the coincidence of those necessary conditions*'.
- IEC 61936 (2002) [11]: The HV installation standard uses selected statistical characteristics from the physiological data in IEC60479 [3] to generate a permissible prospective touch voltage curve. It acknowledges that *'...fault occurrence, fault current magnitude, fault duration and presence of human beings are probabilistic in nature'*.
- UK in 2000's: The UK adopted a design process that allows designers to undertake a QRA based upon the work undertaken at Cardiff University [12][13] in a national annex to the Cenelec earthing standard BS EN50522 [14].
- New Zealand 2000's: The power utility industry produced a risk-based earthing guide in 2003 [15] and followed it with a practise guide in 2009 [16] containing a range of QRA based case studies.
- Australia/New Zealand in 2000's: An industry working group developed a design guide based upon the use of QRA [17]. Subsequently the following Australian and New Zealand earthing related standards have been redeveloped to incorporate QRA: T&D assets AS/NZS 7000 [18], metallic pipelines AS/NZS 4853 [19], and the HV plant standard AS2067 (2016) [20].

As the forgoing survey results show, a number of recent earthing safety standards are making the risk-based nature of the decisions overt rather than hidden and have incorporated the ability to undertake a quantified risk analysis within the earthing design process.
Traditional approaches to managing earthing related risk relied on a combination of recognised controls or prescribed measures and the reduction of touch and step voltages to below particular levels considered or deemed safe. However, it is now clearly understood that these traditional criteria do not ensure survival, should someone be in the touch voltage situation coincident with the earth fault occurring and creating the touch voltage.
For instance, if a person in bare feet was exposed to a touch voltage equal to the standard tolerable touch voltage characteristics tabled in EN50522 and IEEE80, the likelihood of fibrillation occurring when assessed against the best available physiological withstand criteria (IEC60479) is shown in Table 2-1[17][21].

Table 2-1: Comparative fibrillation likelihood.

Earthfault duration (s)	Probability of fibrillation	
	IEC60479/EN50522 $I_b(5\%)$, $R_b(50\%)$	IEEE80 (50kg)
0.2	4.3×10^{-3}	$6.4 * 10^{-3}$
0.5	3.3×10^{-1}	$3.5 * 10^{-2}$
1	1.9×10^{-1}	$2.6 * 10^{-1}$

Clearly the likelihood of fibrillation in all cases is much larger than typical tolerable individual risk targets (such as 10^{-6}). Therefore, traditional safety criteria can only be considered tolerably safe provided there is a low likelihood of an earth fault occurring at the same time as a person being in an exposed position [10][11][22]. Nevertheless, the working group considered the intent and common applications of existing standards and concluded that for the most part their implementation is producing good outcomes.

3 LEGAL AND REGULATORY DRIVERS

A fundamental principle underpinning much WH&S legislation is that those who create risks are responsible for protecting workers and the public from the consequences. The release of the hazardous substance 'electricity' into the environment creates such risks. Although there are differences in the detail within the legal frameworks in various countries, legal and regulatory perspectives are shown to underpin the need for QRA in demonstrating due diligence in explicitly managing risk to meet societally tolerable limits in accordance with WH&S regulations as well as the risk management standard ISO31000 [23]

While it is clear that no such thing as absolute safety exists, it is an engineer's responsibility to make systems as safe as reasonably possible. The following statement from the US [24] clearly defines the regulatory requirement for managing involuntary risk: *'Where an individual person may be exposed to involuntary risk (beyond their control) due to exposure to a hazardous condition then the appropriate regulatory requirement placed upon the body generating the risk was the need to manage the imposed risk increase.'* Without firstly quantifying the expected risk levels we are unable to demonstrate due diligence.

4 RISK MANAGEMENT AND QRA

The general considerations and examples of risk management and tolerable criteria in different countries are introduced with particular focus on the processes recognised within ISO/IEC risk management standards. A risk management framework for organizations is provided in ISO 31000:2009 [23]. The concept of Tolerability of Risk (TOR) and its relation to reducing risk imposed upon people to 'as low as reasonably practicable' (ALARP) is identified as a commonly applied and applicable risk management approach.

Risk tolerance criterion are described by three risk bands; an upper intolerable risk band, a lower negligible risk band and between these two, an intermediate band where risk treatment is managed on some measure of reasonableness. A survey of numerical risk tolerance criteria and general approaches to risk adopted by national safety and regulatory bodies was undertaken. An individual risk increase of 1 in 1 million is commonly used as the lower negligible risk band. In addition, more stringent 'societal risk' conditions apply when more than 1 person could be reasonably expected to be in an 'exposed' position at the time of a fault [17].

The use of probabilistic targets, defining boundaries between unacceptable and negligible risk limits, is not a perfect approach by any means. Weaknesses are acknowledged within the risk management process itself, with provision for checks of sensitivity, criticality and variability of parameters. Moreover, the concept of QRA is shown to be more responsible than other prescriptive approaches, as it attempts to enumerate the real issue of the 'statistical characteristic in the level of risk', which is at the heart of the safety policy setting problem.

Moving from the general risk management to earthing related risk management the probabilistic nature of the shock event is examined alongside the main components of the QRA process when applied to earthing system design. The probability of fatality due to indirect contact with a fault voltage may be expressed simply for independent events as shown in Equation 4-1[1]. It recognizes that in order for a person to receive a fatal shock they must be situated at a point of contact at the same time as they experience heart current of sufficient magnitude and duration to enter fibrillation.

$$P_{fatality} = P_{fibrillation} \times P_{coincidence} \qquad \text{Eqn 4-1}$$

Where

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

$P_{coincidence}$ = f(fault frequency, fault duration, contact frequency, contact duration)

The value $P_{fibrillation}$ is the probability that the heart will enter ventricular fibrillation. It is usually calculated by convolving the applied voltage PDF with the withstand voltage PDF, numerically by Monte Carlo simulation [12][13]. The exposure probability ($P_{coincidence}$) is the probability that a person will be present and in contact with an item at the same time that the electrical potential of the item is affected by the flow of earth fault current. While a non-electrical input such as the demographics of human movement is difficult to quantify, it plays a very significant role in differentiating site risk profiles in real life.

4.1 Analysis Scope

Regarding the scope of the risk analysis, the approach of designers to identifying the locations where staff or the public could be exposed to voltages that occur during earthfault events varies widely across the world. For example, some designers only consider indirect contact voltages associated with electrical facilities themselves (eg within a radius of 1m from the perimeter fence of a substation), while others recognise the responsibility of the owner of the asset under fault to consider any hazardous voltages created by currents flowing during earthfault conditions. The 'system wide' nature of the flow of possibly hazardous fault energy needs to be understood if the real hazard locations are to be identified and the most efficient, cost effective risk mitigation strategy implemented.

5 INPUT PARAMETER IMPACT ON RISK

A number of key earthing design inputs have been investigated to see what variation may be expected to occur, and the effect on the outputs of the design firstly in terms of magnitude of the shock hazard and secondly the risk of fatality. Parameters that have been investigated include: earth fault current magnitude and duration, return current distribution, soil electrical resistivity, earth fault voltage distribution, body current and voltage withstand criteria, fault frequency and person contact frequency and durations.

Detailed case studies reflecting substations within typical representative transmission and distribution networks where used to illustrate the use of QRA in practical cases and to show how variations in input parameters affect the residual risk imposed upon exposed people in a number of representative locations (eg substation mesh voltage, shower in adjacent dwelling).

Transmission Substation Risk Response: Transmission substations in both overhead and underground networks were studied (see Figure 5-1 for overhead line network case).

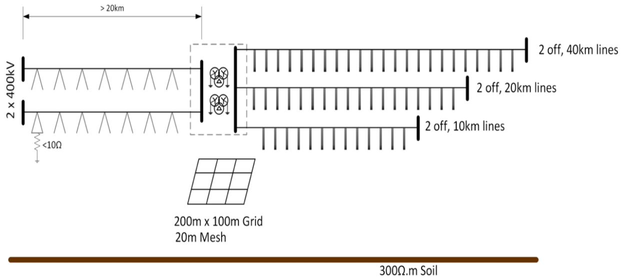

Figure 5-1: 400/110kV underground cable network case

Taking the 400kV fault scenario in an overhead fed substation as an example, a factor of 2 change in the fault current (and hence EPR) led to changes in risk of fatality of some 9 orders of magnitude (for the mesh touch voltage contact scenario investigated) (see Figure 5-2).

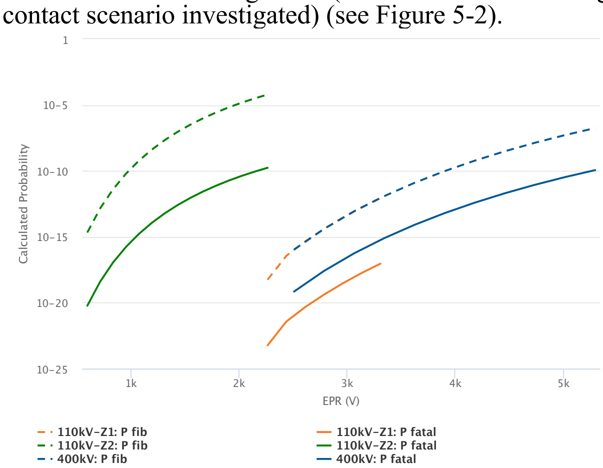

Figure 5-2: EPR variation impact on calculated risk

Another parameter that primarily impacts the fibrillation probability is the fault clearing time. The primary feature of note in this case is the range of the computed probabilities. Taking the 400kV fault scenario as an example, the fastest clearing time has an associated risk of $\simeq 5 \times 10^{-20}$, and the slowest has a risk of $\simeq 3 \times 10^{-7}$ a difference of 13 orders of magnitude, which is caused by only a factor of 5 change in the clearing time. In fact, the range of clearing times under investigation here are likely to encompass the region in which the fibrillation probability is most sensitive, and coincidence probability is least sensitive to changes in clearing time.

The foregoing examples relate to the particular system configuration assumptions and calculation methods used

in the case studies.
The relationship between the input parameters and the computed risk levels is generally non-linear, and different parameters have different impacts on the risk levels. The factors which primarily impact coincidence probability (fault rate, contact rate, contact duration) generally had a more straightforward impact on the computed risk values, and over the range of values considered there was an approximately 1:1 relationship (a 4× variation in input lead to ≈4× change in output). By contrast, the factors that primarily impacted fibrillation probability (EPR, clearing time, and soil model) had a more complex relationship with the calculated risk levels. In addition, the calculated risk levels were much more sensitive to variation in these parameters – changes of 4-5× resulted in many orders of magnitude difference in the calculated probabilities.

Distribution Substation Risk Response: For the specific system configuration examined (see Figure 5-3) the variation in probability of fatality was calculated as input parameters were varied, for a range of neutral point earthing configurations.

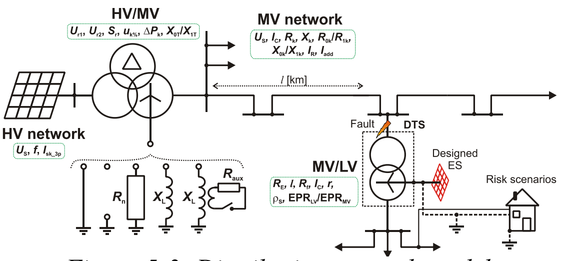

Figure 5-3: Distribution network model

6 QRA INTEGRATED WITHIN STANDARDS

A generic design procedure was developed that incorporates the use of QRA in a staged manner within the main elements of existing traditional design procedures to either support maintaining the present risk profile or develop a business case to justify a site-specific risk mitigation strategy (see Figure 6-1). Figure 6-2 illustrates how QRA could be integrated within an existing design flowchart such as EN50522 [22].

The main difference between the two flowcharts is that the EN50522 process includes a number of simplified steps. While the use of simplifications is a normal part of most design processes, it is always the responsibility of a designer to check that the case under investigation meets the boundary conditions/assumptions governing the use of the simplifications.

Implementing an iterative or staged design process: As for a traditional earthing design, it is normal practise to begin with simplified conservative assumptions and a standard design configuration that meets functional requirements. Often touch voltage/time curves are applied based upon 'first pass' conservative assumptions. If the design does not comply or the situation does not meet the boundary conditions applicable to the design curve, then a QRA may be applied [25][26]. By applying QRA a designer has the ability to more effectively assess the impact of all significant parameters, fine-tune additional mitigation measures and justify expenditure to reduce risk in areas that do not meet TOR requirements.

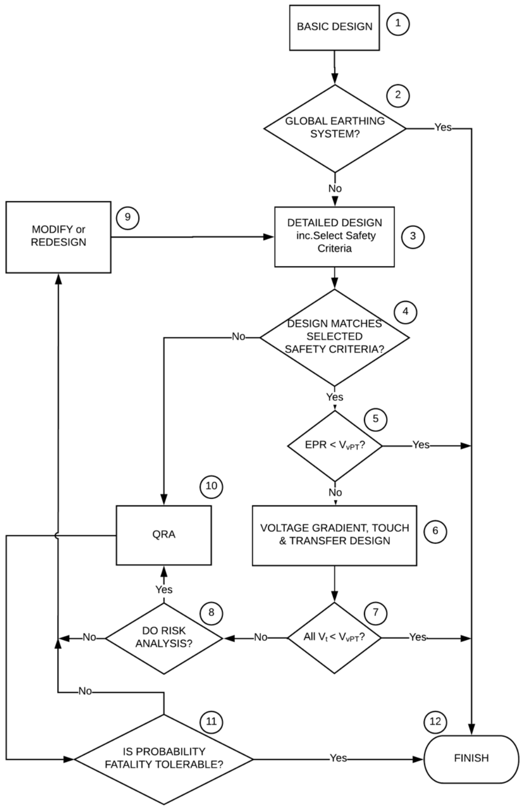

Figure 6-1: Generic earthing system design procedure

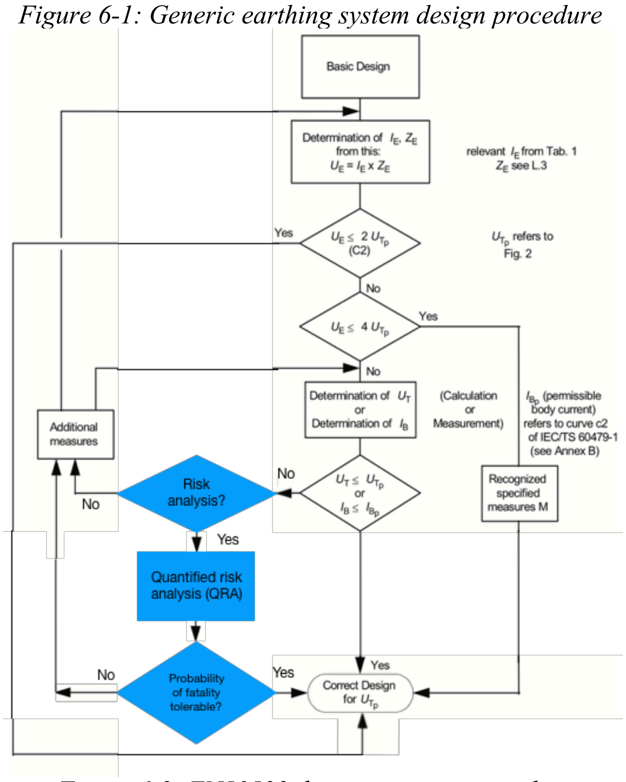

Figure 6-2: EN50522 design process revised to incorporate QRA

Software tools: A software tool was developed in conjunction with the Australian ENA EG-0 Guide [17] to provide users with the ability to assess risk of fatality for a given hazard scenario. The tool entitled Argon [21] was developed within the power utility Ausgrid and made available for free download on the ENA website. An alternate tool based on the same methods and source data has been made available at the request of the Study Committee B3 Chairman to ensure the ongoing availability of a tool to provide a point of reference. The web-based tool is called Argonium [27].

7 CONCLUSIONS

The joint working group published a technical brochure TB749 [28] document that concludes for traditional safety criteria to meet societally tolerable risk exposure targets they must rely upon the low likelihood of the coincidence of an earthfault and a person being in a position to receive a hazardous voltage. The document demonstrates the means by which QRA may be used to determine the tolerability of risk exposure for a person in a given situation, and that voltage criteria alone are unable to prove compliance with tolerable risk criteria. The earthing design process that incorporates QRA empowers the design engineer to objectively address the design parameters that most significantly affect the electric shock risk to the public and utility staff, and to develop optimised risk mitigation strategies.

Based upon the analysis undertaken by the working group it is recommended that asset owners, design houses and standards setting bodies work toward the explicit inclusion of QRA within earthing design processes and communicate clearly the fact that the application of QRA is able to produce 3 key outcomes:

- Reduction of waste where traditional approaches produce overly conservative requirements.
- Reduction of 'risk of fatality' from earthing related (indirect) electric shock where such reduction is justified.
- Provide a measure of risk that allows broad comparison and understanding by non-specialists.

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