USE OF FINITE PROBABALISTIC MODELLING TO ESTABLISH EARTHING HAZARD LIMITS

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ABSTRACT

Safety criteria for earthing related hazards have historically been derived using deterministic processes. To quantify the risk associated with these hazards the current trend is to base safety criteria on probabilistic processes. This paper examines how the selection of probability distribution functions used to derive the criteria can impact the outcome, particularly as these events are low probability with high consequence.

INTRODUCTION

There are a number of mechanisms by which an electric shock can cause harm to human beings. It is widely held that Ventricular Fibrillation (VF) represents the most sensitive of the potentially fatal physiological responses by human beings to electric current [5, 6, 7, 10]. A possible explanation of how a shock might cause VF is provided in [5]. The essence is that current flowing near the heart triggers extra contractions of the heart muscles that upset the normal heartbeat rhythm.

The amount of current required to trigger VF varies between individuals, and is also dependent on the length time it is applied. Understandably there has been little testing performed on humans to determine the precise nature of the distribution of currents causing VF, however, there have been a number of animal studies [12, 9]. The human testing that has been undertaken has typically focused on establishing safe limits that are unlikely to cause VF, either by determining so-called *let-go* currents [6], or demonstrating the effectiveness of high speed disconnection devices in preventing VF [4, 13].

The amount of current that flows through a body completing a shock circuit in an earthed situation is determined by the impedance of the body, the impedances of the other elements in the shock circuit and the voltage driving the circuit. Historically a single value, such as 1kΩ, has been assumed to be representative of the human population's body impedance to establish appropriate hazard limits, including standards such as [11, 3, 8].

IEC60479 describes in detail how the impedance of the human body varies across the population, including its voltage dependence due to the skin impedances breaking down at voltages higher than 200V. This paper describes how the more complex, yet more complete, description of the population's physiological response to electric shock impacts the derivation of suitable safety targets applicable to earthed situations.

BASIS FOR WORKING STANDARDS

There are a number of standards around the world that purport to define safe voltage limits that people may be exposed to, however, in the context of earthing IEEE-Std80 [11] and IEC61936 [1] are two of the most prominent. The voltage limits defined therein are derived via two different methods, and the resulting voltage limits are not equal.

The criteria in IEEE-80 are largely based on the work of Dalziel [7], whereas IEC61936 draws more heavily on the work of Biegelmeier. When a graph of allowable voltage versus fault clearing time are plotted on log-log axes the IEEE-80 criteria describe straight lines, whereas the IEC61936 criteria have an 's-curve' shape arising from the body impedance and allowable current characteristics they are based on. The result is that the allowable voltage curves of these two standards may intersect multiple times, and it is not straightforward to determine which one is more conservative, since it depends on the particular clearing time.

Despite the differences in allowable voltages there is a common theme to the derivation of the safety criteria in IEEE-Std80 and IEC61936; some maximum tolerable current is defined, and a deterministic procedure is applied to convert that current into an allowable voltage. The implied safety of the allowable voltages derived this way relies on the value chosen for maximum permissible current being sufficiently low.

QUANTIFIED RISK SAFETY CRITERIA

In 2010 the Energy Networks Association in Australia released EG-0 Power System Earthing Guide [2], which introduced safety criteria based on the principle of quantified risk management, representing a dramatic shift from the traditional derivation methods for safety criteria. Quantified risk management requires a level of risk be assigned to a hazard, in this instance an electric shock in an earthed situation, and EG-0 used the annual probability of a fatality resulting from a touch voltage as its measure of risk level.

The level of tolerable risk recommended was 10^{-6} per annum for an exposed individual in line with international risk standards for other industries. Notice that the tolerable limit is now defined in terms of the risk level, and not the current through the body, allowing the risk posed by different scenarios to be directly compared.

The probability of fatality put forward in EG-0 has two components: the probability that the voltage hazard would cause VF, and the probability of an individual actually being exposed to the voltage. These component probabilities are termed the *fibrillation probability* (P_{fib}) and the *coincidence probability* (P_{coinc}) in EG-0, and they are related to the probability of fatality by equation (1).

$$P_{fatality} = P_{fib} \times P_{coinc} \quad (1)$$

P_{coinc} is dependent on the fault characteristics and behaviour of people, in other words, how often faults occur, and how often people are in contact with items that might become energized during the fault. EG-0 provides a simple formula for calculating P_{coinc} from fault rate, and contact duration and frequency.

The calculation of P_{fib} is more complicated and relies on data regarding the human body's response to electric shock. EG-0 outlines a Monte Carlo based approach to calculating P_{fib} that amounts to randomly selecting individuals from the population and calculating if the voltage hazard would drive a current through their body that exceeded their tolerance. This approach relies on fitting probability distributions to the physiological data to describe the characteristics of the entire population, however EG-0 does not specify which distributions should be used.

The derivation of traditional safety criteria used the experimental data on the human physiological response to define the tolerable current limits. The focus of this deterministic process was to establish bounds rather than characterizing the entire population. In contrast, the quantified risk approach relies on describing the VF parameters (body impedance and current tolerance) with probability distributions to calculate a risk across the entire population. So while conservative approximations may be valid and useful in the traditional safety criteria derivation process, the quantified risk approach is based on describing the full distributions as accurately as possible, and such approximations are not as useful, and may in fact be counter-productive.

CALCULATING FIBRILLATION PROBABILITY

The experimental results of the human physiological response to electric shock are described by the following probabilistic functions.

- Population current tolerances with respect to the duration that the current is present; and
- Population body impedance with respect to the voltage applied to the body.

Much of the experimental data is presented in terms of ‘*percentile values*’ of the population. These percentile values correspond to points on a Cumulative Distribution Function (CDF), and therefore may be used to fit a probability distribution to the data. The time dependence of the current tolerance, and voltage dependence of the body impedance complicates this process, however fitting can be performed at selected times/voltages along the characteristic curves, and intermediate values interpolated. We have assumed, as have others, that the body impedance and current tolerance characteristics are independent, that is, an individual with the highest body impedance could also have the lowest current tolerance.

As previously mentioned, EG-0 provides a Monte Carlo technique using the fitted probability distributions for estimating P_{fib} that essentially computes the percentage of a set of randomly selected individuals that would have entered VF if exposed to the voltage hazard.

The key step is determining the current that would flow through the body as a result of the applied voltage, taking the other impedances in the shock circuit into account. This is complicated by the non-linear voltage dependant impedance characteristic of the human body, and possibly other non-linear impedances in the circuit, such as footwear with a particular breakdown voltage. Finding the current flowing is an iterative process where initial estimates are made and progressively refined until the equilibrium point is found.

Once the current flowing through the body is determined it may be compared to the tolerance of the individual for the clearing time of interest, and VF is said to result if it is greater than the tolerance.

We propose a method of calculation that is similar to, but subtly different from the Monte Carlo method in EG-0, based on structured sampling of the population rather than random sampling. Whereas the Monte Carlo approach selects individuals randomly and assigns equal weight to the result from each, the proposed method selects individuals with characteristics from specific sections of the distribution, and weights the results by the fraction of the population that individual represents. The main benefit of this approach is that the entire distribution of the population can be covered much more effectively, since by definition individuals with characteristics from the extremes of the distributions are unlikely to appear in a random selection of the population. A secondary benefit is that very low probabilities may be accurately estimated without requiring huge numbers of samples as Monte Carlo methods do.

PROBABILITY DISTRIBUTION SELECTION

A range of feasible probability distributions for body impedance and current tolerance characteristics (Gaussian, log-normal & log-triangular) were used to calculate fibrillation probability curves.

Impact on Fibrillation Probability

Figure 1 compares the calculated fibrillation probabilities for the three current tolerance distributions for a 0.3s clearing time across a range of voltages. A log-normal distribution was used for the body impedance as it was found to fit the data reasonably well. The calculated curves show that the Gaussian (or ‘normal’) distribution exhibits quite different asymptotic behaviour than the other distributions; no matter how low the applied voltage is there is always some finite probability of fibrillation. At the other extreme is the Log-triangular distribution, which has bounded range, resulting in the calculated fibrillation probabilities being 0 for all voltages below some threshold. The log-normal fits between these two, displaying similar asymptotic behaviour to the log-triangular distribution, but a lower threshold voltage before the calculated fibrillation probabilities approach 0.

Increasing the clearing time reduces the differences between the distributions, but the differences in asymptotic behaviour are still clearly evident.

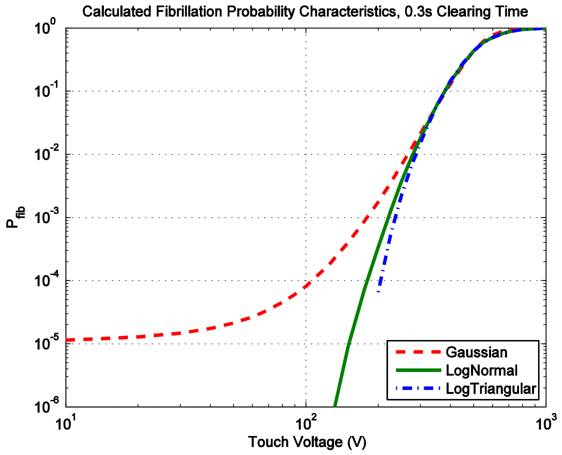

Figure 1: Comparison of Calculated Fibrillation Probabilities for 0.3s Clearing Time

The differences can be traced to the tails of the chosen distribution. The Gaussian distribution is defined over the range $-\infty \le x \le \infty$, whereas the log-normal is only defined over $0 \le x \le \infty$, and the log triangular distribution is further restricted to some range $a \le x \le b$. At the lower voltages, where the differences are most apparent, it is essentially only the *'exceptionally sensitive'* individuals that contribute to the fibrillation probability. Since the Gaussian distribution has the longest lower tail it places more individuals in this range than the other distributions, and so results in a higher calculated fibrillation probability. Conversely at higher voltages the differences are caused by the relative number of *'exceptionally insensitive'* individuals who do not enter VF, and the distributions with the shorter upper tails calculate higher fibrillation probabilities.

Quantified Risk Safety Criteria Impact

Using the selected distributions to derive quantified risk safety criteria curves, as described by EG-0, it was found that the differences between the computed allowable voltage curves are comparatively minor for most of the scenarios laid out in EG-0. This is due to the coincidence probability component of the calculated risk.

Low Coincidence Events

Taking the specific example of the MSPB[1] scenario from EG-0, the allowable voltages, calculated by the Argon[2] software and our own software (with two different current tolerance distributions), were found to have minimal difference across the range of clearing times considered.

The coincidence probability for this scenario varies from approximately 5×10^{-6} to 10^{-5} over the range of clearing times considered, meaning the fibrillation probability must lie between 0.2 to 0.1 to maintain a risk level below 10^{-6}. The voltages resulting in this level of fibrillation probability are very similar for the various choices of current tolerance distribution, so as expected, the derived safety criteria are very similar.

High Coincidence Events

Figure 2 shows the calculated allowable voltages for the ZSSMEN[3] scenario, where the coincidence probability ranges from approximately 0.01 to just over 0.2. The peculiar shape of the Gaussian derived curve is due to the process of fitting the distribution to the data, resulting in the variance being greater between 0.4s and 0.9s than at other times. The voltage limits were constrained to a 12V minimum, and between 0.4s and 0.9s the Gaussian derived curve sits on this lower limit. Recall the calculated fibrillation probabilities displayed a floor at approximately 10^{-5} when using the Gaussian distribution, which causes problems when the coincidence probability is higher than about 0.1.

Interestingly for fast clearing times our software calculated higher allowable voltages than Argon for both Gaussian and Log-normal current tolerance distributions. At this stage no attempt has been made to identify the source of this discrepancy, as the specifics of how Argon calculates allowable voltages are unknown.

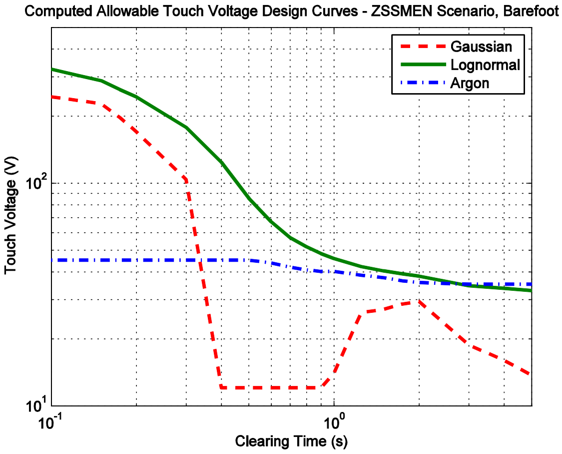

Figure 2: Derived Allowable Touch Voltage Limits for ZSSMEN Contact Scenario with no Footwear

Summary

A plot of the maximum applied voltages for a given fibrillation probability with a 0.3s clearing time, calculated using the various current tolerance distributions is shown in Figure 3. Note that the minimum allowable voltages were constrained to be higher than 0.1V.

It clearly demonstrates that for moderately high values the distributions all result in very similar voltage limits, whereas the voltage limits for low fibrillation probabilities are quite

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[1] EG-0 Scenario for Transmission Substation with secondary voltage $\geq$ 66kV for a backyard near a major substation with a primary side fault.

[2] Developed by the ENA in support of EG-0 and available from their website.

[3] EG-0 Scenario for Transmission Substation with secondary voltage < 66kV for a MEN contact near the zone substation backyard with a secondary side fault.

different. In particular the Gaussian distribution gives counterintuitive results indicating that approximately 1 in 10,000 members of the population would enter VF if exposed to <1V for 0.3s.

The implication of this is that the choice of distribution has relatively little impact on derived safety criteria if the target fibrillation probability is comparatively high, but may have a larger impact if low fibrillation probabilities are required.

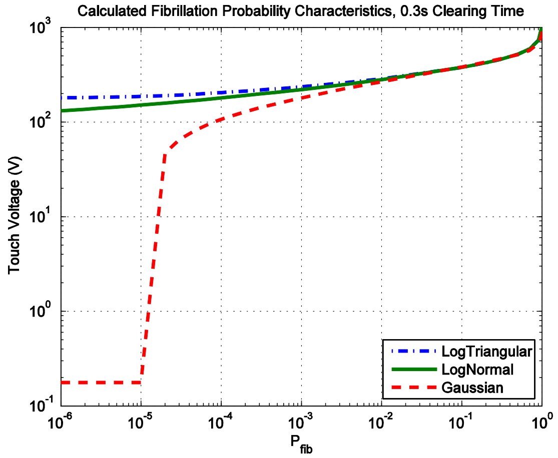

Figure 3: Maximum Touch Voltages for Specified Fibrillation Probability with Different Current Tolerance Distributions, 0.3s Clearing Time, no Footwear, 50Ωm Soil Resistivity

CONCLUSIONS

The quantified risk approach to safety criteria, such as laid out in EG-0, provides a solid basis for the derivation of allowable voltage criteria with some level of confidence in the associated level of risk.

We have demonstrated that the choice of statistical distribution and fitting method can have a sizeable impact on the calculated fibrillation probability, particularly at lower voltages. The differences arising from the various distributions are largely due to differences in their tails. The biggest differences occur at lower and higher voltages where these tails dominate, whereas the distributions tested gave similar results at intermediate voltages where the 'bulk' of the distribution was dominant. Distributions such as the Gaussian, with very long lower tails may exhibit a floor in the calculated fibrillation probability, and in the extreme may give counterintuitive results due to the lower tail extending to $-\infty$.

We believe the Gaussian distribution is an inappropriate distribution for this application; where the analysis is of low probability, high consequence events. The log-normal distribution seems to fit the data better, and be better supported by the literature [4] and intuition. Furthermore, we believe there is merit to investigating truncated distributions, as intuition says there are some electrical hazards that are small enough to never cause fibrillation, (or alternatively, high enough to cause fatality in all instances) and indeed traditional safety criteria are based on this assumption.

The main outcome of this work reinforces the quantified risk based approach to safety criteria. There is a level of risk associated with traditional safety criteria, it is just not explicitly quantified, and therefore is very difficult to manage effectively. The cost of overcoming those limitations is the more complicated calculation process required by the quantified risk approach, and agreement with the populace of an acceptable level of risk.

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