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Charging of Electric Vehicles at Domestic Dwellings Using Protective Multiple Earthing (PME) – Risk Analysis

PE01417/2012/1

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Date Authorised: **23 November 2012**

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Report Authorised for Issue by:	**Tim Roff**
Date of issue:	**23 November 2012**
Project Manager:	**Sue Hall**
Technical Reviewer(s):	**Ron Macbeth**
Editorial Reviewer:	**Dominic Pocock**
HSL Project Number:	**PE01417**

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EXECUTIVE SUMMARY

The use of electric vehicles is set to grow as economic and environmental concerns create a need to reduce reliance upon fossil fuel technologies. As with any new technology, there are risks and benefits associated with the deployment of electric vehicles. The Institution of Engineering & Technology (IET) have produced a code of practice, through IET Standards Ltd, which aims to ensure the safe design, installation and maintenance of fixed electrical equipment used for charging vehicles.

During the consultation process on the draft code of practice, concerns were raised about the connection of charging equipment to supplies in domestic dwellings using Protective Multiple Earthing (PME) and the possibility of electric shock under specific fault conditions on the electricity distribution network. As a result of this the published code of practice effectively prohibited the connection to PME supplies for outdoor vehicle charging. Whilst this avoids the risks associated with PME, it had the potential to give rise to other risks associated with the alternatives as well as being costly and inconvenient for consumers.

Objectives

To objectively determine the level of risk associated with using PME supplies at domestic dwellings in comparison with the risks associated with the alternatives (if data to do this exists), in order to assist evidence-based decision making as to whether to revise the code of practice to allow the use of PME in outdoor electric vehicle charging.

This was achieved by undertaking a formal risk review using event tree analysis together with a sensitivity assessment.

Main Findings

The increase in individual risk of a person being seriously injured or killed associated with permitting the use of PME supplies for charging electric vehicles outside of domestic dwellings was assessed to be within the range 1.1×10^{-6} to 7.8×10^{-9} per year, depending on the assumptions made. This increase in risk will not apply to those individuals who will not come into contact with an electric vehicle, and the number of these individuals will itself depend on the number of electric vehicles in use in society.

The upper increase of risk of 1.1×10^{-6} (just over one in a million) chance per year of injury or fatality is the order of magnitude of the ‘Tolerable’ region in risk tolerability criteria published by the Health and Safety Executive. However, given the large amount of uncertainty in the values used to calculate these risks then a large amount of conservatism has been built into these figures. It is therefore considered that the increase in risk seen from the use of PME supplies for charging electric vehicles at domestic dwellings is unlikely to increase the risk from the ‘Broadly Acceptable’ region, assuming that the base level of risk from electrical hazards to a normal household is already within this region. With this level of risk additional control measures to reduce risk should be implemented if it is reasonably practicable to do so, but a less onerous justification would be required than if the risks were to fall in the higher risk ‘Tolerable’ region.

This finding is also based upon a number of fixed assumptions about the nature of faults on electricity distribution networks, in particular the reliability of their detection and the speed of rectification.

Recommendations

IET Standards should share the findings of this work with those responsible for any proposed amendments to the Electric Vehicle charging code of practice and JPEL64 – Joint IET/BSI Technical Committee for Electrical Installations. The modelling assumptions made should be reviewed by key stakeholders to ensure that they reflect the operating experience of other stakeholders, in particular Distribution Network Operators (DNO) other than those providing data to the project team.

No judgements should be made about the deployment of PME supplies to other applications more broadly than the outdoor domestic electric vehicle charging based on this work. This is because the datasets used and the assumptions made model only the narrow circumstances in which electric vehicles would be charged at a domestic dwelling.

1 INTRODUCTION

1.1 DEPLOYMENT OF ELECTRIC VEHICLES IN GREAT BRITAIN

Electric vehicles have existed for specialist applications for a significant period in history. Electric vehicles as a viable alternative to domestic cars powered by internal combustion engines have been a more recent development. The number of electric vehicles is expected to increase to tens of thousands by 2015 and possibly increase to hundreds of thousands by 2020 [1]. The costs of electric vehicles are expected to drop and there are CO_2 targets for vehicle manufacturers to meet which are likely to incentivise the deployment of this technology.

It is recognised that the success of electric vehicle uptake will be dependent upon consumers having access to reliable recharging facilities. Whilst workplaces and on-street charging will form part of this infrastructure, it is recognised that recharging at home will be a key part of the solution. The Office for Low Emission Vehicles has stated that overnight recharging at home should become the preferred way that the vast majority of plug-in vehicle recharging occurs. Overnight domestic charging provides better environmental benefits as well as avoiding additional demand on electricity distribution networks during the day.

In order to facilitate safe domestic electric vehicle charging, the Institution of Engineering & Technology published a Code of Practice for Electric Vehicle Charging Equipment Installation in 2012 [2].

1.2 ELECTRICITY DISTRIBUTION NETWORKS IN GREAT BRITAIN

After generation and transmission at extra high voltage (up to 400kV), the voltage is reduced in stages to allow distribution, ultimately to individual consumers. Domestic, commercial and light industrial consumers are supplied at Low Voltage (LV), often referred to as 'mains electricity' by consumers.

The exact design of low voltage distribution networks varies, but a supply to individual domestic customers typically comprises:

- Secondary substations which reduce voltage to a nominal 230 volts (phase-earth) from another distribution voltage (e.g. 11kV). These can be installed within a compound at ground level or can take the form of pole mounted transformers.

- Protection equipment (e.g. fusegear) which protects the outgoing circuits from undesired events (e.g. short circuit faults).

- Mains – providing electrical power to a number (up to around 100 [3]) of consumers, these can take the form of either:

    - Underground cable supply

    - Overhead power line supply

- Branches – taking power from a main and distributing it to a smaller (tens of consumers) number of consumers.

- Services – taking supply from a main or branch to an individual consumer, for example a single domestic dwelling or a small block of flats. Individual consumers are provided with a service fuse which as well as providing some limited protection for consumer owned equipment, provides for the disconnection of severe faults on the consumer's installation that could otherwise operate protection on the main that could disconnect other customers.

Faults, for example short circuits, can occur on any part of a LV network, although the consequences for continuity of supply and hazards to consumers will depend on the exact nature of the fault and the location at which it occurs.

1.3 EARTHING & EQUIPOTENTIAL BONDING

The low voltage electricity network used to supply domestic homes in Great Britain is deliberately connected to earth at each secondary substation. This provides a number of practical, safety and economic advantages. However, this connection to earth means that during an electrical fault on a consumer's installation or an appliance, a person in contact with both the live metalwork and the general mass of earth may receive an electric shock. This shock could be fatal, depending on a range of factors, including duration of the shock, the voltage across the person and the impedance of the shock path. The person in contact with the live metalwork may be in contact with the earth directly or via another earthed item, for example a metal water pipe.

A number of measures are used to reduce the likelihood of electric shock occurring and to mitigate the consequences if it does. Two of these measures used to protect consumers in domestic houses are:

- Earthing – in which the metal enclosures of electrical equipment, such as a domestic kettle, are themselves connected to earth. This means that if a fault develops, causing the enclosure to become live, a large fault current will be drawn. This current will operate a fuse, circuit breaker or residual current device (RCD) to quickly disconnect the supply, therefore reducing the <u>duration</u> of the fault.

- Equipotential Bonding – in which the metal enclosures of electrical equipment are bonded (connected) together and to other metalwork which is itself in contact with earth, for example water, gas and central heating pipes. This means that during a fault that all metalwork will be at a similar potential, so that the <u>magnitude</u> of voltage between the faulty equipment and nearby metalwork will be significantly reduced.

Within domestic houses, both earthing and equipotential bonding are used to reduce the risk and consequences of electric shock. However, these measures do not completely eliminate risk, since it is possible to receive a shock during a fault even on a properly earthed piece of equipment. Equipotential bonding will also not provide protection to a person in good direct contact with earth (for example standing on a conductive concrete floor) whilst also in contact with the enclosure of the equipment under fault conditions. However, the use of earthing, equipotential bonding and other measures combined with the typical construction of floors and insulating floor coverings means that the risk of electric shock in a house with a properly designed and maintained electrical installation is very low.

In order for earthing arrangements to disconnect faults quickly, an effective connection to earth needs to be established and maintained. Within Great Britain there are three possible approaches taken and these are described below. The terminology for the systems are based upon a series of letters, which describe the connection to earth (terre in French) and whether the neutral conductor is combined or separate in the distribution network and consumer's installation.

1.3.1 TT Earthing

TT earthing relies upon the provision of an earth electrode at each individual consumer's premises. Typically a connection is made to one or more copper earth rods, earth plates or underground structural metalwork which is buried within the ground to achieve an impedance to earth which is low enough to allow protective devices to operate quickly. Modern standards also require the use of a residual current device[1] (RCD) on TT systems [4].

TT is typically more prevalent for older properties and those in rural areas with overhead supplies. It is no longer common for newly constructed domestic houses to be designed to use TT earthing.

TT systems typically have higher external earth fault loop impedances than the alternatives, as the electrode is dependent upon local soil conditions and moisture content etc. TT systems are vulnerable to deterioration as a result of corrosion or third party damage/disconnection.

TT systems are not vulnerable to some faults which can occur on the electricity network external to the house. For this reason TT systems are currently deliberately selected for some non-domestic premises, for example:

- Supply to caravans
- Marinas
- Petrol filling stations
- Horticultural establishments

In some cases TT is selected as there is a specific legal requirement not to use PME earthing (see below) and there is not a TN-S supply available (see below) and in others guidance advises against the use of PME.

1.3.2 TN-S Earthing

In a TN-S system, the neutral and earth conductors are kept separate both in the distribution network and consumers installation. The earth terminal at the consumer's property is provided by the Distribution Network Operator by means of connection to the metallic sheath of the supply cable. This sheath is connected to an earth electrode

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[1] An RCD is a device which measures the current delivered to a circuit and the current returned. Under normal conditions these values should be the same. When an earth fault is present, not all of the current returns via the neutral conductor and the RCD senses this and disconnects the supply. The use of an RCD rather than a device sensing total fault current provides protection in the event that the TT earth electrode has a higher impedance than needed to operate a conventional overcurrent device (circuit breaker or fuse).

at the substation. In practice due to loss of the outer protective layers this sheath is also in regular contact with earth along its length. TN-S is gradually being superseded by the PME system described below. Some TN-S cables are later converted to PME service.

1.3.3 TN-C-S (Protective Multiple Earthing)

TN-C-S earthing is also known as Protective Multiple Earthing (PME). The term PME will be used throughout the rest of this report for convenience. PME is a well-established system within the UK and elsewhere. This system has a combined neutral and earth conductor in the distribution network but a separate neutral and earth in the consumer's installation (hence TN-C-S).

The PME system has its neutral conductor deliberately earthed at the secondary substation in common with the other two systems. However, a connection to the neutral conductor is also used at a customer's premises to provide an earth terminal for the installation. In addition to these two connections, the neutral conductor is also periodically connected to earth electrodes along its length. PME can be deployed on both overhead lines and underground cables. There are economic advantages to using the neutral conductor for the secondary purpose as an earth conductor, including making cable jointing more straightforward. However, there are also potential safety advantages, because PME provides a very low impedance earth for individual consumers, this ensures that earth faults can be reliably and quickly disconnected.

In spite of these advantages, the PME system is vulnerable to two faults that do not cause the same problem in other systems. These are:

- An open-circuit (disconnection) of the neutral conductor in the supply cable or on the overhead power line. In these circumstances, there is no legitimate return path for current and this can result in the earth terminal in a consumer's property attaining a dangerous voltage, which in turn can raise the voltage of metal enclosures of electrical equipment to a similarly dangerous voltage. The open-circuit fault can be caused by corrosion or third party damage to the neutral.

- Reverse polarity on the network (where a phase conductor is mistakenly transposed with a neutral conductor). In these circumstances the neutral is raised to the phase conductor's voltage and due to the deliberate connection to the neutral, the consumers earthing terminal and equipment enclosures can be raised to a dangerous voltage. Polarity reversal occurs due to human error during network installation or maintenance activities, for example upon making connections to an overhead power line supply. Polarity reversal is not desirable on any type of supply to a consumer[2] but presents an immediate risk if it occurs upstream of the consumer's cut-out on a PME supply.

Equipotential bonding reduces the risk of electric shock during an open neutral/reverse polarity on the supply network to a PME supplied home, but does not eliminate it. The circumstances which normally exist within a domestic dwelling (dry, covered floors)

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[2] *Polarity reversal on any LV supply can lead to latent electrical hazards in that equipment may be 'live' when it appears to be switched off, because single pole switching will be incorrectly carried out in the neutral conductor. This creates a hazard under fault conditions, replacement of light bulbs in exposed fittings and for electrical work for which safe isolation practices (which would detect this fault) have not been followed. However, in the case of polarity reversal upstream of the consumer's cutout on a PME supply, a more immediate hazard is presented in that all metalwork will become live immediately and return paths via metal water/gas pipes may give rise to heating effects and fire risks.*

together with the use of equipotential bonding and the advantages of PME have been considered to reduce the risk of electric shock to an acceptable level, such that the most common form of earthing provision at new connections is PME. However, it is recognised that the use of electrical equipment supplied by PME may pose an additional risk when used outside of the equipotential zone, for example outdoors. Accordingly, a precautionary approach is taken and the use of PME supplies are either legally prohibited or discouraged in published guidance for the supply of all or some parts of specific non-domestic installations, such as:

- Marinas
- Caravan & camping sites
- Construction sites
- Outside broadcast vehicles

This precautionary approach has been practiced since the introduction of PME and is not known to be based on any formal risk analysis exercise.

1.4 USE OF ELECTRICITY OUTDOORS

The use of electricity outside of a dwelling can potentially result in an increase in risk for the following reasons:

- Use of equipment outdoors may provide a harsher environment in which electrical equipment degrades more rapidly or becomes damaged. In practice this is addressed by the specialised design of equipment for use outdoors, for example designing the product to prevent the ingress of water or to prevent foreseeable mechanical damage.

- Consumers indoors will often be standing on materials that provide insulating properties, unlike the ground outdoors. The equipotential zone provided indoors as a result of equipotential bonding will not be present outdoors, so during an earth fault, a consumer may be in good contact with the general mass of earth (or metalwork at earth potential) at the same time as the metal enclosure of faulty electrical equipment. Many consumer products for use outdoors are of Class II (double/reinforced insulation) construction to eliminate the risk associated with earth faults (though other electrical hazards will still exist). However there is no prohibition on the use of Class I (earthed) equipment outdoors.

- When the human body becomes wet, the skin impedance reduces significantly. This means that current flow through the body during an electric shock will be greater than if the skin is dry. This together with other factors, such as the duration of the shock will influence the severity and overall outcome.

It is important to note that there will be the potential for an increased risk of electric shock arising from the use of Class I equipment outdoors irrespective of the type of earthing system deployed. However in the case of PME supplies there is the additional possibility of electric shock as a result of faults on the external Distribution Network Operator (DNO) network – open-circuit and reverse polarity events. It is the risk of these additional events occurring that is the subject of this project.

1.5 TOLERABILITY OF RISK

Once an estimate of the level of risk posed by a particular hazard has been identified, it is then necessary to assess whether or not further measures should be taken to reduce the risk, or whether the risk is too high and should be considered unacceptable. HSE uses a method published in “Reducing Risks Protecting People” [5] (known as R2P2) to determine whether or not a risk is ‘unacceptable’, is ‘tolerable’ or ‘broadly acceptable’. This forms part of the “Tolerability of Risk” (TOR) framework illustrated in Figure 1.

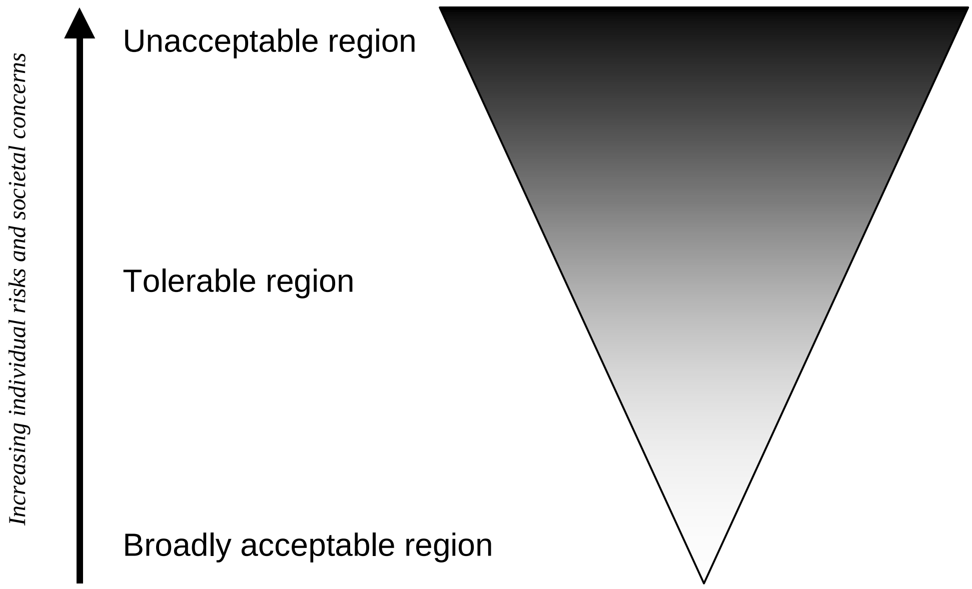


Figure 1 HSE Framework for the tolerability of risk [5]

The TOR triangle represents increasing levels of individual risk and societal concerns for a particular hazardous activity from the bottom of the triangle to the top. It includes three zones or regions, in which different approaches to evaluating risk and reaching decisions as to whether or not it is reasonably practicable to implement additional risk reduction measures are appropriate.

- Unacceptable region - the dark zone at the top represents this region. For practical purposes, a particular risk falling into this region is regarded as unacceptable, whatever the level of benefits associated with the activity, and would be ruled out unless the activity or practice can be modified to reduce the degree of risk so that it falls into one of the two regions below.

- Broadly Acceptable - the light zone at the bottom represents this region. The levels of risk characterising this region are comparable to those that people regard as insignificant or trivial in their daily lives, and are typical of the risk from activities that are inherently not very hazardous, or from hazardous activities that can be, and are readily controlled. Within this region, additional risk control measures must be implemented if it is reasonably practicable to do so, but detailed arguments would not usually be needed to support the decision.

- Tolerable - the zone between the unacceptable and broadly acceptable regions is the 'tolerable' region. Risks in this region are typical of the risks from activities that people are prepared to tolerate in order to secure certain benefits, such as employment, lower cost of production, personal convenience or the maintenance of general social infrastructure. Within this region, additional risk control measures must be implemented if it is reasonably practicable to do so, and the greater the level of risk (i.e. the further up the TOR triangle the risk is situated), the greater the level of detail is needed in arguments to support the decision.

The TOR framework can in principle be applied to all hazards. When determining reasonably practicable measures for any particular hazard, whether the option being considered is reasonably practicable or not depends in part on where the boundaries are set between the unacceptable, tolerable and broadly acceptable regions. HSE has established indicative numerical individual risk criteria (applicable to estimates of the total risk from an activity) for the boundaries between the regions. These criteria, and the assumptions underlying their derivation are given in R2P2 but, in summary, the boundary between the 'broadly acceptable' and 'tolerable' regions is taken to be one chance in a million per year of fatality or $1x10^{-6}$ per year. Therefore, risks equal to or lower than $1x10^{-6}$ per year will not normally require excessive additional risk reduction measures or detailed (e.g. cost-benefit) assessments to be made.

2 PROJECT SCOPE

2.1 BACKGROUND

IET Standards Ltd requested that the Health & Safety Laboratory (HSL) undertake this project to better understand the risks of electric shock associated with the charging of electric vehicles from a domestic electricity supply whilst the vehicle is located outdoors. Specifically, the project aimed to examine the level of risk associated with permitting outdoor charging from domestic dwellings that feature a PME (Protective Multiple Earthing) facility. It was also intended that the project model the comparative risk associated with alternatives to PME as it was possible that other risks would be created by installing alternative measures to avoid the use of the PME system at domestic dwellings. In practice the project team was unable to obtain data relating to the alternatives (TT earthing) so the analysis was limited to the increase in risk associated with PME for comparison with risk tolerability criteria.

In January 2012, IET Standards Ltd published a new code of practice for electric vehicle charging equipment installation, following a period of consultation with key stakeholders. This guidance provided advice to electrical installers who were installing dedicated electric vehicle charging equipment in domestic, commercial, industrial and on-street settings. Whilst many electric vehicles are supplied with a means of charging via a temporary connection to a domestic socket outlet, the guidance aims to ensure that, where possible, consumers provide dedicated fixed charging facilities for electric vehicle connection at their homes for safety reasons.

During the consultation, concerns were expressed by some stakeholders about the installation of fixed charging facilities at homes which feature an electrical installation using the TN-C-S earthing system, also known as Protective Multiple Earthing (PME). This means of earthing is described previously in section 1.3.3.

As the charging of an electric vehicle will often take place outdoors, and the vehicle is of Class I (earthed) construction, there exists a risk that if a network fault occurs which results in PME earth being raised to a dangerous voltage with respect to ‘true’ earth. In these circumstances, the body of the electric vehicle would also rise to a similar voltage and present a risk of electric shock to a person in contact with the vehicle body and:

- The general mass of earth (the actual risk of shock would depend on factors such as ground conditions and footwear etc.); OR

- Metalwork connected to another earthing system, e.g. street furniture, if this was accessible.

It should be noted that the operation of residual current devices (RCDs) and the manual/automatic disconnection of the vehicle from supply (other than by unplugging) will not remove the shock risk as earth connections are not currently switched and will therefore remain connected.

Many manufacturers of electrical consumer products for use outdoors use Class II (double/reinforced insulation) construction which eliminates the risk of electric shock under this and other fault conditions. It is relatively straightforward for the designers of commonly used outdoor electrical appliances (e.g. lawnmowers) to specify Class II construction. The project team were advised that it is not technically or economically feasible to provide Class II on-vehicle equipment due to the size of the vehicle’s electrical load when charging and the vehicle's construction. It is not within the scope of this project to evaluate the validity of this conclusion.

Given the concerns of those consulted and the current uncertainty about the level of risk posed by allowing the use of PME supplies for outdoor charging, the code of practice as published effectively prohibits this. Instead, installers are asked to select alternative arrangements from a suite of options. However, the technology currently available in the marketplace effectively restricts this to:

- TT earthing system (necessitating an earth electrode at consumers' premises) for the vehicle charging circuit alone;

- Conversion of the whole dwelling's installation to a TT earthing system (again necessitating an earth electrode).

Unless and until other technology becomes available, the guidance as written results in the following disadvantages:

- Additional risks may be introduced as a result of the TT earthing system not achieving acceptable impedance values or deteriorating as a result of future soil and groundwater conditions.

- There may be other electric shock scenarios created as a result of simultaneous contact between the TT earth and other equipment in the same or adjacent premises being connected to the PME system.

- There will be an economic cost associated with retrofitting earth electrodes at premises previously reliant upon PME. This may in turn discourage the fitting of dedicated fixed charging equipment at consumer's homes which could result in a greater use of temporary connections with the associated electrical and other (e.g. tripping) hazards.

2.2 SCOPE OF WORK

IET Standards Ltd therefore requested a quantitative evaluation of the increase in the level of risk associated with changing the code of practice to allow PME supplies to be used for outdoor domestic electric vehicle charging. This was to allow:

- Comparison of the resulting level of risk with risk tolerability criteria (e.g. that published in the HSE R2P2 guidance) to determine whether the risk is suitably small enough to be accepted without additional controls.

- Comparison of the results with the risk analysis exercise previously undertaken in-house.

- That in calculating the increase in risk, the trade-off between the additional risks of using PME (network faults resulting in vehicle becoming live) with the additional risks of avoidance measures reliant upon TT earthing (e.g. deterioration of earth etc.) was included if possible. In practice the project team were unable to determine whether there is in fact any increase in risk associated with TT earthing as the testing and maintenance of domestic earth electrodes is at the discretion of individual householders and there is not a known source of practical failure data.

- A sensitivity analysis was undertaken in order to better understand the effect of any assumptions made within the calculation of risk and provide a risk range depending on the assumptions taken.

2.3 OVERVIEW OF METHODOLOGY

The approach taken to determine the overall level of risk is shown in Figure 2.

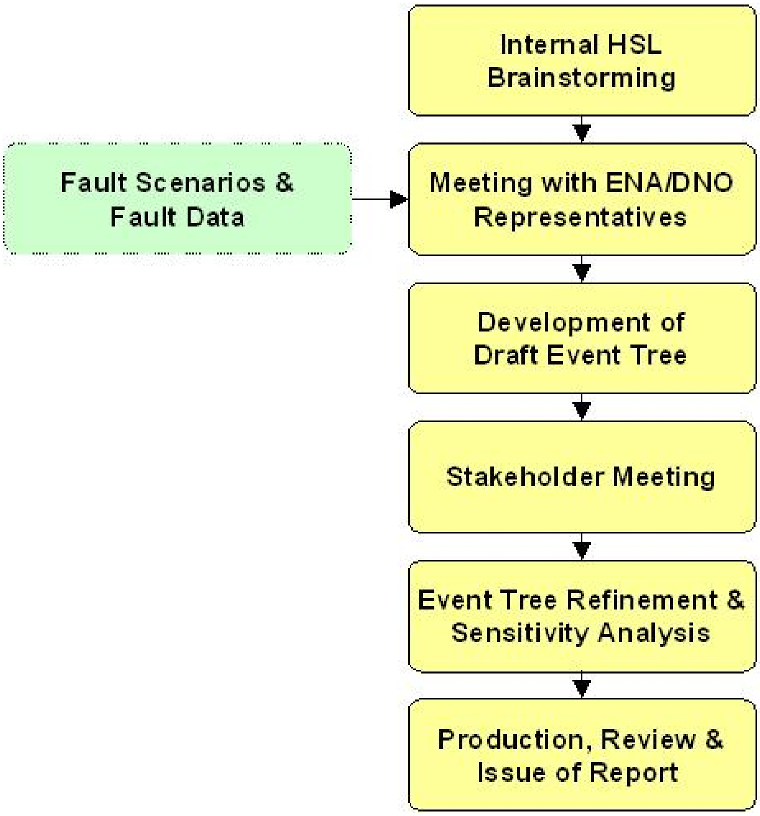


Figure 2 Project Methodology

Internal HSL Brainstorming – in this phase, members of the HSL team met internally to develop the initial fault scenarios which were used to construct the event trees. This drew upon the team's professional knowledge, the fault scenarios envisaged in the code of practice and the Energy Networks Association's (ENA) G12/3 publication [6] (which details network requirements for PME) and the consultation comments provided to the team by IET Standards Ltd. At this stage HSL staff developed the event trees qualitatively, without populating them with data. This ensured that the data needed in future phases could be identified.

Meeting with ENA/DNO Representatives – the HSL team met with representatives of the Energy Networks Association and colleagues from the power distribution sector with detailed knowledge of earthing systems and failure modes. At this meeting, draft event trees were discussed to verify that we had included all credible network faults in relation to PME.

Development of Draft Event Trees – the team drew together the qualitative and quantitative information gathered to develop event tree(s), populated with event data in order to understand the resulting provisional risk level.

Stakeholder Meeting – the HSL team met with IET Standards Ltd and the other stakeholders involved – The Society of Motor Manufacturers and Traders, Energy Networks Association and Energy UK. This enabled the team to present the draft event trees and to discuss whether the resulting analysis was comprehensive and whether the assumptions underpinning any elements were fair.

Event Tree Refinement and Sensitivity Analysis – the HSL team refined and finalised the event tree, and populated it with data gathered and refined throughout the project. The assumptions and uncertainties in the data were then subjected to sensitivity analysis to determine how the level of risk would change if the assumptions or data were changed.

Production, Review and Issue of Report – this report has been subjected to HSL's internal technical and editorial review to ensure quality prior to issue.

2.4 KEY LIMITATIONS

The following issues were excluded from the scope of the project work:

- Evaluation of the feasibility of risk-reduction measures within the distribution network, the consumer's installation or on-board the electric vehicle.

- Validation of, or commentary on, the conclusion that using Class II charging equipment is not technically or economically feasible for vehicle charging.

- Evaluation of the generic risks associated with the use of electricity outdoors or through consumer's installation electrical faults. Instead, we will consider the additional risks associated with the unique nature of PME supplies.

- Consideration of the use of PME supplies at commercial or industrial premises, given the diversity of building/parking configurations indoors and outside.

- Evaluation of the human factors issues that may increase risk as a result of consumers electing to use temporary supplies due to cost-aversion to TT fixed supplies.

- A cost-benefit analysis of the alternatives to PME, although this will be straightforward for the client to undertake, drawing on the risk data produced. It should be noted that a cost-benefit analysis is often indicated only if the risk level is higher than that indicated by the 'broadly acceptable' region.

3 APPROACH

3.1 OVERVIEW

In order to estimate the increased risk of receiving a potentially fatal electric shock from having an electric car plugged into a residential PME system, an event tree process was used. In this approach, the probability of exposure to an electrical fault is used as the starting point with “branches” then extending onwards with probabilities to individual questions being given along the way. The probabilities are then multiplied together to give an overall probability of death or serious injury.

It should be emphasised at this stage, that for this study, it is the **additional** risk posed by permitting the connection of the electric vehicle to a PME supply outdoors that is being measured. There is a residual, background risk for any householder in using electrical equipment, should there be a fault on the equipment or within the consumer’s fixed electrical installation. It is not possible to measure what this value of the residual risk would be, but it is possible to estimate the additional risk posed by permitting the electric vehicle to be connected to a PME supply and considering the unique risks associated with this system.

Once the additional level of risk has been obtained, it is then necessary to determine whether or not this is acceptable. General practice assumes that, if the risk of death to the individual falls below 1×10^{-6} chance per year, then it is broadly acceptable. Given that the risk within this study is a relative risk, not an absolute risk, then the values should fall significantly below the 1×10^{-6} chance per year value in order to be reasonably certain that the overall level of risk will not fall outside the broadly acceptable region (assuming that the background risk is below this level).

To fully understand this, if it is assumed that the additional risk from having an electric car connected to a PME supply is 1×10^{-8} per year, then it is not adding a significant amount of risk to the background level, whatever the background level may be. For example:

- If the background level was 1×10^{-7} per year then the total level of risk would now be 1.1×10^{-7} per year
- If the background level was 1×10^{-9} per year, the total level of risk would now be 1.1×10^{-8} per year

Both of these overall risks are still significantly below the 1×10^{-6} chance per year value. As the additional risk from having an electric car approaches the 1×10^{-6} chance per year value, then it becomes more likely that the total level of risk will fall outside the broadly acceptable region and into the tolerable region, where a more thorough assessment of the feasibility and practicability of additional control measures to reduce risk would be expected.

3.2 DETECTION & RECTIFICATION OF NETWORK FAULTS

The specialist advice available to the team from DNO representatives suggested that open-circuit neutral and reverse polarity events are likely to be readily detected even in circumstances where no injury or electric shock results. In particular when an open-circuit neutral event occurs, it is common for a range of distinctive power quality issues to present to consumers which are then reported to the DNO. For example, the fact that neutral current is returned via the DNO earth electrodes which are of higher impedance to the normal neutral return path could result in a significant reduction in voltage at consumer's installations. In addition as the neutral is no longer effectively earthed it becomes subject to displacement dependent on the unbalanced loads across the phases. This can cause the supply voltage to properties to increase and decrease over time depending on the distribution of loads. These effects cause distinctive symptoms such as flickering/dimming lighting and damage to sensitive consumer electronics, such as televisions.

DNO call centre operators receive training to recognise and respond quickly to reports from consumers which indicate the possibility of open-circuit neutral events.

It should be noted that the assumptions listed in Appendix A apply to all of the modelling work undertaken.

3.3 EVENT TREE DATA

The final event trees can be found in Appendices B, C and D. Various other branches were considered during the development of the tree but these were ultimately dismissed. The reasoning behind this decision is discussed below.

Initially the event tree was separated into day time and night time as it was considered that there may be differing levels of risk during the day and at night. In particular, there might be a greater likelihood that an open-circuit neutral fault on the electricity network would be detected during the day (when consumers would notice the power quality issues described above), or that the car is more likely to be plugged in at night.

In terms of the likelihood of detecting the fault during the day compared to at night, it was realised that there were a number of assumptions that would need to be fed into this. The following non-exhaustive observations illustrate this:

- If the onset of night time is considered to be when a person returns home from work, they may be more likely to detect an open-circuit neutral fault at this time as they will be more likely to be using a large number of electrical items.
- Later on at night, however, if they are asleep and therefore not directly using electrical appliances, they are not likely to notice any of the characteristic power quality issues if an open-circuit neutral event occurred.
- During the day, most consumers are likely to be at work and will not detect a relevant fault.
- Shift workers, on the other hand, may notice problems well into the night.
- Some people will go out in the evenings and may therefore not detect a fault at night.

There is no way to easily quantify any of the above events. Similarly for the varying probability of whether the car would be plugged in during the day or during the night, again a number of scenarios were recognised. For example:

- Some people may return from work, plug the car in and then unplug it before going to bed, preferring not to leave it plugged in overnight.

- Others may leave it plugged in the entire time that it is not being driven.
- Shift workers will plug the car in at different times from day workers.
- Patterns of behaviour at weekends will generally be different than during the week, although not for those that work weekends.

Again, it was felt that it was not possible to quantify all of these different scenarios.

Based on the above reasoning, it was decided to keep the event tree as simple as possible. There was already a high degree of uncertainty around some of the inputs and adding in further, difficult to quantify scenarios, would simply act to add further uncertainty.

Once the structure of the tree was decided, the data needed to populate it was determined. It was decided that, due to the general level of uncertainty at all stages of the event tree, three scenarios would be considered. These are the “Worst case” (most cautious/pessimistic), “Median case” and “Best case”. This gives an indication of the level of sensitivity of the results. The data is described in the following section.

3.4 DESCRIPTION OF THE DATA

3.4.1 Reports of damaged equipment

Open-circuit neutral events often lead to property damage, for example damage to consumer electronic equipment (like televisions), fire and overheating of electrical components. Some DNOs therefore monitor the occurrence of open-circuit neutral events along with details of actual damage claims and incidents with the potential to result in a report of damaged equipment. Data relating to reports of damaged equipment was obtained from two DNOs for the years 2005 to 2011 (Company A and Company B). This data provides an indication as to the number of open-circuit neutral faults that occurred each year, together with an estimate of the number of properties that could potentially have been affected. The data should be comprehensive as it contains the number of customers who could have been affected by the fault, regardless of whether or not they reported damaged equipment. It is expected that most, if not all open-circuit neutral faults will be picked up in this data and so it can be considered a reliable data source.

However, it is possible that in the case of open-circuit faults on individual services, that they will present as a loss of service and there will not be associated power quality issues and property damage. This is because in a house with plastic gas and water services there may not be any return path for the neutral current and therefore electrical equipment will fail to function at all. Such a situation would still pose a risk of electric shock until rectified, but within a home with insulating floor coverings and effective equipotential bonding it is possible that no adverse effects would be detected at all. This limitation is addressed using the National Fault and Interruption Reporting Scheme (NaFIRS) data described in later sections.

The data from the two DNOs is detailed in Table 1 and Table 2 below. The data lists the number of incidents and, the number of potential customers affected for companies A and B.

Table 1 Data for Company A

Year	*Number of incidents*	*Number of potential customers affected*
2005	75	866
2006	89	960
2007	120	1632
2008	106	1610
2009	112	1886
2010	107	1959
2011	105	1666
Total	714	10579
Average (Mean)	102	1511
Total 2005 to 2006	164	1826
Mean 2005 to 2006	82	913
Total 2007 to 2011	550	8753
Mean 2007 to 2011	110	1751

Table 2 Data for Company B

Year	*Number of incidents*	*Number of potential customers affected*
2005	49	14
2006	62	453
2007	53	463
2008	40	388
2009	37	494
2010	49	630
2011	56	786
Total	346	3228
Average (Mean)	49	461
Total excluding 2005	297	3214
Mean excluding 2005	50	536
Total 2007 to 2011	235	2761
Mean 2007 to 2011	47	552

For Company A, there appeared to be a step jump in the number of incidents between 2006 and 2007. This change is due to Company A moving to the same reporting method as Company B. Data for Company A prior to 2007 must therefore be discarded.

There seems to be a significant increase in the number of potential customers for Company B for 2010 and 2011. This may be due to increased copper theft. It should also be noted that there appears to be a lack of reporting for 2005 for this Company and so this year of data must be discarded. To be consistent with Company A, it is proposed that the five years, 2007 to 2011 are used, noting that this gives a potentially pessimistic view for Company B.

To get the likelihood of an open-circuit neutral event occurring, the average number of potential customers needs to be divided by the number of connected properties which is different for Company A and B. This gives likelihoods of 7.96 x 10^{-4} chance per year of a neutral fault for Company A and 3.68 x 10^{-4} chance per year of a neutral fault for Company B. This means that Company A sees, on average, twice as many faults per year per property as Company B. This may be due to the difference in the type of LV cable used by both companies. That of Company A is more vulnerable. Whilst Company A is not installing any new systems with this cable type, it is also not replacing existing cables and hence the number of these cables is not decreasing. It would not be expected, therefore, that a decrease in the number of neutral failures will be seen by Company A over the next few years.

Company A and Company B have similar LV networks, which means differences in failure rates are not due to differences in the networks.

Given the difference in rates between the two companies, the incident frequency from Company A will be used for a “Worst case” scenario, whilst that from Company B will be used for a “Best case”. The “Median case” will be taken as the midpoint between these two values i.e. 5.82 x 10^{-4} per year.

Additional data was obtained from a third DNO. This provided the number of neutral faults that occurred for the years 2009 to 2011 (plus data for the first months of 2012) but did not provide the potential number of customers affected. It was also based on reported equipment damage information but a lower limit was placed on the value of the equipment damage of £1000. If a customer’s report was for less than this amount, then the fault would not be recorded in this dataset. The number of neutral faults from this DNO (Company C) is shown in Table 3.

Table 3 Data for Company C

Year	***No. of neutral faults***
2009	71
2010	101
2011	118
2012	87

At first glance, it would appear that Company C sees a similar number of neutral faults as Company A. The number of customers supplied by Company C, however, is approximately 3.5 times greater than Company A. Assuming that the observed frequency of neutral failures should be approximately similar across the country; it would appear that there is potentially a large level of under-reporting for Company C. Without additional information to explain the differences in the proportion of neutral faults for the two companies, and without the potential number of customers affected for Company C, it is not possible to use the information obtained from Company C directly. The data could mean that there is a much lower level of under-reporting for companies A and B, which therefore provides additional support to the use of the data from these two companies.

3.4.2 NaFIRS data

The National Fault and Interruption Reporting Scheme (NaFIRS) database contains records of various different types of faults on differing parts of the distribution network. The insurance data already discussed may not fully reveal open-circuit neutral faults occurring on individual services; instead these may present as a loss of service and be quickly rectified without the nature of the fault being recorded. For the purposes of this study, the number of individual service open-circuit neutral faults also needed to be identified.

Open-circuit neutral faults are not recorded directly within the NaFIRS database but, instead, are encompassed within several broader categories. In order to try and extract these faults from the database, the first stage was to extract from 20 years of data only those incidents where the cause of the incident was due to:

- Corrosion
- Third Party Damage

As these were thought to be the only categories that would fit with an open-circuit neutral event, other causes were clearly not relevant (e.g. DNO switching activities).

The extraction process provided data for the years 1990 to 2010 in individual spreadsheets, one for each year. The data was then further interrogated to try and extract records that could only apply to single services and this was amalgamated to provide the total number of incidents and the number of consumers involved per year. The mean values across the 21 years were 4043 incidents affecting 25365 consumers. It was recognised that these figures still included faults that would not be classed as open-circuit neutrals. An assumption was therefore made that 50% of the faults could be assigned to this type of failure. This is likely to be an overestimation as open-circuit neutral faults are not considered to be particularly common, but without any additional information to apportion the number of failures, it was considered to be a cautious but sensible value to use.

One point worthy of note is that, according to the data - there are - on average, approximately 6 consumers affected by the open-circuit neutral faults. In some individual cases, this value was over 100 consumers. Given that the data has been extracted to only cover single service faults, this figure seems large. It is recognised that a single service fault may affect a block of flats, and therefore more than one consumer. A single service may also cover more than one property (due to ‘loop in’ wiring), in fact, possibly up to 4 or 6 individual houses. This does not, however, explain why over 100 consumers may be affected by one fault.

On further discussion with stakeholders it was found that, if a service fault occurs that causes a fuse or fuses to operate at the local distribution substation, then this would still be classed as a service fault, although it would affect supplies to all customers on the low voltage feeder. This could lead to up to 100 consumers being affected, although it is unlikely that any more than 100 would be affected. In terms of this project, this type of fault is unlikely to be associated with an open-circuit neutral failure (as these faults are not automatically cleared by conventional LV protection installed in substations) and so should not be included within the data. It is difficult, however, to determine exactly which data points should be excluded, as it is not clear which faults will be due to this mechanism. Including all the data points will lead to a conservative (safer) estimate of the number of open-circuit neutral service faults so it was decided to retain them all, noting that the actual values will be lower than those quoted.

The NaFIRS database covers the whole of the UK. In order to generate an incident frequency for the number of potential customers affected by open-circuit neutral faults that occur at the individual service level, it is necessary to divide through by the number of residential properties that use PME. The number of residential properties for Great Britain was obtained from the National Population Database (NPD) [7] and is approximately 26.7 million. This does not cover Northern Ireland, or the Isle of Man however. Estimates of the population for these two areas respectively were obtained from the Northern Ireland Statistics and Research Agency (NISRA) and the World Bank and were given as 1.8 million for Northern Ireland [8] and 83000 for the Isle of Man [9]. The population of Great Britain, from the NPD, is approximately 62.5 million. In order to calculate the number of residential properties in Northern Ireland and the Isle of Man, the ratio of residential properties to the population was calculated for Great Britain (26.7 million/ 62.5 million) and this was then multiplied through by the total population for the two areas of interest (1.88 million). This gave an approximate number of residential properties for the Isle of Man and Northern Ireland as 800000. The total residential population for the UK was therefore calculated as 26.7 + 0.8 million = 27.5 million. Approximately 85% of residential properties are believed to be connected to a PME system, so the value of 27.5 million was multiplied by 0.85 to derive the number of residential properties that are connected to PME (23.3 million). This then allowed the likelihood of a service level open-circuit neutral fault to be calculated by dividing the average number of consumers affected per year (25365) by the number of residential properties connected to PME (23.3 million) and multiplying by 0.5, assuming 50% of the faults are due to open-circuit neutral failures, giving a value of 5.4×10^{-4} chance per year of a service level open-circuit neutral failure. Table 6 illustrates how this likelihood is used within the event trees.

3.4.3 EID data

The Electrical Incidents Database (EID) is an HSE database which explicitly records open-circuit neutral failures (as well as other incidents) throughout Great Britain. This database was interrogated and it was found that, in 2011, there were 271 open-circuit neutral failures nationwide. From Company A and Company B there were 161 such failures in 2011. Given that the data from the two companies should be included in the EID data, it would imply that there were 110 such failures for the rest of the country. Company A and Company B supply approximately 15% of properties nationwide (obtained from the National Population Database). It would therefore be expected, assuming that the number of open-circuit neutral faults is approximately similar across the country, that there would be significantly more than 110 faults reported for the rest of Great Britain. This therefore implies that there is a significant level of under-reporting in the EID database and the data cannot be used directly.

The EID data additionally provides information on the number of reverse polarity incidents that occur each year. These will also cause a potential risk to the customer so it is necessary to obtain a failure rate for such incidents. Given the previous discussion, it was decided that the EID data on reverse polarity faults could not be used directly, due to the level of under-reporting in the database. The ratio of reverse polarity to open-circuit neutral faults could be obtained, however, assuming the same level of under-reporting for each type of fault. An average ratio across the years 2001 to 2011 was calculated to be 3:2 open circuit neutrals to reverse polarity incidents. To calculate an incident frequency for reverse polarity faults, this ratio was applied to the total frequency of open-circuit neutral faults, obtained from summing the frequencies obtained from the NaFIRS data and either Company A or Company B. From discussions with industry, it is generally considered that the frequency of reverse polarity incidents is likely to be considerably less than that for open circuit neutrals. The calculated ratio therefore appears to lead to a relatively high level of incidence for reverse polarity. In the absence of more substantive data, however, it was deemed that this was the best course of action to take. It is important to note however that:

- Reverse polarity affecting an entire main is not a very credible event.
- Reverse polarity on a cable supply is not particularly credible, particularly on 'Waveform' cable which is designed to allow straightforward like-for-like connection between mains, branches and services.
- Reverse polarity downstream of the service cut-out (e.g. at the meter) will not result in metalwork becoming live (though it does have other safety implications as previously described).

It is likely, therefore, that the approach taken will lead to a conservative estimate of the number of reverse polarity incidents each year.

The reverse polarity data is used in conjunction with the likelihood of an open-circuit neutral fault and the exposure time, to generate an overall probability of exposure to a fault that could potentially cause injury or death to a consumer. Given that the estimate of the likelihood of a reverse polarity fault is likely to be conservative, then the overall probability of exposure is also likely to be conservative.

3.5 OTHER VALUES FROM THE EVENT TREE

3.5.1 Exposure

In addition to calculating the probability that either an open-circuit neutral or reverse polarity fault could occur, an estimate of the number of hours that a person would be exposed to the fault was also required. From discussions with experts, a figure of 6 hours was decided upon for both types of faults. This assumes that the DNO is able to respond to a fault within two hours of an initial call, and able to fix it within a further 4 hours. It was assumed that a person would call the DNO as soon as they detected the fault (which would be readily detected due to the characteristic power quality issues) and that the training given to telephone centre call staff enabled them to recognise the potential seriousness of such faults.

It was also felt that those open-circuit neutral faults on individual services which might present as loss of service would be similarly quickly rectified given the priority the DNOs give to loss of service events at consumers' premises.

In order to calculate the total time a person could potentially be exposed to a fault over a year, the 6 hours was divided by the number of hours in a year (8760) and was then multiplied by the overall probability of a fault occurring. This gives the overall annual probability of exposure to a relevant fault.

3.5.2 Is the car plugged in?

An estimate was required as to what proportion of the day an electric car would be plugged in for. As there is no data for this, it was assumed that, in the “Best case” scenario, the car would be plugged in for 8 hours every day, given that it currently takes around 8 hours to charge the car. This is equivalent to a third of every day, which, after rounding, was taken to be 30%. In the “Worst case” it was assumed that a person was out of the house for 9 hours a day, five days a week. The car was plugged in for the remainder of the time. This gave a probability of, after rounding, 70% that the car was plugged in. The “Median case” was taken as the midpoint between these two values and hence a value of 50% was chosen.

After further discussion, it was recognised that some proposed initiatives will encourage users to plug the car in overnight. There are likely to be tariffs that encourage overnight charging and there are also some innovative approaches being considered whereby electric vehicle batteries might be used as a distributed storage medium, permanently connected to the network when not in motion and able to store and return power to the network. Regulatory initiatives may also be put in place to encourage owners to only plug it in at night. This may lead to the “Best case” scenario, whereby the car is plugged in overnight for 8 hours at a time, or it may lead to the “Worst case” whereby the car is plugged in all the time when it is not in motion.

It is also recommended by manufacturers that the car is plugged in overnight in winter in order that the battery is warm for starting in the morning. This could be interpreted as being similar to the “Best case” scenario where the car is plugged in for 8 hours a day on average. Alternatively, if a user is likely to plug the car in as soon as they get home, then it will approximate to the “Worst case” scenario.

On the other hand, evidence from existing users is that they are either only “topping up” the battery, i.e. charging for 2 or 3 hours at a time), or that they are only charging it once every 3 days or so. This would imply that even the “Best case” scenario is being overly pessimistic.

The conclusions drawn from these conflicting sources of information were that the three values chosen for the scenarios appear reasonable.

3.5.3 Someone touches the car

An estimate was required of the probability that, assuming the car is plugged in, a person touches the car, either in passing or as they try to enter it. There was no data available for this so expert judgement was used. In the “Worst case” it was assumed that there was a 100% probability that someone touches the car, whilst it is plugged in and whilst there is a relevant fault on the network. This would be equivalent to considering someone leaving to go to work in the morning after having left the car plugged in overnight, with a relevant fault on the network. In the “Best case”, a value of 25% was assumed as it was recognised that there is always a chance that someone could pass the car and touch it, whether this is the owner, another member of the household, or a visitor (including postmen, delivery people etc.). A value of 50% was chosen for the “Median case” as it lies between the other two values.

3.5.4 Person receives a large enough shock to cause serious injury or death

The severity and consequences of electric shock that a person would receive from the car will be dependent on a number of factors. These include the skin impedance of the individual (dependent upon weather conditions), what footwear (if any) they are wearing, how much of their body touches the car, which part of their body touches the car, whether they are thrown away from the vehicle by the shock or instead are held to it by muscular contractions and the overall duration of the shock.

The effects of current flow on the human body and the risk of death associated with different electric shock scenarios are well understood and documented in standards [10]. This data is used within electrical design work, for example to determine maximum disconnection times for electrical equipment under fault conditions.

Unfortunately, in the case being modelled there are considerable uncertainties about key parameters that would allow an accurate assessment of risk, for example the following parameters might vary significantly in the event of an open-circuit neutral event:

- The touch voltage present upon the car in relation to 'true' earth.
- The duration of any shock.
- The exact shock path (although hand to foot is the most likely).
- The skin impedance (related to environmental conditions such as precipitation).
- Impedance of footwear and surface conductivity.

There is some anecdotal evidence from the electrical industry to show that many electricians have received electric shocks during the course of their work without sustaining any long-term injury, although it is well known that fatalities do occur as a result of electrical contractors receiving an electric shock.

Given the uncertainties above, it was decided in the "Worst case" scenario that there would be a 100% probability of receiving a large enough shock to cause death or serious injury if any electric shock occurred. This value is considered to be very conservative (i.e. pessimistic) but, in the absence of data, had to be considered a possibility. In the "Best case", the probability would be 10% and, in the "Median case", a value of 30% was chosen. It was considered by a panel of experts that even the 30% value may be on the conservative side, although it is impossible to know for certain how many electric shocks without serious injury or death occur each year.

In order to try and derive an estimate from data of the likelihood of a person receiving a shock large enough to cause injury or death, the EID database was investigated as this contains the number of fatalities, injuries and near misses by cause each year. A calculation could then be performed relating the number of fatalities and injuries to the number of near misses. It has already been stated that this database appears to be subject to under-reporting but it may be surmised that the under-reporting may be consistent for all types of faults and possibly for all types of injury/near miss etc. Indeed, it may be considered more probable that near misses are likely to suffer more under-reporting than either fatalities or injuries, leading to any values calculated in this way being conservative as many of the near misses may not have been recorded.

The calculation was performed across average values calculated over the years 2000 to 2011, and for open-circuit neutral faults, reverse polarity faults, and the two fault types combined. The average number of reported fatalities, injuries and near misses is reported in Table 4.

Table 4 Summary of the fault data from the EID database

Consequence	***Open-circuit neutral***	***Reverse polarity***	***Total***
Fatality	0	0	0
Injury	15	3	18
Near miss	94	71	165

The percentage of injuries to near misses is recorded in Table 5 (noting that there were no fatalities recorded).

Table 5 Percentage of injuries to near misses

Fault cause	***Percentage of injuries to near misses***
Open-circuit neutral	16.0
Reverse polarity	4.2
Total	10.9

The overall indication from Table 5 is that a figure of 11% for the likelihood of injury or fatality from an electric shock would not be unreasonable. This, however, is dependent on the definition of near miss. This includes events that may or may not have led to a person receiving an electric shock. In order to provide an estimate of the likelihood of a person receiving a shock large enough to cause serious injury or death, it is necessary to use data that is purely for people receiving an electric shock. As the near miss data includes incidents where no shock was incurred, it is likely that any calculation will lead to an underestimate of the required value. On the other hand, the injury data includes minor as well as serious injuries. It may be that there are significantly more minor injuries than serious injuries so the use of this data may lead to an overestimate of the actual value. It is possible that the combination of the underestimation from the near miss data and the overestimation from the injury data may cancel each other out, leading to a reasonable estimate of the likelihood of fatality or serious injury. It is not possible, however, to state this with any certainty and hence, whilst the data is interesting, it may not be used directly. It does, however, lend support to the values proposed in the event trees and leads to the premise that the “Worst case” value of 100% is likely to be extremely conservative. A further consideration is that the above tables record the harm caused by these events in circumstances in which the use of Class I equipment connected to a PME supply outdoors is rare, which may lead to an underestimate of the risk of harm if outdoor electric vehicle charging were permitted.

3.6 USE OF DATA IN EVENT TREES

The data from the following sources were used:

- Insurance data from the DNOs
- NaFIRS data – to provide better coverage of service level faults
- EID data – to provide a ratio with which to uprate the above two sources of data to include reverse polarity events.

In order to calculate an overall probability of exposure to an open-circuit neutral or reverse polarity fault, the likelihood of an open-circuit neutral fault occurring on a main was added to the likelihood of an open-circuit neutral fault occurring on an individual service and the likelihood of a reverse polarity fault. The total was then multiplied by the exposure time (which was 6/8760). The values used in the calculations are shown in Table 6.

Table 6 Summary of the likelihoods used to derive the probability of exposure to an open-circuit neutral or reverse polarity fault

Fault type	***Worst Case***	***Median Case***	***Best Case***
Open-circuit neutral on the main	8.0×10^{-4}	5.8×10^{-4}	3.7×10^{-4}
Open-circuit neutral on the individual service	5.4×10^{-4}	5.4×10^{-4}	5.4×10^{-4}
Reverse polarity	8.9×10^{-4}	7.5×10^{-4}	6.1×10^{-4}
Total	2.2×10^{-3}	1.9×10^{-3}	1.5×10^{-3}
Probability of exposure	1.5×10^{-6}	1.3×10^{-6}	1.0×10^{-6}

4 RESULTS

A summary of all the probabilities discussed in Sections 3.4 and 3.5 is contained in Table 7, together with the final results, which are obtained by multiplying all the probabilities in each scenario together. It should be noted that the final probability is the additional risk posed to an individual by owning an electric vehicle and connecting it to an outdoor PME supply, not the absolute risk of death or serious injury from an electric shock by any cause.

Table 7 Summary of the likelihoods and probabilities used in the event trees

Branch of the event tree	***Worst Case***	***Median Case***	***Best Case***
Likelihood of exposure (chance per year)	1.5×10^{-6}	1.3×10^{-6}	1.0×10^{-6}
Probability that the car is plugged in?	0.7	0.5	0.3
Probability that someone touches the car	1	0.5	0.25
Probability that a person receives a large enough shock to cause death or serious injury	1	0.3	0.1
Final additional risk of death or serious injury (chance per year)	1.1×10^{-6}	9.6×10^{-8}	7.8×10^{-9}

From Table 7 it can be seen that, in the “Worst case” scenario, the value of the additional risk of death or serious injury posed by having an electric car plugged into the PME system, relative to the residual background risk, is of the order of 1×10^{-6} per year. Given the uncertainty in the inputs used to derive this value then cautious values have been deliberately used in each branch of the event tree, some of which may be deemed unrealistic. This suggests that the actual increase in risk would be much less than the calculated value. It should also be noted that the values in Table 7 represent the risk of serious injury or death. The 1×10^{-6} chance per year in the tolerability of risk criteria refers to a risk of fatality. In all cases, the risk of death is likely to be lower than the figures given in Table 7, making it less likely that the addition of the electric car is adding significantly to the overall level of risk. Even if this calculated value were considered to be correct then at worst the risks would be within the ‘Tolerable’ region, where any reasonably practicable risk reduction measures would need to be implemented. The risks generated would not come close to being ‘Intolerable’.

The “Median case” has a relative additional level of risk of approximately 1×10^{-7} per year. This means that it is unlikely that the addition of an electric car will take the overall level of risk outside the broadly acceptable region. The calculated risk value for the “Best case” is 7.8×10^{-9} which may be considered negligible, at least in terms of the additional risk being added by having an electric car plugged into the PME system.

In order to fully understand the final figures, the “Median case” value of 1×10^{-7} per year equates to approximately 6 additional fatalities/serious injuries per year, assuming that every person owns an electric car. If 10% of the population owns an electric car, this equates to approximately one additional death/serious injury every 2 years, due to owning and running an electric car.

There is a large level of uncertainty in the values used within the event trees for all scenarios. Even in the “Best case” scenario, however, the probabilities that have been combined to make up the overall probability of being exposed to a relevant fault during the year may be considered conservative as the number of faults on individual services is likely to be significantly lower than those estimated from the data. This means that, in the "Worst case" scenario where cautious values have been chosen along all branches of the event tree, the risk value calculated is likely to be significantly higher than reality. The fact that the calculated increase in risk only marginally exceeds the 1×10^{-6} chance per year value detailed in the risk tolerability criteria suggests that the real value for the additional risk posed by having an electric car plugged into a PME system may not increase the overall level of risk by a margin large enough to move it into the tolerable region (assuming that the background level is in the broadly acceptable region), especially when it is considered that this value also contains the risk of serious injury as well as death.

5 DISCUSSION & CONCLUSIONS

The resulting increased level of risk associated with permitting connection of electric vehicles to PME supplies seems to exist within the ‘broadly acceptable’ region of risk tolerability. The calculated increase in risk for the ‘Worst case’ scenario is of the order of magnitude to be on the threshold between the ‘broadly acceptable’ and ‘tolerable’ regions of risk tolerability. However, the assumptions made and the uncertainty in the available data has led to very cautious estimates being made for the inputs to the ‘Worst case’ scenario thereby leading to a cautious estimation of the increase in risk.

This conclusion is based upon the assumptions listed within the report and in particular those detailed in Appendix A.

6 RECOMMENDATIONS

IET Standards should share the findings of this work with those responsible for any proposed amendments to the Electric Vehicle charging code of practice. The modelling assumptions made should be reviewed by key stakeholders to ensure that they reflect the operating experience of other stakeholders, in particular Distribution Network Operators other than those providing data to the project team.

7 APPENDIX A – ASSUMPTIONS

- An open circuit neutral on a PME system supplying a domestic dwelling will always be detected as a result of the associated power quality issues being reported by consumers. We are therefore assuming that there are no latent (undetected) open circuit neutrals within the external DNO network.

- The DNO call centre operators have received training in, and will always recognise an open-circuit neutral situation (due to the characteristic power quality issues) and prioritise an emergency response.

- DNOs all have the capacity and capability to provide a 24 hour response to open-circuit neutral reports.

- Taking into account response times (assumed 4 hours) and 2 hours to identify the location of the fault and isolate the main (thus removing the hazard) we will assume that an open-circuit neutral exists for an average of 6 hours.

- The multiple earths installed on the PME system will not be effective in reducing the touch voltage on the electric vehicle to 'safe' values during an open-circuit neutral fault. This is a cautious/pessimistic assumption.

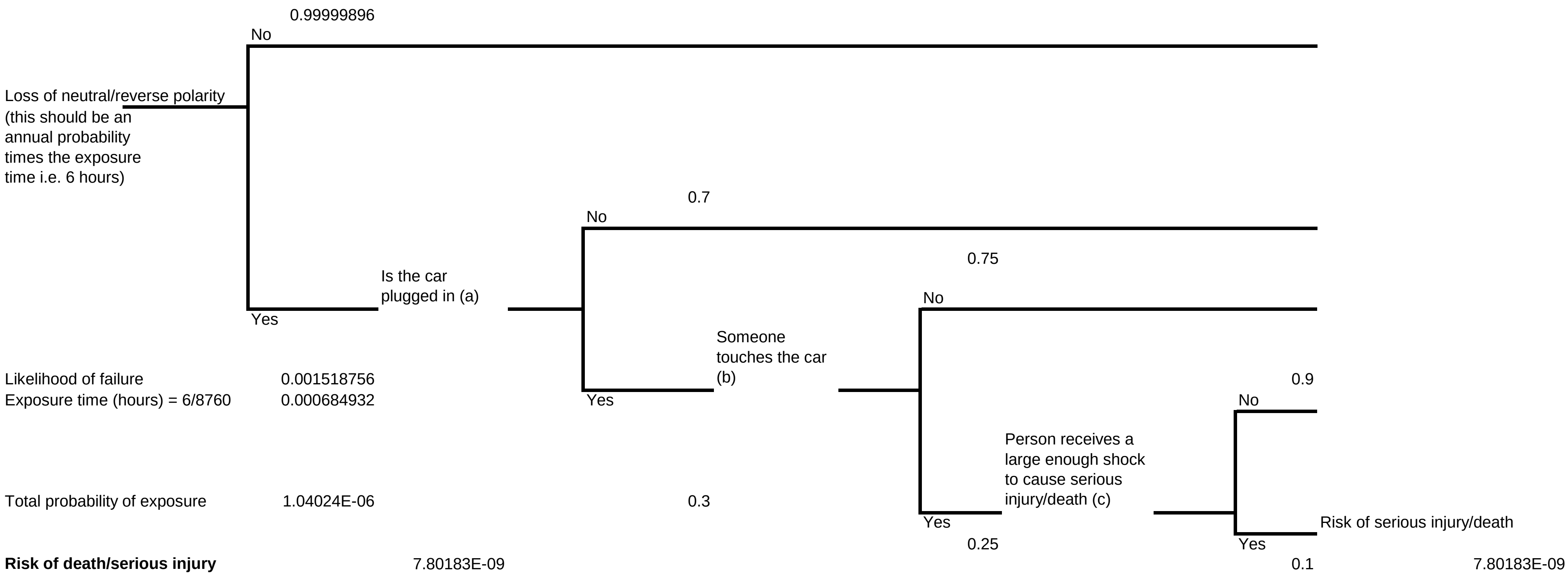
- During normal and fault conditions (e.g. heavy L-N fault) on the DNO PME network (with the exception of open-circuit neutrals) there will not be a significant voltage difference between the PME earth and local/true earth. This difference will amount to a few volts and will not create a risk of serious/fatal injury in relation to an electric vehicle connected to the PME earth facility.

- The vehicle on charge will be treated as a large metal structure that is effectively connected to the PME earth facility. This is a cautious/pessimistic assumption and discounts the possibility that vehicle coatings/lacquers provide any degree of insulation.

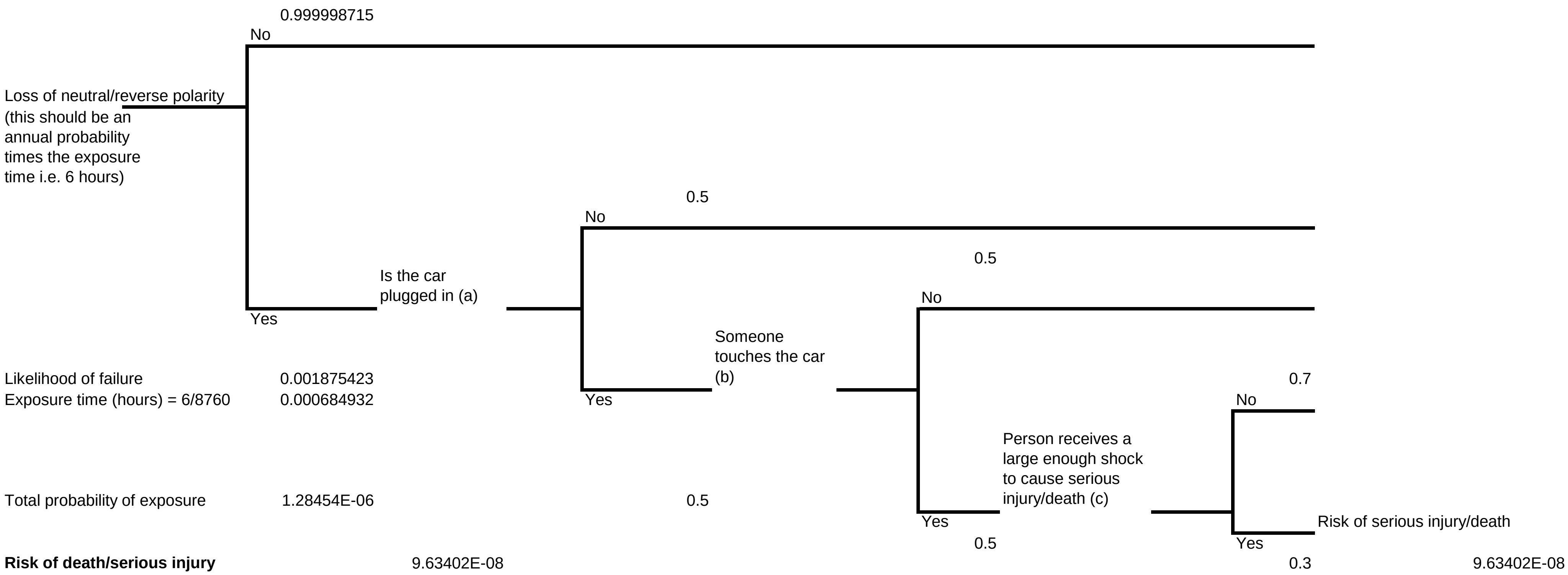
- The failure of one or more of the multiple earths, or the failure to ensure that neutral links are retained in link boxes does not give rise to risk of shock at the vehicle unless an open-circuit neutral occurs at the same time.

- In modelling the connection of the vehicle to the PME earth facility, we will assume that the principal shock path would be hand-foot between the vehicle and 'true' earth. We will assume that simultaneous access to other earthing systems (e.g. TT installation on street furniture) would be restricted by future requirements in the code of practice if connection to PME were permitted.

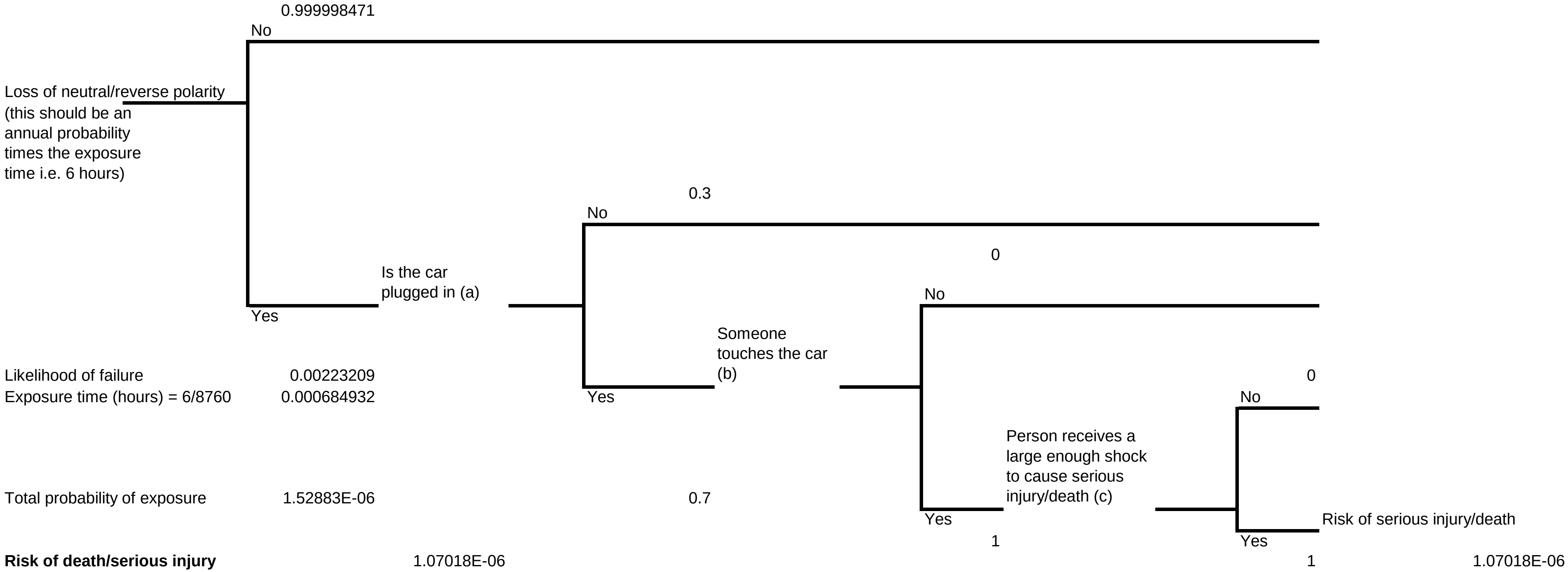
8 APPENDIX B – “BEST CASE” EVENT TREE



9 APPENDIX C – "MEDIAN CASE" EVENT TREE



10 APPENDIX D – "WORST CASE" EVENT TREE



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