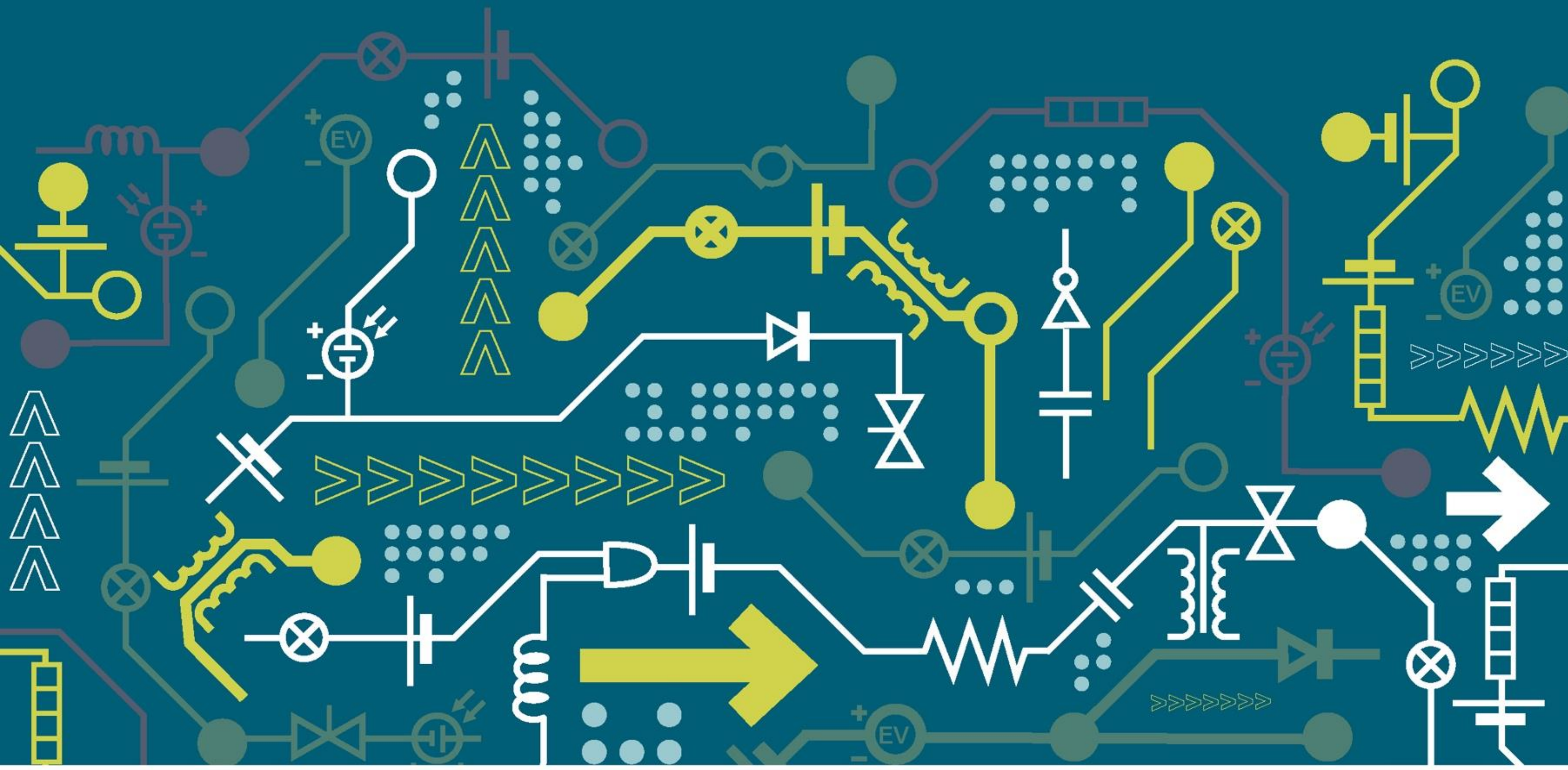
WPD INNOVATION

LV Sensitive Earth Fault Project

CLOSEDOWN REPORT

March 2020



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Version Control

Issue	Date
1	19.02.2020

Publication Control

Name	Role
Faithful Chanda	Author
Paul Jewell	Reviewer
Jon Berry	Approver

Contact Details

Email

wpdinnovation@westernpower.co.uk

Postal

Innovation Team
Western Power Distribution
Pegasus Business Park
Herald Way
Castle Donington
Derbyshire
DE74 2TU

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Executive Summary

The project, Low Voltage (LV) Sensitive Earth Fault Protection, was designed to be carried out in two stages, Stages 1 and 2. In Stage 1 of the project Western Power Distribution (WPD) was exploring the potential of being able to install Sensitive Earth Fault Protection on LV feeders as a temporary retrofit before the commencement of any live working. This protection would act to help prevent severe injury or death from inadvertent human contact with a live phase conductor during work on an LV feeder.

Stage 2 was to establish the functional requirements and to develop a proof of concept for an item of wearable technology capable of detecting current flow in the body of an operator working live on the LV network.

Stage 1 of the project was aimed at exploring whether:

- A good quality earth connection can be readily made in LV substations, suitable for carrying current from a direct short to earth in the substation, for sufficient time for the local fuse to rupture; and
- The risk of fitting the additional protection equipment is lower than the existing risk of live working.

Stage 2 of the project was designed to:

- Determine the conditions that it is necessary for any sensor to be able to detect and those that it should be immune from;
- Develop a functional specification for the sensors in order to determine the required sensitivity and immunity of the sensors to detect current flow through the body of the wearer and reject the effects of external magnetic fields.

The LV Sensitive Earth fault Protection Project was managed and delivered by EA Technology. It was funded by WPD's Network Innovation Allowance (NIA). The driver for the project was the need for WPD to gain better insight into potential methods to make suitable connections to the LV fuseboard for a 'fault thrower' type device.

The challenge of the project was to develop a desktop model capable of trials in a representative environment, on one or more LV feeders and being able to apply existing technologies, combined in a novel manner, to deliver increased levels of safety of "live line" workers. The success of the project was incumbent upon developing a prototype device or system which can readily be applied to the LV network to further improve the safety of live LV working and also to establish that any system which may be developed whilst able to detect contact does not improve the safety of live LV working either by virtue of its application making the overall task more hazardous or being unable to prevent false positives from the detection system leading to unnecessary additional supply interruptions.

The total project cost was £166,835 and was intended to be completed in 15months. Stage 2 of the project was not completed because a decision was taken to terminate the project. However, EA Technology went on to do the preliminary work on Stage 2 and results of that analysis are described in this report.

1 Project Background

Although safe methods of working on energized LV feeders have been developed and are common practice across all Great Britain Distribution Network Operators (DNOs), they cannot prevent accidental contact between workers and live conductors. Such accidents result in injury and can result in death.

The protection typically applied to the LV distribution network, in the form of LV feeder fuses, provides protection against large currents due to short circuits. The fuses avoid rapid heating and physical disruption of network components. This protection therefore can prevent physical injury of people near network components in the event of a network fault. However this protection is not designed to, and is not able to, respond to the low levels of current caused by accidental human contact, which can deliver a fatal electric shock.

WPD sought to explore to install Sensitive Earth Fault Protection on LV feeders as a temporary retrofit before the commencement of any live working. This protection would act to help prevent severe injury or death from inadvertent human contact with a live phase conductor during work on an LV feeder. It is preferable for such a protective device that it can be retrofitted to a feeder before work commences and can be removed after the work is completed by staff who are authorised to carry out the work.

The protection device that is required must therefore detect that contact has occurred and remove the supply before severe injury or death occurs. Survival from electric shock is dependent on the magnitude and duration of current flow. Therefore, there might be a useful trade-off between the required sensitivity of detection (and hence false negatives) and the required speed of action of a device to remove supply.

It is preferable for the device(s) to be easily fitted and removed in a relatively short time so as not to significantly increase the time typically required to carry out work on an LV feeder.
It is preferable for the fitting and removal of the device to not require any supply interruption.

2 Scope and Objectives

This project aimed to develop and prove the efficacy of methods which may be readily applied to the existing system to remove the supply in the event of a dangerous inadvertent contact with a live conductor when live work is being undertaken on the LV distribution system. A previous, WPD internally funded project considered the potential application of existing, fast acting LV switching devices to cause an LV feeder to be shorted to earth, hence rupturing the LV fuse and removing the electrical supply from the feeder before the flow of electric current could cause a fatality. It established that a good quality earth connection can readily be made in LV substations, suitable for carrying current from a direct short to earth in the substation and causing the local protection to operate within sufficient time. It also established that the risk of fitting additional protection equipment is lower than the existing risk of live working. That initial project provides comfort that a method to detect accidental contact could be practically achieved, and that it should be possible to implement appropriate fast-acting protection. This project sought to determine a method which can detect the inadvertent contact and take fast action to remove the supplies and make the situation safe.

The aims of Stage 1 of the project were to:
To produce and demonstrate one or more prototype devices which can:

- Detect contact between a human and a live phase conductor of an LV feeder; and
- Cause mains supply to be removed from the feeder before serious injury or death occurs.

Objective	Status
A workstream to test alternative methods to detect contact between a human and a live phase conductor, select the preferred option then produce and test a prototype detection device	Completed
A workstream to define and test a retrofit device which can act on receipt of a signal to cause mains supply to be quickly removed from an LV feeder	Completed
A workstream to integrate the prototype supply interruption and detection devices and then test them in the field.	Completed

Table 1: Objectives

3 Success Criteria

Success Criteria	Status
A prototype device or system which can readily be applied to the LV network has been successfully developed which can further improve the safety of live LV working.	Completed
It is established that any system which may be developed whilst able to detect contact does not improve the safety of live LV working either by virtue of its application making the overall task more hazardous or being unable to prevent false positives from the detection system leading to unnecessary additional supply interruptions.	Completed

Table 2: Success Criteria

4 Details of Work carried Out

EA Technology carried out a desk study investigation of possible methods for detection of contact and removal of supply. The findings of this investigation are shown in Appendix 1.

The project was divided into four workstreams:

- Workstream 1: to provide assurance that a good quality earth connection can be readily made in LV substations, suitable for carrying current from a direct short to earth in the substation, for sufficient time for the local fuse to rupture; and that the risk of fitting additional protection equipment is lower than the existing risk of live working;
- Workstream 2: to test alternative methods to detect contact between a human and a live phase conductor of an LV feeder, select the preferred option then produce and test a prototype protection device;
- Workstream 3: to define and test a retrofit device which can act on receipt of a signal to cause mains supply to be quickly removed from an LV feeder;
- Workstream 4: to integrate the prototype supply interruption and detection devices and then test them in the field.

The project was established as a staged programme of work targeted at achieving the project aims in the shortest and most cost-effective manner whilst ensuring that the outputs of each gate were reviewed and approved to meet WPD’s aims and expectations. Gates were defined at which the findings of the previous stages were reviewed and decided whether it was appropriate to continue with the investigation of an approach, or to halt the investigation and pursue an alternative, or indeed to close the project.

4.1 Workstreams

4.1.1 Quality of earth connection and risk assessment

This workstream was designed to explore whether:

- A good quality earth connection could be readily made in LV substations, suitable for carrying current from a direct short to earth in the substation, for sufficient time for the local fuse to rupture; and
- The risk of fitting the additional protection equipment was lower than the existing risk of live working.

The tasks in this workstream were to:

- Consider methods for making a temporary earth connection in a distribution substation, suitable for carrying current from a direct short to earth in the substation, for sufficient time for the local fuse to rupture. Telephone and email correspondence with selected WPD staff to discuss options;
- Identify existing Insulation Piercing Connectors, suitable for making a temporary phase connection into paper or plastic insulated, energised LV phase conductors (The connector would be left in situ in a safe condition when the connection is removed and would be available for repeat use if subsequently required);
- Identify and procure Rogowski Coil current measuring devices that are considered to be likely to be suitable for temporary fitting to LV feeders to measure the aggregate current through all three phase conductors and neutral conductor (but not earth conductor(s);

- Visit a WPD training centre to trial options for making connections and test that they are electrically good; mechanically robust; and easily and safely fitted. And to assess the ease of fitting the Rogowski devices and associated safety risks.

4.1.2 Detection

Stage 2a: Investigate Residual Power Frequency Current Detection
This approach was preferred by EA Technology because it has the potential advantage of relatively low cost plus simple and quick installation. Whether it can be used in practice will depend on the relative magnitude of current to earth through a human in contact with a phase conductor and the leakage current to earth from the feeder and any loads connected to the feeder, plus WPD views on acceptable accidental safe current exposure for a staff member and the view of the Health & Safety Executive (HSE) of the use of this approach to protect staff during live working.

The key tasks within this phase were to:

- Liaise with WPD to identify substations to fit the Rogowski devices in order to measure residual currents;
- Visit selected substations, fit devices to a number of LV feeders and measure residual currents to ascertain typical values and estimate the numbers of false positives and false negatives for given trigger currents;
- Review authoritative studies of the impact of electric current on humans, compare with the residual currents measured and produce recommendations for use or otherwise of this approach. Specify a prototype residual current protection relay for practical deployment on LV feeders;
- Document the findings of this stage, for review by WPD.

Gate: Review of the feasibility of this method of detection.

Stage 2b: Using sensors in Personal Protective Equipment (PPE) to detect human contact with a phase conductor
This optional stage would explore the practicality and behavioural issues of protecting life by adding sensing technology to PPE to detect current passing through a human body in contact with a phase conductor. Detailed planning and costing of this option would only be produced if the outcome from stage 2a is negative and WPD wishes to explore this option.

The key tasks within this stage were to carry out:

- Theoretical study into options for using Portable Earth (PE) to detect human contact with a live phase conductor;
- Behavioural study into the possibility of avoided usage;
- Risk assessment to determine the likely risk reduction compared to current live working practice.

Gate: Review of the feasibility of this method of detection.

Stage 3a: Produce a prototype residual current protection relay for practical deployment on LV feeders.
This optional stage would produce a prototype device which would be temporarily installed in a distribution substation during live working to detect current passing through a human body in contact with a phase conductor. Execution of this stage is dependent upon the outcome of the stage 2a gate review.

The key tasks within this stage were to:

- Produce design of the proposed prototype residual current protection relay;
- Produce one prototype residual current protection relay;
- Lab test the prototype residual current protection relay;
- Document the design and the results of lab tests for review by WPD;
- Meeting to discuss further testing requirements including engagement with HSE

Gate: Review of the prototype residual current protection relay and the results of the lab tests. The project could not develop a suitable device which was easy to connect to live networks so the stage was stopped in favour of later stages.

Stage 3b: Integrate sensors into PPE and test detection of human contact with a phase conductor
This optional stage would produce prototype PPE which incorporates sensing technology to detect current passing through a human body in contact with a phase conductor.

The key tasks within this stage were to:

- Identify options for sensing devices suitable for fitting into selected PPE equipment (probably Hi-Vis vest);
- Engage with manufacturer of selected PPE equipment (probably Hi-Vis vest) to identify constraints for fitting sensors;
- Produce prototype(s) for test;
- Testing (would probably have to produce a test rig or engage an existing testing resource;
- Review meeting

Gate: Review of the practicality of this method of detection. The review showed that whilst the prototype PPE was feasible it would be unlikely that a detection could then drive a remote automatic disconnection system in the timescales required to protect the operator. The development of the PPE was therefore stopped.

Stage X: Explore other methods for detection of contact between a human and a live phase conductor of an LV feeder.
A number of alternative methods have been considered. These are described in Appendix 1.

4.1.3 Supply Interruption

Stage 4: Investigate production and installation of a fast-acting "Fault-Thrower" to divert current to earth and pull down phase voltage sufficiently quickly to protect life, causing the existing fuse to rupture.

This approach was preferred by EA Technology because it has the advantage that no supply interruption is required to install and remove the device, provided that safe live working practices are followed to connect the device.

The key tasks within this phase were to:

- Confirm that the functionality of the Alvin Circuit Breaker is suitable for this purpose and document such functionality for review by WPD;
- Modify Alvin Circuit Breaker firmware to enable additional self-tests including measurement of connection impedance and source impedance and estimation of speed of disconnection using the existing LV fuse;
- Produce a transceiver device to produce a radio signal and a matching transceiver device to trigger the Alvin Circuit Breaker on receipt of a signal from the remote transceiver device, when used external to the distribution substation;
- Attend Review

Gate: Review of Alvin Functionality, proposed methods for connection and triggering.

Note: The triggering device, although required for safe testing of the prototype, could possibly be used as a manual backup triggering device, operated by WPD staff, if the detection method is found in practice to be insufficiently effective in all cases (if and when it is deployed).

Stage 5: Produce, install and test a prototype fast-acting "Fault-Thrower"

The key tasks within this phase were to:

- Produce and lab test a "Fault-Thrower" device (Based on ALVIN in a box with flying leads);
- Install on one phase of an LV feeder way at a selected distribution substation.
- Manually trip the "fault thrower" device. Compare measured speed of disconnection and self-test estimate. Document outcome;
- Attend Review

Gate: Review of performance of device. If judged adequate, then the workstream is completed. If not, then consider stage Y or close the project.

Stage Y: Identify and install fast acting protective LV circuit breakers.
This stage was not completed as the feasibility of connecting the devices to live feeders was not successful.

4.1.1 Integration and Testing

The protection device required must detect that contact has occurred and remove the supply before severe injury or death occurs. Survival from electric shock is dependent on the magnitude and duration of current flow. Therefore, there might be a useful trade-off between the required sensitivity of detection (and hence false negatives) and the speed of action of a device to remove supply.

It is preferable for the device(s) to be easily fitted and removed in a relatively short time so as not to significantly increase the time typically required to carry out work on an LV feeder. It is preferable for the fitting and removal of the device(s) to not require any supply interruptions.

4.2 Stage 2 Analysis

Although EA Technology were not necessarily required to complete Stage 2 of the project, they still continued with the assessment and study to determine the required sensitivity and immunity of the sensors. The analysis was seeking to detect the current flow through the body of the wearer whilst rejecting the effects of external magnetic fields. The analysis is discussed below:

4.2.1 Required Current Sensitivity

To determine the required current sensitivity, it is necessary to consider the potential contact points and current paths through the worker and consider the effect of body resistance in those current paths on the anticipated magnitude of current flow.

4.2.2 Body Impedance

International Electrotechnical Commission (IEC – Technical Standard) IEC TS 60479-1 provides the reference values for body impedance most typically employed in the assessment of hazards due to touch and step potential in substation earthing design. In this project, as part of the study, efforts were made to analyse a range of values which are not exceeded by 5%, 50% and 95% of the population. The typical requirement in HSE assessments is based on protective measures which would protect at least 95% of the population.

To determine the minimum sensitivity for a range of contact conditions we utilised the value not exceeded by 95% of the population, i.e. 95% of the population will have a body impedance at or below the values given, the highest impedance values and hence the lowest current values which must be detected are for dry contact conditions.

The diagram shown in Figure 1 below indicate the percentage of the internal impedance of the human body for the part of the body concerned in relation to the path hand to foot.

In order to calculate the total body impedance (ZT) for a given current path, the internal partial impedances (Zip) for all parts of the body of the current path have to be added as well as the impedances of the skin of the surface areas of contact. The numbers outside the body show internal portions of the impedance to be added to the total, when the current enters at that point.

The area of contact clearly has the potential to affect the overall impedance of the body, for lower contact areas and for touch voltages above 200V the skin may break down more readily reducing this effect. In addition, the conditions which are of most concern is when a person makes contact with a live electrical conductor and is unable to break contact, this is most likely to occur when a closed grip has been made to establish contact leading to a contact area around the size of the palm of a hand. In IEC TS 60479-1 this is considered to be a large contact area.

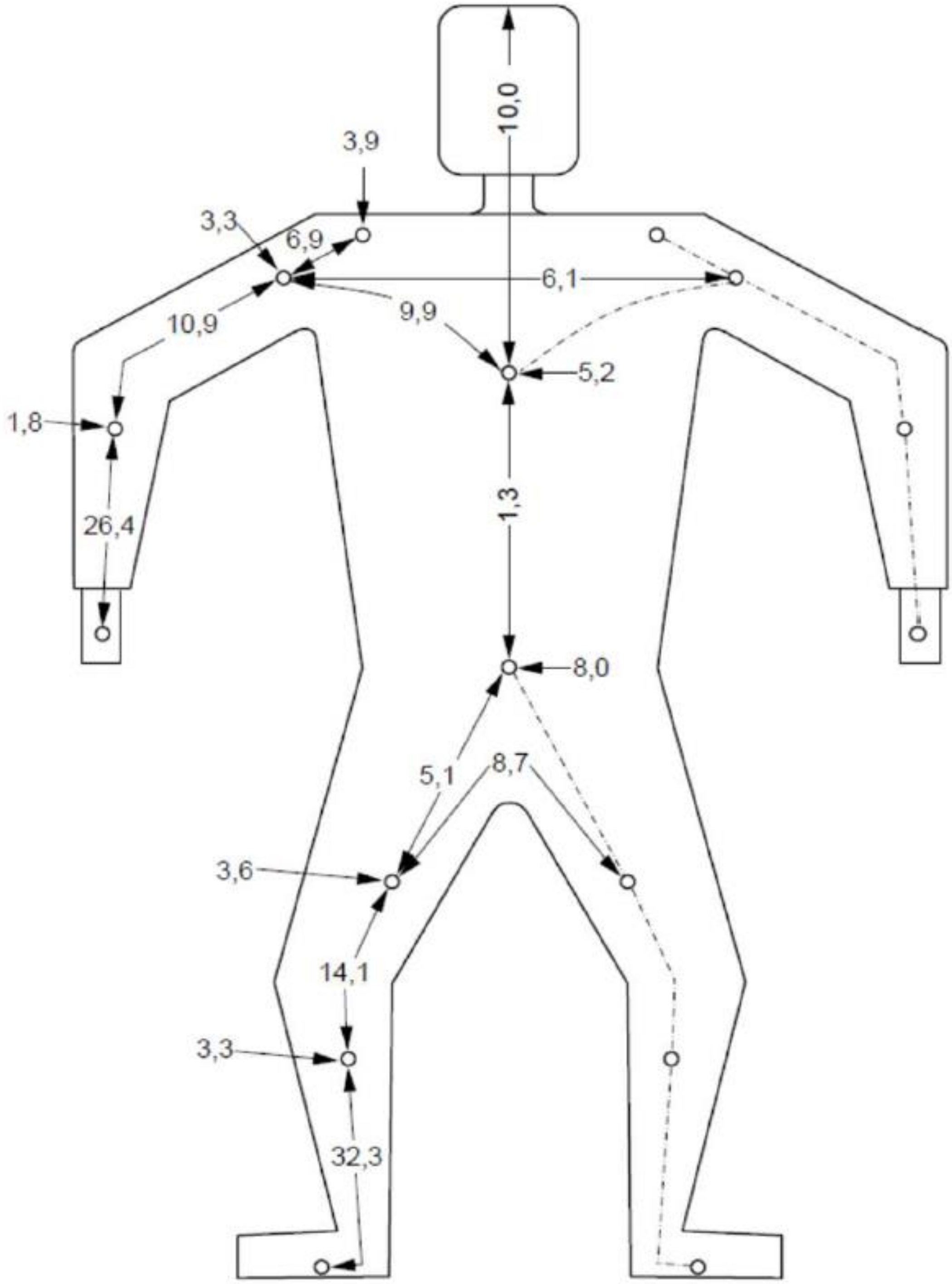


Figure 1: Internal Partial Impedances of the Human Body (from Figure 1 IEC TS 60479-1 Ed4.0)

Considering the body impedances given in IEC TS 60479-1 for large area contact dry conditions, the levels of current shown in Table 3 could be expected to flow in the body for the differing contact conditions. The values are based on a low impedance return path through the exit point.

Current Path	Body current values for body impedance not exceeded by percentage of population		
	5%	50%	95%
Left hand to Left Foot Right Foot	0.290	0.184	0.118
Both Hands to Both Feet	0.458	0.267	0.163
Left Hand to Right Hand (ph-ph)	0.679	0.500	0.373
Left Hand to Right Hand (ph-e)	0.339	0.209	0.133
Right Hand to Left Foot Right Foot	0.290	0.184	0.118
Back to Right Hand	0.472	0.273	0.166
Back to Left Hand	0.472	0.273	0.166
Chest to Right Hand	0.449	0.263	0.161
Chest to Left Hand	0.449	0.263	0.161
Seat to Left Hand or Right Hand	0.429	0.253	0.156

Table 3: Body Current Values - Dry Conditions Large Contact Area

The lowest value of current is the hand to foot passage which is the highest impedance path. These values are for contact of duration up to 100ms and would be expected to increase for durations in excess of this as the touch voltage would exceed 200V leading to the breakdown of the surface impedance of the skin.

4.2.3 Effects of Body Current

The effects of Body Current are described below.

The threshold of perception is where the person would be aware of the current flow. It is dependent upon several parameters including the area of the body in contact and the conditions of contact (dry, wet and salt-wet) and the physiological characteristics of the individual.

The threshold of reaction again depends upon the area of contact, the contact conditions and the physiological characteristics of the individual. However, IEC TS 60479-1 assumes a value of 0.5mA independent of duration for the threshold of reaction when touching a conducting surface.

IEC TS 60479-1 describes immobilisation as the effect of electric current such that the body (or part of the body) of the affected human being cannot move voluntarily. The effect may be due to current flowing through the muscle itself or through nerves associated with the muscle of the associated part of the brain.

The threshold of let go is also affected by parameters such as the contact area the shape and size of the electrodes and the physiology of the individual. IEC TS 60479-1 has a figure of around 5mA which is believed to cover the entire population whereas a value of 10mA is assumed for adult males.

The threshold of ventricular fibrillation depends upon physiological parameters such as the anatomy of the body, the state of cardiac function as well as electrical parameters such as the magnitude and duration of current flow and the pathway. With sinusoidal alternating current at 50 or 60Hz there is a significant decrease in the threshold for fibrillation if the duration exceeds one cardiac cycle. For shock durations below 0.1s fibrillation may occur for current magnitudes above 500mA and is likely to occur for current magnitudes of several amperes only when the shock occurs within the vulnerable period of the cardiac cycle. For shocks of these intensities and durations longer than one cardiac cycle reversible cardiac arrest may occur. The curves used within IEC 60479-1 to illustrate the thresholds of fibrillation are based on information from electrical accidents (the lower level for longer durations) and from animal experiments (the higher level for shorter durations). The two levels are joined by smooth curves.

The thresholds for different effects of alternating current are illustrated in Figure 2 below.
Up to 0.5mA shown by line “a”, perception is possible but there will usually be no ‘startled’ reaction.

From 0.5mA up to curve b perception and ‘startled’ involuntary muscular contractions are likely but there will usually be no harmful electrical physiological effects.

Curve b and above strong involuntary muscular contractions, difficulty in breathing and reversible disturbances of heart function and immobilisation may occur. These effects increase with current magnitude, usually no organic damage would be expected.

Above curve c1 patho-physiological effects may occur such as cardiac arrest, respiratory arrest and burns or other cellular damage, the probability of ventricular fibrillation increases current magnitude and duration.
Moving from c1-c2 the probability of fibrillation increases to around 5%, moving from c2-c3 the probability of ventricular fibrillation increases to around 50%, beyond c3 the probability of fibrillation is above 50%.

Ventricular fibrillation is fatal because it prevents the heart from pumping preventing blood flow and the transport of oxygen to the brain. However, other effects of electrical accidents may also prove fatal, these may affect respiration and may prevent the person from calling out for help. For example, hand to hand contact may cause the chest cavity to contract preventing breathing and inhibiting a call for help.

The levels of current which have been assessed as the maximum which may be expected to flow in the various ranges of body impedance all exceed the threshold of immobilisation as described above and are also well above the threshold for fibrillation for a longer duration current flow. Given this and the potential for currents above the b curve threshold but below the c1 threshold to also present life-threatening conditions it may be necessary to consider setting a threshold for detection at or below the threshold of curve b.

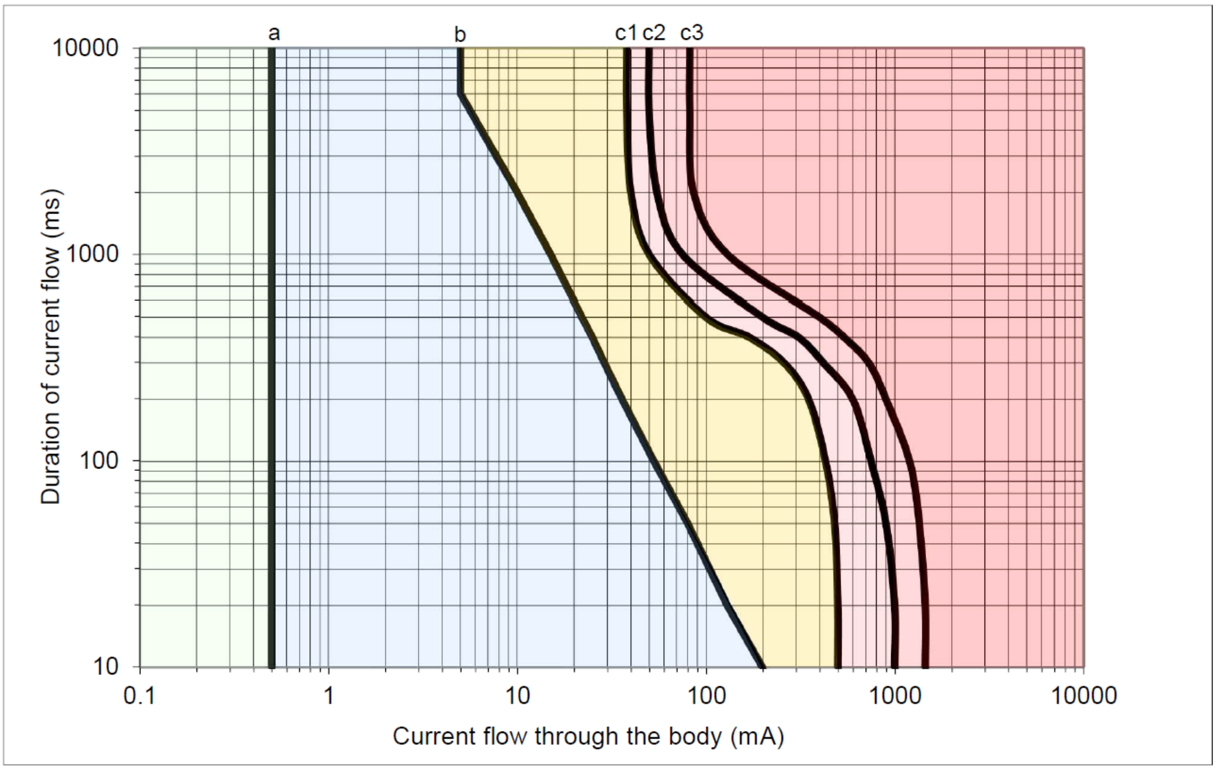


Figure 2: Time/Current zones of effects of alternating currents (15Hz to 100Hz) for a current path left hand to feet

4.2.4 Required Electro-magnetic Field Immunity

There are two aspects to the specification of the sensor capabilities for this application, the required sensitivity, and the required immunity to external magnetic fields.

A number of potential suppliers of sensors were contacted for details regarding the external field rejection capability of their sensors. One company, GMC Instruments, responded with the following information which described the tests they had carried out to establish the accuracy of the sensor in the presence of a defined level of current in a conductor at a defined distance from the sensor.

4.2.5 GMC Instruments - External Field

The PRO~flex head was placed 100 mm from the conductor (measured from the outer edge of the Flex to the outer edge of the conductor). The meter was nulled, a current of 1000A 40 Hz was applied. The head was rotated, keeping the same distance from the conductor. The largest deviation was recorded.
This test was conducted on 11 PRO~flex heads and results are in Table 4 below.
Requirements: External Field = ± 1 % of reading.

Max	Min	Mean	Std Dev	A + (3 * B)
0.112	0.018	0.037	0.030	0.128

Table 4: Results

5 Performance Compared to Original Aims, Objectives and Success Criteria

The available information from the manufacturers regarding immunity levels or external field rejection was quite limited. Only one manufacturer approached offered any detailed information. This rather than describing the level of external field immunity described the level of error measured for a given set of conditions. We therefore considered the level of magnetic field generated under these conditions and compared this to the expected magnetic fields at a reasonable working distance from the cable to establish whether immunity is likely to be achievable.

Objective	Performance
A workstream to test alternative methods to detect contact between a human and a live phase conductor, select the preferred option then produce and test a prototype detection device	This workstream was completed and produced a specification for a product. It was not developed into a prototype as the detection device needed to work in conjunction with the supply interruption device which could not be developed for easy live installation. Without that link to the other workstream, the device in this workstream was just a local warning device which, whilst useful, did not fulfil the whole ambition of the project.
A workstream to define and test a retrofit device which can act on receipt of a signal to cause mains supply to be quickly removed from an LV feeder	This workstream was completed and a device was developed based on an LV automatic switch device. The practicality of installing this device on a live network was identified as a limitation during the testing phase. The work was completed when a suitable low risk solution to live connection could not be realised.
A workstream to integrate the prototype supply interruption and detection devices and then test them in the field.	Due to the limitations in the completion of the workstreams above, the project was stopped before field testing of a whole solution was required.

Table 5: Performance Compared to Original Aims, Objectives and Success Criteria

6 Required Modifications to the Planned Approach during the Course of the Project

A number of possible approaches were identified. Those that EA Technology considered to be more likely to succeed were investigated first. At each gate review, the requirements of the project were considered taking into account the other options in order of lowest to highest estimated cost, complexity and practicality of roll-out. Throughout the lifecycle of the project gates were defined at which the findings of the previous stages were reviewed and decided whether it was appropriate to continue with the investigation of an approach, or to halt the investigation and pursue an alternative, or indeed to close the project. Some elements of the project were de-scoped as learning from the project improved understanding.

7 Project Costs

Activity	Budget (£)	Actual (£)	Variance (%)	Comment
Project costs	167,000	13,195	92	It was decided that no further work was required on the project and hence the project was stopped at Stage 1.
Total	167,000	13,195	92	Project cost was below the budget by 92%.

Table 6: Project Costs

8 Lessons Learnt for Future Projects

It was recommended that the project should proceed to the second stage to develop a proof of concept prototype which can be assessed for actual levels of sensitivity and immunity.
The recommendations from EA Technology of this task were as follows:

- The detection threshold should be set at 5mA.
- Consideration could be given to a stepped response with higher currents in excess of 30mA operating to initiate tripping of the supplies in a near instantaneous time whilst currents below 30mA but above 5-10mA could have short delay.
- Further, based on the available data from a manufacturer it appears encouraging that sufficient immunity from the effects of external magnetic fields may be achievable.

9 The Outcomes of the Project

EA Technology were able to construct a model to determine the individual magnetic fields developed by conductors of a cable. The individual magnetic fields were summated to yield the net magnetic field expected in a plane perpendicular to the cable extending 1500mm either side of the cable and 1500mm above the centre of cable. From the model EA Technology were able to determine the magnetic field at various distances from the cable.

From the modelling it was concluded that it was unlikely anyone working live on an open cable will have their body as close as 10cm from the cable without being in danger. Considering the likely working distance of the body from the cable is at armslength the magnetic field will be much reduced. Arms-length is approximately 500mm.

Secondly, the initial functional requirements of the sensor as determined from the assessments are that it should be capable of detecting currents as low as 5mA whilst producing errors in measurement less than 1mA when subjected to a differential magnetic field across the sensor of around 25μT. The results of the analysis on the requirements for the Electro-Magnetic Field Immunity are in Appendix 2 of this report.

Overall, the project has made the following conclusions:

- It has been determined to consider large contact areas as these are taken in IEC TS 60479-1 to represent an area approximately equal to the palm of a hand;
- It has been determined based on the typical range of body impedances that all of the considered current paths have the potential to give rise to body currents in excess of 100mA;
- There are other conditions which may occur due to an electric shock which may also prove fatal without the initiation of ventricular fibrillation, these may occur at lower current levels, as low perhaps as 5-10mA;
- Based on an assessment of the potential magnetic fields around an LV cable as calculated based on a number of current conditions and the stated external field performance of an example sensor it appears possible that sufficient immunity from external fields may be achievable.

10 Data Access Details

Any data produced during the course of the project will be available to share in accordance with WPD's data sharing policy:

www.westernpower.co.uk/Innovation/Contact-us-and-more/Project-Data.aspx

For more information on this project, please visit: https://www.westernpower.co.uk/Innovation/Projects/Current-Projects/LV-Sensitive-Earth-Fault-Protection.aspx

11 Foreground IPR

No foreground IPR has been developed for the project.

12 Planned Implementation

There is no planned implementation for the outputs of this project. That said, the desktop study and outcomes in this report have established technical characteristics to complete Stage 2 of the project necessary to establish the functional requirements and to develop a proof of concept for an item of wearable technology capable of detecting current flow in the body of an operator working live on the LV network.

It is, therefore, recommended that further work, including tests and measurements as set out below in the Appendix 1 & 2, be undertaken to validate and help prevent severe injury or death from inadvertent human contact with a live phase conductor during work on an LV feeder.

Glossary

Abbreviation	Term
DNO	Distribution Network Operator
HSE	Health & Safety Executive
IEC – TS 60479-1	International Electrotechnical Commission (IEC – Technical Standard) TS 60479-1 provides the reference values for body impedance most typically employed in the assessment of hazards due to touch and step potential in substation earthing design.
LV	Low Voltage
NIA	Network Innovation Allowance, a government sponsored scheme to encourage innovation in energy networks and services.
PE	Portable earth
μT	Micro Tesla, a unit of magnetic strength
WPD	Western Power Distribution

Appendix 1- Options Considered

1. Detection

a) **Change in phase current** - Not feasible: change will be smaller than normal load variations.
b) **Residual Current Detection** - Possibly: Will depend on the relative magnitude of current to earth through a human in contact with phase conductor and leakage current to earth from feeder and loads connected to the feeder.

I. Issues:

1. Three phase supply. Load current could return via alternative phase or neutral.
2. Would need to detect small difference between large currents (typically 400A per phase)
3. This difference is less than 165mA rms. providing current interruption is within approximately 1 second (believed to be the 0.5 percentile point for onset of Ventricular Fibrillation) ref: "Deleterious Effects of Electric Shock", C.F. Dalziel, Geneva 1961 found at http://www.electriciancalculators.com/dalziel/dalziel_study.pdf
4. Greater current is possible if interruption is faster I = 165 T-0.5 mA ref: ibid
5. This is beyond the accuracy of commercial Current Transformer (CTs) measuring currents of 400A.
6. So cannot measure individual currents and combine electronically, must combine the currents magnetically.
7. Must measure overall current flowing through an area which includes all phase conductors and neutral (but not the earth sheath - in case the current through the human is returning through the sheath).

II. Possible Practical Solutions:

1. Possibly could use a Rogowski coil - it could be fitted around cores (and neutral but not earth sheath...will have to test)
2. Do large buildings have "industrial scale" Residual Current Detection (RCD) protection?
3. If so, is the specification suitable for DNO LV feeders (circa 400A three phase)?
    a) Yes: http://protekuk.co.uk/RCBO-3-Phase-Metal-Enclosures-and-Plastic-Enclosures/RCBO-3-Phase-Metal-Enclosures/Fully-Adjustable-400A-3-Phase-RCBO-with-Metal-Enclosure
    b) And there is a 630A version:
    c) http://protekuk.co.uk/RCBO-3-Phase-Metal-Enclosures-and-Plastic-Enclosures/RCBO-3-Phase-Metal-Enclosures/Fully-Adjustable-630A-3-Phase-RCBO-with-Metal-Enclosure
4. However fitting such devices would require wholesale replacement of the existing LV board.

III. Actions required:

1. Check geometries of common LV boards to see if it is possible to fit a Rogowski coil.
2. Fit to a number of LV feeders and measure residual currents to ascertain typical values and estimate number of false negatives at given trigger currents.

c) **Resonance Earthing System** - Possibly: Resonance Grounding (Impedance Earthing) is widely used at (Extra High Voltage) EHV and Medium Voltage (MV) in Europe, for both Overhead and Underground circuits. It works by "tuning" an inductance between neutral and earth so that current to earth is zero from any single point on a phase conductor. It could in principle be adapted for LV use.

I. Issues:
1. Will depend on whether conventional resistive earth can be easily removed.
2. Also will depend how capacitive the circuits are - however modern systems
3. Unlikely to be practical in Protective Multiple earthing (PME) circuits - too many earth points
4. Theory at:
http://www.ece.mtu.edu/faculty/bamork/EE5223/Ground%20Fault%20Protection%20resonance%20neutral.pdf

II. Possible practical solution:
1. Modify a self-tuning resonant grounding system for use on LV circuits.
III. Actions required:
1. Ascertain proportion of PME feeders
2. If sufficiently small proportion, then contact a manufacturer to discuss practicality and cost of modification and fitting.

d) **Active detection using higher frequencies** - Possibly: 5th harmonic injection is used on resonant earth systems to locate faults.
I. Issues:
1. Will depend on the relative impedance of human and other items connected to a phase conductor.
II. Actions required:
1. Literature survey to determine if the impedance of human beings to various frequencies has been studied since the work of Dalziel.
2. Investigate capacitive and inductive coupling methods for signal injection
3. Measure earth leakage of various frequencies to earth on typical LV feeders - hence determine "typical leakage impedance"
4. Compare relative impedance of human and leakage and assess if theoretically feasible or not.

e) **Active detection using Direct Current (DC)**

I. Issues:
1. Will depend on the relative DC impedance of human and other items connected to a phase conductor.

II. Actions required:
1. Literature survey to determine if the impedance of human beings to DC has been studied since the work of Dalziel.
2. Investigate practical methods for DC injection (n.b. DC injection is used in Germany as a Loss of Main (LOM) protection signal)
3. Measure earth leakage of DC to earth on typical LV feeders - hence determine "typical DC leakage impedance"

4. Compare relative DC impedance of human and leakage and assess if theoretically feasible or not.

2. Remove Supply

a) **Install fast-acting circuit breaker as fuse replacement** - Possible: But would require a short interruption to install and to remove.

I. Issues:
1. Can a circuit breaker act fast enough?
a) The Alvin Circuit Breaker (CB) opens in 8mS or less.
b) To be lower than the 0.5 percentile point for onset of Ventricular Fibrillation $I < 165 / \sqrt{0.008}$ i.e. $I < 1845$ mA
c) This is outside of the range of validity of the Dalziel study, however it suggests that a highly sensitive detector is not required - so avoiding false positives appears feasible.

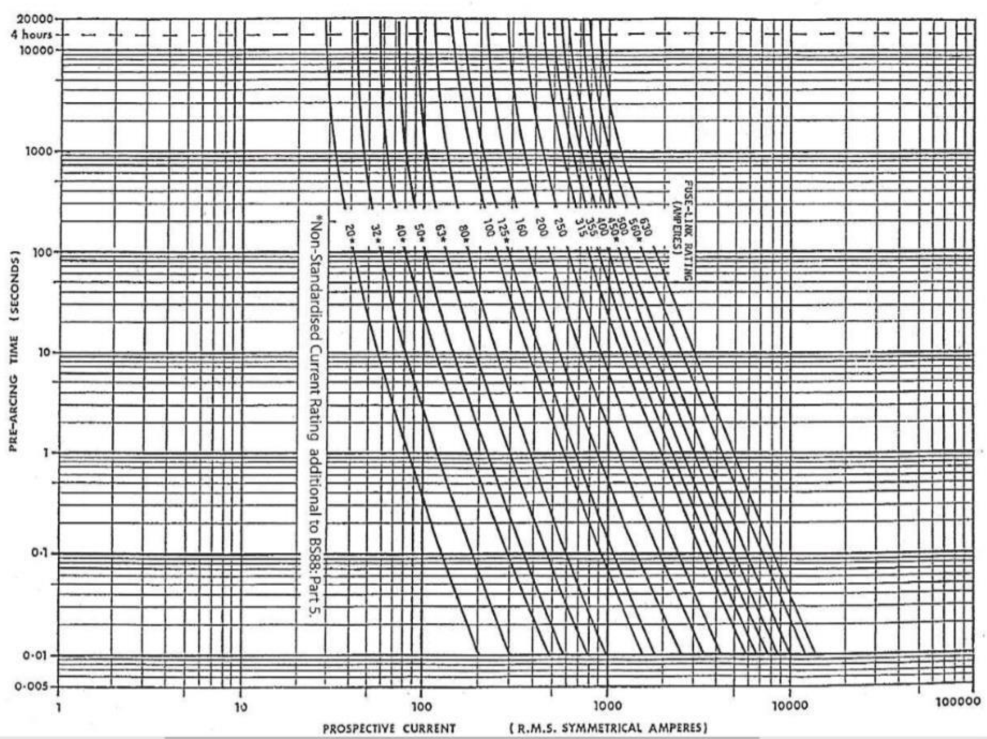
b) **Install a fast-acting "Fault-Thrower"** to divert current to earth and pull down phase voltage - Possible: An advantage is that no interruption is required provided safe live working practices are followed to connect the device.

I. Issues:
1. How fast will a fuse operate? (Aim for around 8mS or less)
2. What current is required to get this speed of rupture?
3. What minimum resistance is required for a device when closed?
4. Could a thyristor device satisfy the requirement?

II. Actions:
1. Review standard fuse characteristics.
2. Calculate device resistance.
3. Review thyristor device specifications
4. Review switch specifications

Standard Fuse Characteristics

Type J - Time/Current



A distribution substation with a radial HV feed and solid earth PME LV feeders has a typical fault level of 19.4MVA and a maximum fault current of 27kA.

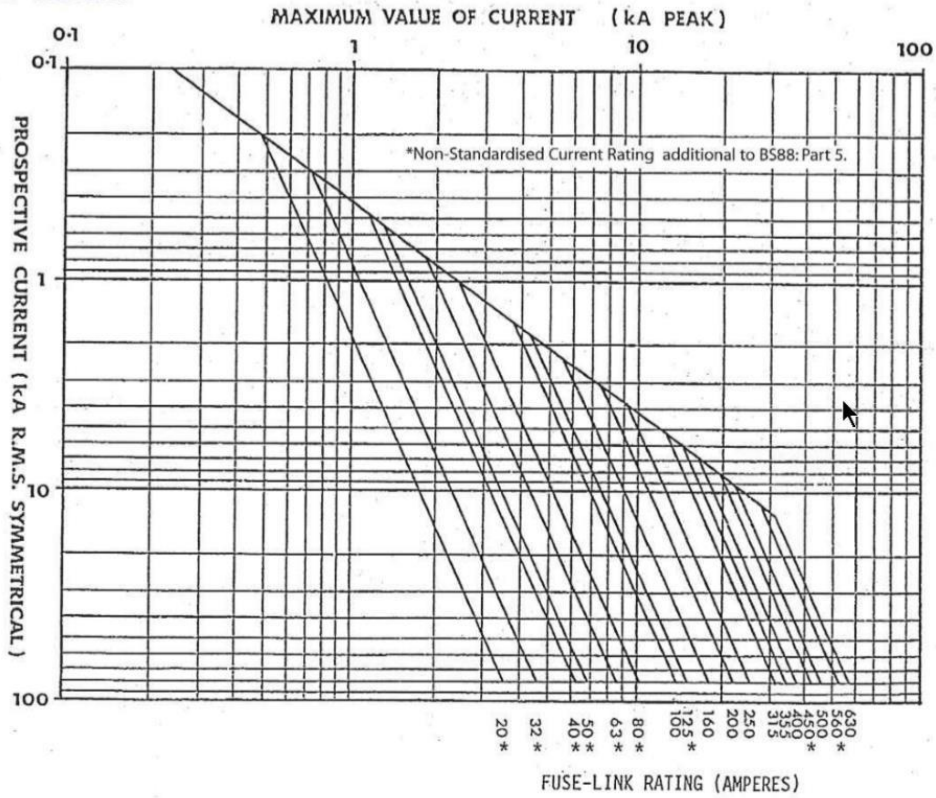
LV	Solid Earthed (PME)	27kA	19.4MVA

From
http://www.enwl.co.uk/about-us/long-term-development-statement/policies-and-technical-references/system-earthing-and-fault-levels

Fusing to protect Thyristor and Insulated Gate Bipolar Transistor (IGBT) devices (has typical overload characteristics of semiconductors) (found at:
http://ep-us.mersen.com/fileadmin/catalog/Literature/Brochures/BR-Semiconductor-Fuse-Applications-Guide-Brochure.pdf

The Thyristors used in the Alvin Circuit Breaker have an overload rating of 15kA for 10mS @ 25degC and 13kA for 10mS @ 125degC. Alvin uses 2 in parallel.

Type J - Cut-Off Current



Appendix 2

The PRO-flex head comprises a length of coil with a connector, enabling a loop to be created. The length of the coil is 450mm. The diameter of a 450mm coil is approximately 150mm.

In order to determine the magnitude of the magnetic field which is responsible for the GMC Instruments test result the magnetic field is calculated at 100mm and 250mm (the opposite side of the coil), for comparison with the stated performance of the sensor coil.

In order to scale the GMC Instruments test current error to determine the error at the assumed working location, the magnetic field is also calculated at 500mm and 650mm (the opposite side of the coil), i.e. for the assumed working location.

At 100mm from the cable the magnetic field for 1000A is 1737μT. At 250mm the magnetic field is 755μT.This magnitude of field differential, approximately 1000μT, across the sensor gave rise to the error of 112mA for a 1000A current.

At 500mm and 650mm (at each side of the coil for the assumed working location) the magnetic field for a cable current of 1000A drops to 388μT and 300μT. The field differential across the sensor coil is therefore expected to be over an order of magnitude lower in a working location than in the GMC Instruments test.
Due to the reduction in magnetic field differential it is reasonable to expect that there would be significantly lower level of current measurement error with the sensor at this distance from the conductor.
Note that this modelled magnetic field is still for a single conductor with 1000A.

Even a highly unbalanced level of current will exhibit some degree of cancellation of the magnetic fields, so the magnetic field differential seen at this more realistic working distance from the cable with realistic conductor currents is likely to be significantly lower still.

Some sample data from the Falcon project was provided. With this data there were examples of higher levels of current, around 200A, but these showed comparatively low levels of current unbalance being between 4% and 7%. Where higher levels of unbalance were seen at around 25% the current the current magnitudes were typically closer to 100A. In addition, a limited number of examples of data from the OpenLV project were reviewed. Although the levels of unbalance were much higher, in the region of 40-70% the actual current magnitudes were significantly lower. Taking the values for the middle example with unbalance levels of around 25% and doubling the current magnitudes yields provided a more extreme set of conditions.

Based on these example levels of current imbalance described above the following results shown in Table 7 below were obtained.

	Phase A	Phase B	Phase C	Neutral	Magnetic Field (µT) @ 0.1m & 0.25m	ΔB0.1 (µT)	Magnetic Field (µT) @ 0.5m & 0.65m	**ΔB0.5 (µT)**
1	212A	209A	204.5A	13.25	89.5	64.9	10.1	2.75
	12.4º	131.5	255.4º	80º	24.6		7.35	
2	118.9A	82.2A	79.4A	38.2A	159.2	97.5	30.41	7.1
	0º	120º	238.8º	3º	61.6		23.31	
3	56.1A	77.3A	48.1A	24.3A	26.62	19.01	3.20	0. 8 5
	5º	116.5º	241º	290	7.60		2.35	
4	237.8A	164.4A	158.8A	76.4A	318.45	195.07	60.8	14.2
	0º	120º	238.8	3º	123.38		46.6	

Table 7 - Examples of unbalanced currents and resulting magnetic fields

Example 1 has a relatively low level of current unbalance which is reflected in the lower magnetic field magnitudes compared to the other examples with lower current levels. The differential magnetic field expected at the assumed working distance is 2.75µT.

Example 2 has a greater level of current unbalance and generates higher magnetic fields as a result than the more balanced higher current values of example 1. The differential magnetic field at 50cm is expected to be 7.1µT.

Although Example 3 has the highest level of unbalance in the examples the lower level of current produces the lowest field with a differential magnetic field at 50cm of 0.85µT
Example 4 is a scaled version of example 2 with double the current magnitude, this yields double the magnetic field compared to example 2 which is to be expected. However, the differential magnetic field for such conditions is still only 14.2µT

The values in Table 7 above are based on a 300sqmm Waveform cable with the red phase conductor at the top of the trefoil with the cable centred on the origin of the calculation space. The larger separation between core centres maximises the difference in relative position between the core conductor and the calculation point. Calculations with cores in different orientations and also with 4 core cables yield very similar results with only very small differences in the differential magnetic field <1µT for the 50cm working distance.

From the results in Table 7 above it can be seen that differential magnetic field expected at realistic working distances and with realistic levels of current and unbalance is 2-3 orders of magnitude below the differential magnetic field which gave rise to the error levels quoted in the manufacturers test data. On this basis if the response of the sensors is linearly related to the magnetic field then the error may be expected to be below the current level that we wish to detect in the case of contact with a live conductor.

This suggests that sufficient immunity for external magnetic fields may be achievable.

The calculations of magnetic field have assumed that the measured values are all at 50Hz. It is possible that some measured currents may include levels of third harmonic in the neutral conductor as these triplen harmonics are zero sequence currents and are additive in the neutral. Applying filtering to the sensor to capture only frequencies close to the fundamental would limit their effect and may further reduce the values of differential magnetic field to which the sensor would respond.

References to some of the elements discussed in this report can be found in:
[1] IEC TS 60479-1 Ed 4.0 2005 Effects of current on human beings and livestock – Part 1 General Aspects
[2] GMC Instruments – PRO-flex Electrical Verification Report: 2008

Western Power Distribution (East Midlands) plc, No2366923
Western Power Distribution (West Midlands) plc, No3600574
Western Power Distribution (South West) plc, No2366894
Western Power Distribution (South Wales) plc, No2366985
Registered in England and Wales
Registered Office: Avonbank, Feeder Road, Bristol BS2 0TB

wpdinnovation@westernpower.co.uk
www.westernpower.co.uk/innovation