Managing LV Arc Flash Hazards – Arc Flash beyond HV and the development of an Arc Flash Estimator Tool

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Abstract

Low Voltage Arc Flash hazards pose one of the greatest risks on a distribution network. The hazard is site specific, hard to assess and is highly sensitive to system impedance, transformer design and protection. As you move downstream fault levels tend to reduce but clearing times and the associated hazard levels can counterintuitively increase. It is therefore important to go beyond the infinite bus and to include actual fuse characteristics and real system data within the assessments. The site specific variability of the hazard and the need to measure, control and mitigate it, has led to the development and distribution of the Arc Flash Estimator tool to field staff and designers. Expeditious on site assessments of the hazard levels at or downstream from any transformer on the Network are now possible along with the ability to appropriately adjust fusing. This paper uses examples to demonstrate how an open and democratised approach to the assessment of LV arc flash hazards has driven change and how it has led to the first full distribution protection review since 1986.

Introduction

The inherent nature of a distribution network means that LV is more abundant than HV, has more associated assets, more failure points, more faults and so creates vastly more exposure and risk. Each day more people work, play and live at the LV end of a distribution network than at the high voltage end; yet relatively little engineering attention is typically paid to it.

Regulatory and resourcing pressures tend moved the focus to upstream projects which generally have greater reliability outcomes and are easier to manage. Potential outcomes include an erosion of institutional technical knowledge of LV systems and a 'reactive' treatment of related issues.

The Arc Flash Estimator (AFE) project was initiated in response to the updating and development of Delta's PPE and Arc Flash policies, which in turn was informed by the recommendations of the EEA Guide for the Management of Arc Flash Hazards [1].

The EEA guide required, through a policy statement, that a programme be produced for the assessment of the arc flash hazards of all assets across the network. The EEA guide foreshadowed the Health and Safety at Work Act 2016 (HSWA) and the subsequent revision of the SM-EI handbooks in 2015.

The new explicit requirements, regarding arc flash hazards, (i.e. SM-EI Section 3.716-3.720) align well with those of the Electrical (Safety) Regulations 2010 (ESR) which require: that Works not be unsafe, have maximum practicable sensitivity and minimum practicable operating times (Clause 34).

The goal of the AFE is to quickly allow arc flash hazards (AFH) to be assessed, avoided and minimised; and allows *minimum practicable operating times* to be determined. AFH assessments, in part using the AFE, have become routine, widespread and a necessary part of safety policy and procedures for field staff, designers and the engineering team.

Background

Low Voltage Arc Flash Hazards (AFH) pose a significant risk on a distribution network with both workers and members of the public exposed. LV arc flash hazards are site specific, hard to assess and are highly sensitive to system impedances, protection and design.

Late in 2014, to address LV arc flash risks, blanket PPE requirements and operational/working restrictions were introduced on the LV side of transformers. These restrictions were based on the transformer's rating and included the requirement to de-energise any transformer above 400kVA when LV fuses were changed or operated, or when it was being worked on. Category 2 PPE was required at and below 200kVA, with category 4 PPE required between 200kVA and 400 kVA.

These blanket rules proved problematic operationally, and when tested by detailed calculations were often shown to be invalid with a transformer's rating being a bad proxy for the attendant arc flash hazard. Some larger transformers were found to have a low AFH, whilst some smaller transformers had an unacceptably high AFH.

This led to an increasing number of calculations being 'called in' to the engineering team and a subsequent rise in the issuing of dispensations for what was effectively routine work.

It was found to be difficult to write an effective policy that a) covered routine situations and b) could be communicated effectively. A new approach was required based on site specific details, so that that the AFH could be managed appropriately: assessed, avoided and minimised.

The repetitive requirement for arc flash assessments initiated the development of the Arc Flash Estimator (AFE) in mid-2015. Its key objective was to make arc flash hazard assessments routine, widespread and a necessary part of safety policy and procedures.

Arc Flash Hazards

Arc flash hazards (AFH) are normally classified as a significant hazard under the HSWA due to their potential for serious harm [1]. This means that where practicable the hazard should be eliminated; where this is not practicable it should be isolated and finally, where this is not practicable, it should be minimised and PPE provided to those exposed to the hazard.

To undertake any of the above steps the hazard must first be identified and then quantified. It is only then that the AFH can be managed appropriately.

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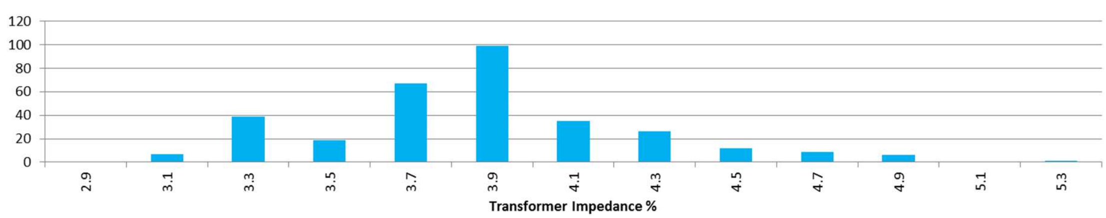
Arc Flash Hazard Assessments

In order to estimate an LV arc flash hazard at a particular location, transformer, fuse and system data all had to be brought together to assess the hazard. When undertaking calculations, information was often unknown, hard to find, or undocumented with for example, only 35% of transformer impedances and less than 20% of fuse ratings recorded in the GIS. Where information was missing or not readily accessible reasonable assumptions needed to be made.



Count	Mean	10th Percentile	90th Percentile	95th Percentile
320	3.2%	3.8	4.3	4.6

Figure 1: Example Distribution of Recorded Impedances 3/50kVA Transformers (11kV)

Where transformer impedances were unknown, it was not seen as reasonable to consistently use the worst case values as the variations are large and the impact on the final AFH significant. Statistically methods were therefore employed to give a percentile value across a cohort of similar transformers on the network. Similar, for instance, could mean those transformers manufactured by Tyree, operating at 6.6kV and rated at 400kVA.

The importance of fusing cannot be understated when assessing and managing arc flash hazards. Fortunately network fusing practice had remained stable for many years with standard fusing tables consistently used. To appropriately manage the AFH it was also very important to look beyond the existing hazard and see, by changing fuse types and sizes, what level the hazard could be reduced to.

The HV feeder impedance also proved to be a major factor in fault levels and clearance times, with in many cases, it being as significant as the transformer impedance itself. As you move downstream on a feeder, fault levels tend to reduce but clearing times increase for a similarly fused transformer of the same rating. Longer clearing times mean longer exposure and typically higher hazard levels. It is therefore not appropriate to assume that an infinite bus supplies a transformer, as this would typically under-represent the actual hazard. It is therefore very important to include the feeder and system impedances when assessing the AFH.

LV Arc Flash Estimator

The Arc Flash Estimator (AFE) is an offline hazard assessment tool that uses Network asset and system data to estimate the arc incident energy (AIE) at or downstream from any new or existing distribution transformer on the Central and Dunedin Networks.

It is available to all Delta staff and can be used in the field with very little training. In a few seconds, using validated drop down menus, the potential arc flash hazard levels at an existing or new substation can be assessed.

The AFE includes periodically updated, spatially mapped distribution transformers and circuit breaker tables. The XY coordinates in these tables allow the radial separation of any distribution substation and its associated upstream circuit breaker to be determined.

The length and impedance of each feeder is unique with various mixes of conductors and cables used. To get a good approximation of the feeder impedance to a transformer, each feeder was profiled separately; factors are then introduced to give the best approximation of the impedance to a site based on the feeder and actual radial distance. As we run more calculation checks with actual impedances and distances these factors can be further optimised.

The time current curves (TCC) for over a 100 fuses (both HV & LV) have been incorporated in the AFE. Fuses that are currently not used on the Network have now been included to offer choice and to ‘crowd source’ safer designs.

The Arc Flash Estimator in Use

The following four examples of different 300kVA substations seek to demonstrate the functionality and utility of the AFE and the variability of the potential AFH:

Example	Substation Name	Voltage [kV]	HV Fault Level [kA]	Feeder Distance [km]
1	Sturdee St 24	6.6	18	0.1
2	Lovelock Gardens	6.6	6.2	2.2
3	CC12 (Cromwell)	11	2.5	2.4

4	GO108 (Glenorchy)	11	0.2	38

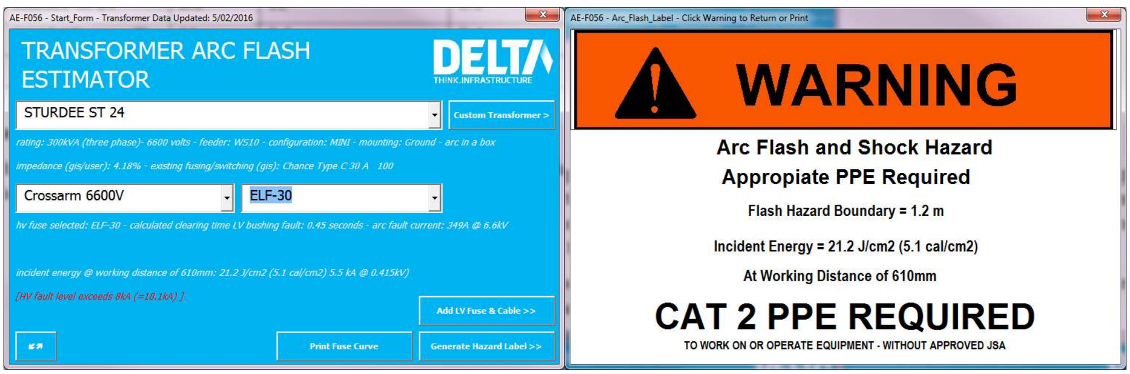
Table 1: Four Examples of 300kVA Substations

Example 1: Sturdee St 24 Substation (High Fault Level / OH Fuses)

This is a dual ratio (11/6.6kV) mini transformer installed in 2014, protected by 30A current limiting dropout fuses. The HV fault level, at 18 kA, is relatively high as a result of its proximity to the Ward Street Zone Substation and 6.6kV operation.

As can be seen in Figure 2 below, the AFH is assessed to be 21 J/cm2 (5.1 cal/cm^2) with a minimum of Category 2 PPE required. Cooper ELF fuses have been used at this site due to fact that the HV fault level exceeds the rating of standard expulsion fuse tubes.

Using the AFE it can also quickly be seen that the potential incident energy could be reduced to below 3 J/cm2 (0.8 cal/cm^2) with the installation of Safelink switchgear. Given the additional cost to install switchgear it could be argued that the minimum practical clearing time has been achieved using the existing overhead fuses.



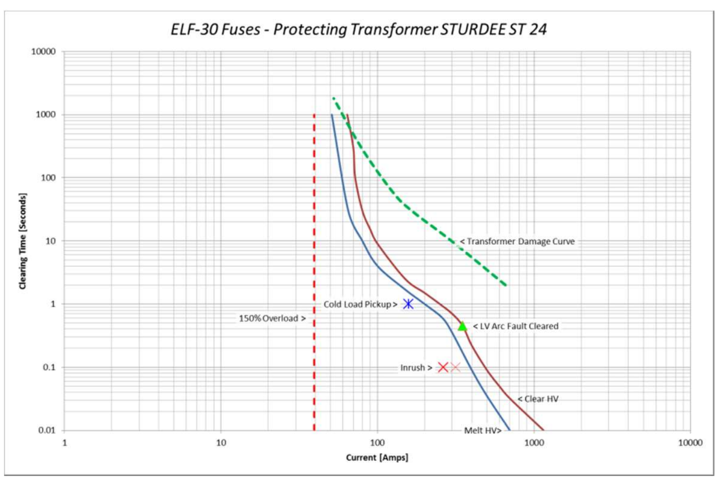


Figure 2: Assessment of LV AFH at Sturdee St 24 Substation – Dunedin

Example 2: Lovelock Avenue Gardens Substation (Old Assets / Oil Switchgear)

The Lovelock Avenue Gardens substation was installed in 1971 and is a good example of an older LV board with extensive 'exposed live parts'. This in combination with the high arc

incident energy (from AFE) would mean that access for inspections etc. should be restricted until the issues are addressed. The minimum approach distances (MADS) in SM-EI [2] can form the basis for access control and competency requirements.

The AFE indicates that the HV fuses could be reduced to 40A and so reducing the AFH and incident energy level to around 5 J/cm2 (1.2 cal/cm2). Such a level is coincidentally the threshold for the arc flash boundary calculation and that at above which secondary degree burns are seen as possible [4], it is also give as a target in the EEA Guide [1].

Figure 3: Assessment of LV AFH at Lovelock Avenue Gardens Substation – Existing

Example 3: CC12 – Cromwell (New World) Substation (Group Fusing)

CC12 is a 300kVA substation installed 20 years ago; it is currently group fused with a 200kVA transformer through an ABB SDAF and 50A fuses.

As can be seen in Figure 4 below the AFH assessment indicates that the transformer should be de-energised prior to the LV board being worked on or operated. This is due to the clearing time being estimated at close to 5 seconds.

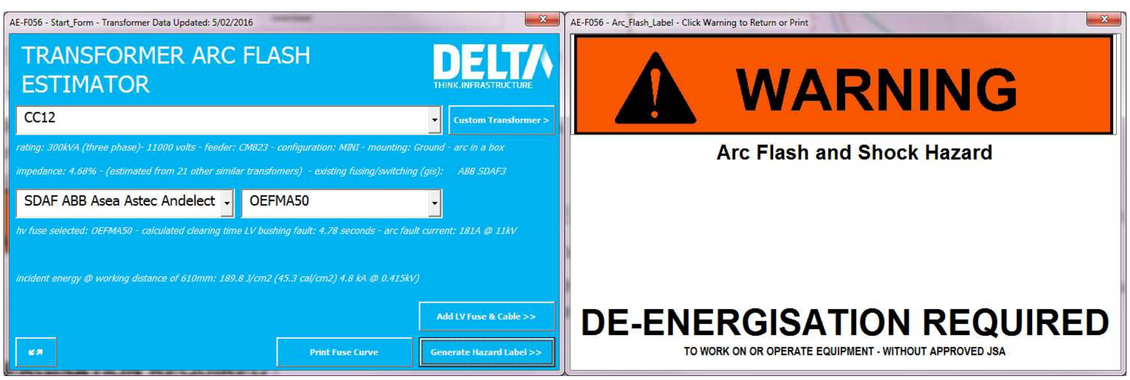


Figure 4: Assessment of LV AFH at CC12 – Cromwell – Existing

This switchgear is scheduled for replacement: the new Safelink switchgear will now facilitate individual 25A fusing of the two transformers and so significantly reduce the AFH and allow the equipment to be more easily worked on or operated, thus improving reliability of supply to a busy supermarket.

A 400A NH fuse and a section of cable can be also added to the AFE to assess the AFH at the main switch board in New World (See Figure 5).

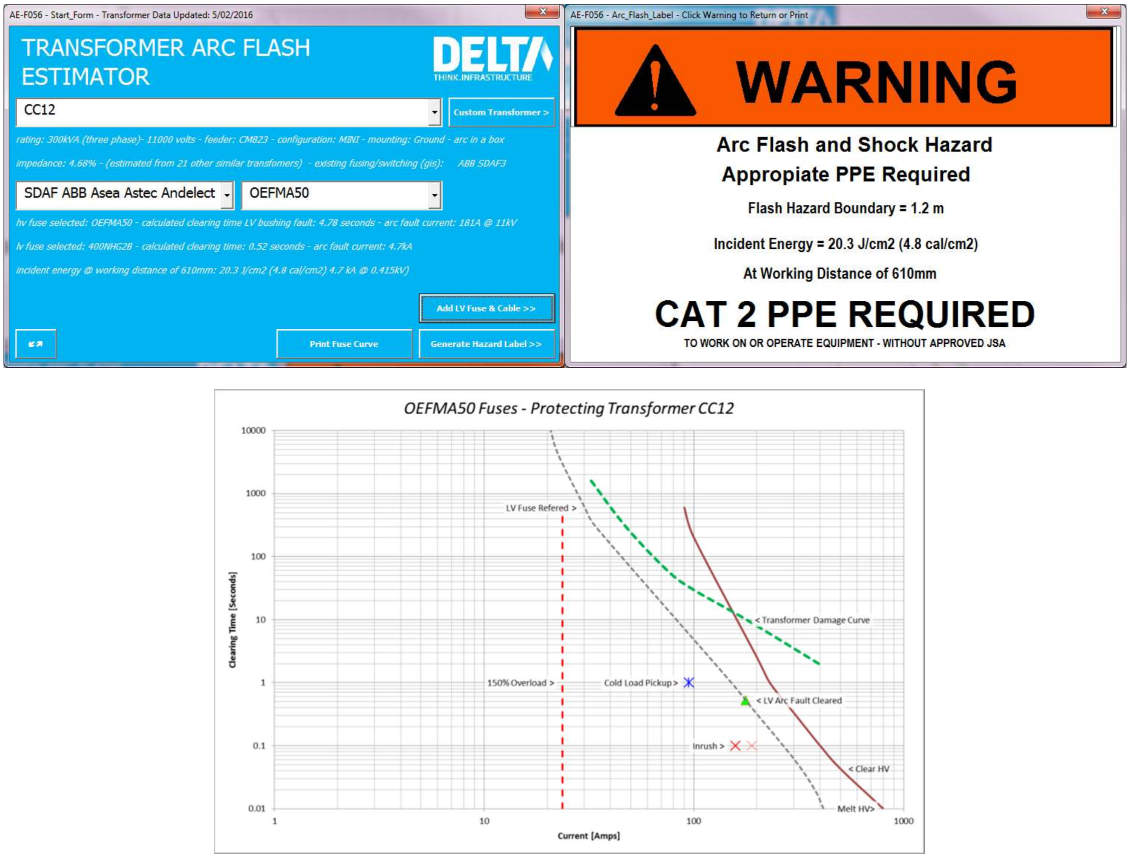


Figure 5: Assessment of LV AFH at New World MSB – Fed from CC12 – Existing

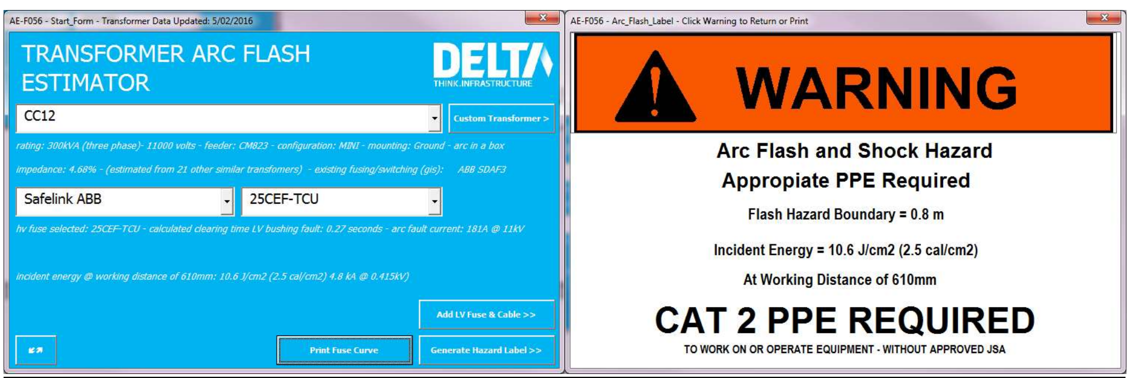


Figure 6: Assessment of LV AFH at CC12 – Cromwell - Upgraded[1]

[1] Please note that Category 2 is Delta's lowest PPE requirement to operate or work on transformers without a job safety analysis having been approved: the AFE applies Delta's PPE policy.

Example 4: GO103 – Glenorchy (Modern Asset / Low Fault Current)

The forth example is a transformer installed last year at the campground in Glenorchy. As was the standard practice 30A type K dropouts protect this transformer. As can be seen in Figure 7 there is an estimated clearing time of 22 seconds which leads to a very high incident energy level and AFH; this substation would require de-energisation prior to operation or any work being undertaken at the LV side.

These fuses are too high and could be reduced, to 20 or 25A, to achieve the *minimum practicable operating times* as required by the ESR's. The fuses in this transformer will have to be reduced in size.

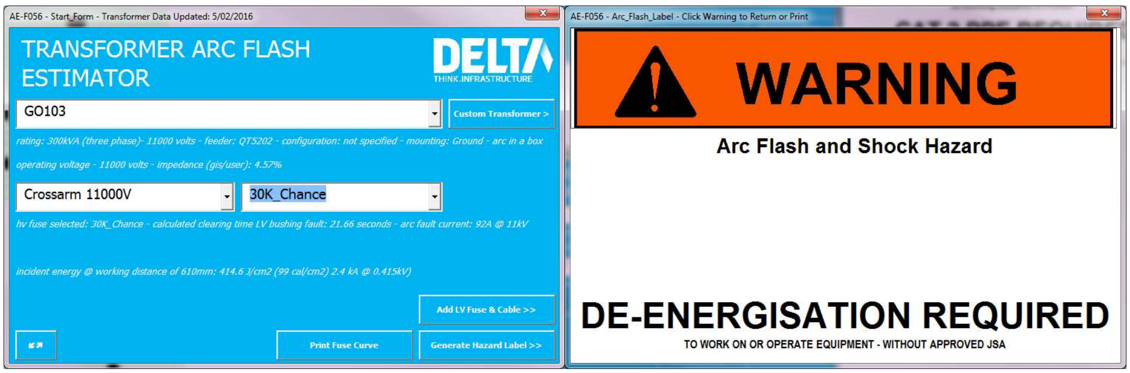


Figure 7: Assessment of LV AFH at GO108 – Glenorchy - Existing

	Existing Protection	AFH J/cm^2 (cal/cm^2)	Alternative Protection	AFH J/cm^2 (cal/cm^2)
Sturdee St 24	30A ELF	**21 (5)**	Safelink 40A	**3 (0.8)**
Lovelock Gardens	63A Oil	**40 (9.5)**	40 A Oil	**5 (1.2)**
CC12 (Cromwell)	50A Oil	**190 (45) X**	Safelink 25A	**11 (2.5)**
GO108 (Glenorchy)	30 A Type K	**415 (99) X**	20 A Type K	**34 (8)**

Table 2: Assessment Example Summary – Existing/Alternative Protection

The examples above demonstrate the variability in incident energy levels and show the protection measures that we can consider or deploy to help manage AFH. As can be seen it is often the distant transformers or lower fault level transformers that represent the biggest challenges, AFH and risks.

It is obvious that some distribution substations are inherently safer than others due to their design or location and that some smaller transformers present a higher AFH than some larger substations.

The more calculations that were undertaken the more variability in clearing times, and so associated arc flash levels were found.

The AFE allows alternative options to be explored and acts as a guide towards the best solution.

Brave New World

The AFE project has landed just as the Health and Safety at Work Act came into force. Whilst the previous requirements of the ESR were open to interpretation, the HSWA appears to have teeth (“carrot, sermon, **stick**” to quote an EEA presentation) and has the attention of a high level audience in most companies. The HSWA has reinforced key terms and principles such as SFAIRP, ALARA and requires better practice and Safety in Design (SiD).

AFH assessments are more than mere incident energy level calculations, they are about real risks and what is possible or achievable within a given company.

Conclusion/Summary

The AFE project is ongoing and iterative and is intended to raise questions, awareness and discussion. Imposed top-down rules based on poor visibility don’t work well; neither does a laissez-fair approach. A bottom up approach empowering field staff and the sharing of knowledge is the preferred path.

We have now moved to situation specific bespoke designs for distribution transformer fusing and away from prescriptive practices.

The AFE answers the following questions:

- What is the AFH at or downstream of a transformer?
- What is the minimum practicable AFH achievable?

Identifying what is practicable is subjective and location/company specific. Once we have assessed the AFH and examined alternatives, we can then work through what is practicable. Armed with information intelligent informed compromises can be made.

The Arc Flash Estimator has now become very widely used by field staff, engineering and designer teams to facilitate the best practice management of arc flash hazards. Field staff were originally sceptical of arc flash as an issue. Using the AFE, they now have a better appreciation and ownership of the issue. The AFE initiative has driven change and led to the first full distribution protection review since 1986. More people are becoming engaged and conversant with arc flash hazards and their control.

Acknowledgments

Thanks should go to all those passionate Delta staff that have consistently asked difficult questions, demanded easy answers and so driven this process.

Abbreviations

AFH	Arc Flash Hazard
AFE	LV Arc Flash Estimator
AIE	Arc Incident Energy
AFC	LV Arc Flash Calculator
HSWA	Health and Safety at Work Act 2015
SFAIRP	So Far as is Reasonably Practicable
ALARA	As Low as Reasonably Achievable
SiD	Safety in Design
ESR	Electricity Safety Regulations 2010
EEA Guide	EEA Guide for the Management of Arc Flash Hazards – See [1]
PPE	Personal Protective Equipment
JSA	Job Safety Analysis

Definitions

Arc Flash Boundary	When an arc flash hazard exists, an approach limit at a distance from a prospective arc source within which a person could receive a second degree burn if an electrical arc flash occurred Note: A second degree burn is possible by an exposure of unprotected skin to an electric arc above the incident energy level of 5 J/cm2 (1.2cal/cm2)[4]-[Article 100]
The 2 Second Rule	D4.3 - NFPA – 70E – 2015 states: "It is likely that a person exposed to an arc flash will move away quickly if it physical possible, and 2 seconds is a reasonable maximum time for calculations. Sound engineering judgement should be used in applying the 2-second maximum clearing time, because there could be circumstances where an employee's egress in inhibited"[4]
JSA	A step by task analysis to identify hazards and control methods that need to be put in place to manage risk.
Incident Energy	The energy per unit area on a surface, located a certain distance from the potential arc source, generated during an electric arc event. Incident energy is measured in units of Joules or calories per square centimetre: 1 calorie = 4.184 Joules. PPE rating must exceed or equal incident energy.
Network	Aurora Energy Limited's Distribution Network

References

[1] Guide for the Management of Arc Flash Hazards, EEA 2011

[2] SM-EI, Safety Manual – Electricity Industry, Parts 1 to 3, EEA, 2015

[3] IEEE Std 1584: 2002, IEEE Guide for Performing Arc-Flash Hazard Calculations

[4] NFPA 70E - 2015, Standard for Electrical Safety in the Workplace

[5] AM-NTP003 - Arc Flash PPE Review for Aurora Network

[6] E(S)R - Electricity (Safety) Regulations 2010

[7] A. Wright and P.G. Newbury, Electric Fuses 3rd Edition, IET Power and Energy Series 49 2008

[8] ENA NENS 09-2014, National Guidelines for the Selection, Use and Maintenance of Personal Protective Equipment for Electrical Arc Hazards.

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