Arc Flash Risk Assessment

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Notice: The following has not been peer reviewed. Just a with anything you read on the internet, it should not be taken as factual in any way. The following represents my opinions. I am offering it up as a straw man argument in the hopes of advancing the risk assessment approaches being taken when evaluating arc flash hazards with regards to issues like "normal operation", "racking out breakers", and "doors open/closed".

One of the big issues surrounding risk assessments with arc flash hazards is the regular issue of whether or not PPE should be required. It is clear from reading NFPA 70E that this has been given consideration by the 70E Committee. For instance in the definition of Arc Flash Hazard, there is this tidbit:

> *Informational Note No. 1: An arc flash hazard may exist when energized electrical conductors or circuit parts are exposed or when they are within equipment in a guarded or enclosed condition, provided a person is interatcing with the equipment in such a manner that could cause an arc flash.*

Section 170.7(C)(15) describes how the arc flash PPE requirement is decreased by "1, 2, or 3 numbers" but does not explain how this was determined. This provides no help when risk assessments are being performed especially when the tables in Section 130.7(C)(15) are not being used.

In addition, this methodology contains an inherent flaw. PPE reductions may occur because the incident energy is reduced. Typically this would occur either because of modifications to the task (moving the worker further away from the equipment) or because of modifications to the equipment (decreasing trip times). Decreases in likelihood are just that. If the likelihood has become so remote that it is an acceptable risk, then PPE is no longer required. Otherwise, PPE suitable to prevent the hazard is necessary.

Another proposed methology, probabilistic risk assessment, follows similar reasoning to the 70E Technical Committee methodology. In this method, the likelihood is multiplied by the incident energy to derive a lower PPE requirement. The inherent fallacy with this methodology is that again, a reduction in likelihood does not mean that the injury is reduced if an incident occurs.

What is clearly needed is a quantitative approach to examining the likelihood of an arc flash occurring. Looking to standards, most risk assessment standards such as IEC 61508 or ANSI B11.TR3 use a quantitative approach to risk assessments. In these methodologies, each hazard for a given task is rated using two different parameters: the severity of the injury, and the likelihood that the injury will occur. These two parameters are compared to a risk ranking matrix which is typically company specific and not spelled out in the risk assessment standard.

In the case of severity of injury, without any particular PPE, if the arc flash incident energy (typically calculated using IEEE 1584 method) exceeds 1.2 cal/cm^2, a 2nd degree or worse injury will occur. Although a 1st degree burn may still be possible, there is no data to evaluate these lesser potential injuries. If arc flash PPE is worn correctly, then it is preseumed to function properly even in the event of an arc flash. Most quantitative risk assessments assign injuries to a ranking of either "severe" or "slight" so the lack of a range of injury information is not a strong limitation.

The second parameter is the probability that the employee will be exposed. This paper will cover calculation of this second parameter in detail.

Typical risk ranking matrix requirements for a "severe" injury result in a likelihood requirement of either 10^{-5}, 10^{-6}, or 10^{-7} injuries/year.

Task Breakdown

A careful analysis of the various electrical tasks shows that each can be categorized into one of the following categories, labeled A through E, in order of increasing likelihood of an arc flash hazard.

Category A – The risk is the same as "just walking by", such as performing a visual, infrared, or PD inspection (after the doors have been opened). This is the case described above where there is no interaction whatsoever with the equipment.

Category B – This category considers very minor interaction with the equipment such as checking the settings in a digital protection relay, reading a meter while operating a meter switch, or resetting an overload relay (externally). Failures in this case are a function of failures of the control circuits that then have to esclate into a failure of the power circuits.

Category C – This category considers energizing or de-energizing equipment using a mechanism that is specifically intended to make or break under load such as load break disconnects or circuit breakers. This definitely constitutes interacting with the equipment but since the equipment is designed to work under loaded conditions, the failure rate is a function of the equipment itself.

Category D –This category considers energizing or de-energizing equipment using non-load break mechanisms such as non-load break switches or racking breakers in and out. The risk is substantial because it depends on both the reliability of the operator and the equipment.

Category E-- This category considers energizing or de-energizing conductors directly. The conductors are not specifically designed for this purpose.

A pool of likelihood data is required to account for the types of equipment in use. Fortunately IEEE Std. 493 has a large data set containing the required information. The following summary table shows some of the likelihoods published in that document:

Device	Average Failure Rate/year
Above ground cable, above ground, <600 V	0.00007
Fixed (molded case/insulated case) CB	0.000007
Draw-out circuit breaker	0.001
GIS gear (post 1985)	0.0002[A]
Vacuum gear w/ electromechanical trip	0.0007[B]
Switchgear controls	0.02
600 V disconnect switch	0.0006
MV disconnect switch	0.002

[A] Source: Brown, *Electric Power Distribution Reliability*

[B] Source: Powell reported 0 trips in 20,000 unit-years yielding a trip rate of 0.000025 for a vacuum interrupter. IEEE data on component failures suggests that 5% of circuit breakers tested had failed power components while 14% had failed electro-mechanical trip units. A weighted average is thus (0.000025 x 5 + 0.001 x 14) / 19 = 0.0007.

Next, depending on the type of activity, the specific failure modes and failure rates for circuit breakers are of interest as follows:

Failure Mode	Drawout %	Other types %
Failed while opening or closing	9	10
Misoperation (did not open or close as expcted)	78	10
Failed in service (not opening or closing)	10	73
Failure discovered during testing	3	2
Other	0	5

Finally, IEEE also published data on the failure type:

Failure type	Breakers	Disc. Switches	Open wire	Cable	Joints	Terminations
L-G arcing fault	33%	15	34	73	70	55
L-L arcing fault	10	4	23	1	9	4
Other	57	81	43	26	20	41

Using this data, the likelihood of failure can be calculated for each of the possible task categories as follows:

Category A: "Just Walking By"

Failure rates are dependent on the equipment but can be calculated as the failure rate per year multiplied by the failure type. In addition, an exposure rate will have to be calculated which is equal to the amount of time per year that an individual is potentially exposed to the hazard. This latter category depends on the activity but is typically a very small number. For example, the task of reading an arc flash sticker performed 10 times per year for 3 minutes per time is 0.5 hours / 8760 hours/year = 0.00006. Multiplying by the failure rate for drawout circuit breakers (0.001) and arc flash likelihood assuming solidly grounded bus (43%) yields a likelihood of 0.000000025, using 1974 vintage breakers.

Category B: Interacting with Controls

Failure rates are dependent on both the likelihood of a control system failure and an arcing fault within the equipment. There are several potential failure modes of interest. For drawout breakers, these would be failure while opening or closing (9%). Again, 43% resulted in arcing faults but since the data may be skewed at this point due to narrowly focusing on the failure mode, the fault type will be ignored (assume 100% of faults are arcing faults). Failures for drawout breakers are again 0.001 failures/year, for a total rate of 0.00009 failures/year. At this point we reach a crossroads because it becomes necessary to mix the control system failure rate in failures/year with the breaker failure rate. In this case since the circuit breaker failure rate is only called upon on demand at a rate significantly less than once per year, we can use the approximation P_{FD} = (failure rate) * (1 year) / 2 = 0.000045. Multiplying by the switchgear controls failure rate (0.02) yields a final likelihood of an arcing fault of 0.0000009.

Category C: Energizing/De-Energizing with Interrupting Capability

Failure rates are again equipment dependent. The major difference is that in this case, interaction is happening. We are again concerned with the failure mode. So for a drawout breaker, the failure rate is

0.001 failures/year times 9% failures during operation for a likelihood of 0.00009.

Category D: Energizing/De-Energizing without Interrupting Capability

This category is very similar to Category C. The major difference is that in this case, human unreliability has to be taken into account. Taking the case of a low voltage (600 V class) disconnect switch, the inherent failure rate is 0.0006. A case could be made that nearly all failures only appear during switch operation. 19% of those result in arcing faults of some type, so the mechanism itself can fail with a rate of 0.000114/year for a failure rate involving the switch itself only (electro-mechanical failure). The arcing fault by itself is relatively harmless unless the load has not been removed, in which case the failure will result in a serious arc flash. The HEART method for evaluating human unreliability gives an average failure rate of 0.09 for the task. Multiplying yields a likelihood rate of 0.00001/year. The two failure rates can then be added together for a total likelihood of 0.00017.

Category E: Energizing/De-Energizing without Design for Purpose

This category is nearly entirely dependent on human reliability. Taking the case of terminating a cable while live, 59% of termination failures result in an arcing fault. Human unreliability for a restoration task is 0.26 if done without procedures or supervisory staff, resulting in a likelihood of 0.15. If this task is done routinely and there are procedures and supervision available, the average unreliability drops to 0.003 and the likelihood drops to 0.002 failures/year.

Modifiers

A number of modifications to the basic results are also possible as follows:

Elevate Category C equipment to D, and D equipment to E after a fault since the state of the equipment (in good repair, capable of interrupting a fault) is now in question.

Multiply failure rates by 2 when equipment is operating in a poor environmental condition (as per IEEE 493 frequencies).

Multiply failure rates by 0.5 when proper maintenance is performed (following NFPA 70B or NETA MTS practices).

If the system is operating ungrounded, multiply all failure rates for equipment unless the insulation is rated at 300% or more due to transient damage caused during a fault. For example when tripping a drawout breaker (Category C task) with control wiring that is not rated for 300% insulation factor (typical CPT construction), the failure rate increases to 0.004 failures/year, but for a disconnect switch, the original failure rate remains intact. Multiply all failure rates by 10% since over 90% of failures are L-G if maintenance procedures are in place to aggressively remove arcing faults within 24 hours. Otherwise, multiply by only 70% since two thirds of subsequent faults will result in a burndown. So for example when tripping a drawout breaker, the failure rate is 0.004 failures/year, 9% of them occur during operation of the breaker, and only 10% of those result in an arcing fault assuming aggressive maintenance practices resulting in an overall likelihood of 0.000036.

If the system is operating with a resistance grounding system in place, the same methodology is used for ungrounded systems except that transients are now controlled and the factor of 4 maintenance does not need to be considered. The failure rate for the previously mentioned breaker becomes 0.00009.

Multiply by 3 for Categories D and E for inexperienced personnel as suggested by the modifiers for HEART.

Worked Example

Assume that the risk ranking matrix requires a maximum likelihood of 0.0000001 for major personnel injuries (1 in a million) and that the calculated (IEEE 1584) incident energy for a particular molded case breaker is 3 cal/cm^2. Assume that it is solidly grounded with an electro-mechanical trip unit, and that average maintenance is being performed.

Question 1: Is PPE required while performing LOTO on this breaker if it is operating normally?

This is a Category C task. The failure rate for a molded case breaker is 0.000007 failures/year. 10% of the failure modes occur during opening or closing, for a failure rate of 0.0000007 failures/year assuming 100% of those trips result in an arcing fault. Answer: It is less than the required maximum likelihood, so PPE would not be required.

Question 2: Is PPE required while performing LOTO on this breaker if a fault is known to have occurred so that maintenance can be performed?

In this case, the breaker is in an unknown state, and becomes a Category D task. Using the failure rates for switches (0.0006), and that 19% of switch failures are arcing faults, the failure rate is now 0.000114. The person performing the LOTO may have also forgotten to remove the load from the circuit resulting in an overall failure rate of 0.00017. This is far greater than the hurdle rate of 1 in a million...PPE is required.

Question 3: Is PPE required while performing LOTO on the upstream breaker without a fault if the breaker is a draw-out type?

This is again a Category C task. Failure rates for drawout breakers are 0.001/year, and 9% of failures occur during opening or closing, for an overall failure rate of 0.00009/year. Yes, PPE is required.

Question 4: Can we do something about the drawout breaker to eliminate the PPE requirement?

Install a high resistance ground system with an automatic trip eliminates 90% of L-G faults. Install vacuum breakers (0.0007). Install self-diagnostic electronic trip units (source: SEL Inc. 85% of trip unit failures detected). Follow manufacturer/NFPA 70B maintenance requirements (multiply by 0.5). Total failure rate is thus 0.0007 x 0.09 x 0.1x 0.5 x 6/19 = 0.000001.

Question 5: Does the PPE requirement disappear when withdrawing the drawout breaker if the above modifications are performed?

No. It is a Category D task and equivalent to opening and closing a disconnect. Failure rate is 0.00017 x 0.1 = 0.000017 which is quite low but still above the hurdle rate of 1 in a million.

Conclusions

The results of this analysis seem to match closely with the cases where the 70E Technical Committee has deemed the risk to be remote and thus assigned a PPE requirement of “0” in the tables. In other cases, PPE is definitely required. However, the conclusion that PPE can be reduced by “1, 2, or 3 categories” does not follow. Based on likelihood of injury, either adequate PPE is required or not. A reduction in PPE could be viable only if the incident energy is reduced. This report provides a methodology for using quantitative risk assessment methodology to determine when PPE would be required even if the engineering approach to risk assessments is performed.