A Practical Methodology to Arc Flash Mitigation Strategy

Solution Guide

Abstract

Arc flash is a serious problem that has spawned a wide range of possible strategies for mitigation. Facility managers and consulting engineers should use a methodology to sort through the various mitigation strategies and prioritize them for optimal deployment in a facility/electrical system design. This practical solution guide describes one approach based on the well-accepted Failure Mode and Effects Analysis (FMEA) concept and illustrates its use in examining a range of potential mitigation strategies. Engineers can use this model and process to examine their existing facilities or new designs.

Introduction

Increased awareness of the problems and dangers associated with electrical hazards in the workplace has prompted the development and deployment of new code requirements and compliance activities. In response, engineers and equipment manufacturers have created a variety of products and solutions targeted at mitigating these hazards. Arc flash, given its potentially deadly results, has been a particular focus for the development of mitigation products and strategies. As a result, the facility manager or consulting engineer can be faced with a complex set of choices when developing mitigation strategies in a new system or when upgrading an existing system.

The industry has responded with guidelines and methodologies to help sift through options to mitigate hazards for activities that could generate arc flash and other dangerous events. Applying an FMEA model is of particular value because it can generate metrics for prioritizing and comparing various mitigation strategies. An engineer can combine a standard cost/benefit analysis methodology with FMEA to create an optimal deployment strategy. The FMEA methodology captures the knowledge and experience of the engineer and leverages industry standard measurements and metrics to produce an analysis that is as objective and data driven as possible.

This solution guide explains the FMEA methodology for the analysis and selection of hazard mitigation strategies. Then an illustrative example shows how to analyze a variety of arc flash mitigation strategies for activities that could unintentionally create an arc flash event. The example identifies common industry metrics used as part of the FMEA methodology. An engineer should feel more confident and capable in using FMEA for a specific power analysis.

Arc Flash Mitigation Strategies: A Short Background

Arc flash events occur during an electrical fault or short circuit condition that passes through a physical arc gap. An arc flash event can expel very large amounts of deadly energy caused by the ionization of the air, creating a temperature hotter than the surface of the sun as well as rapid gaseous expansion. An engineer can use three basic techniques to reduce the potential damage (or equivalently, reduce the amount of incident energy experienced):

1 **Shorten the duration of the event, which directly reduces the amount of incident energy that results.**

2 **Limit current generated, which directly reduces the amount of incident energy available.**

3 **Increase the distance between the event and the operator to reduce the human impact of the incident.**

Facility managers may also employ other mitigation techniques to reduce the impact of incident energy, such as using heat-and-flame resistant clothing, personal protective equipment (PPE) or other physical barriers.

To rank hazards and evaluate a variety of mitigation approaches, engineers often turn to ANSI Z10[1], a classification hierarchy of hazard control measures. This well-recognized approach to arc flash mitigation is described in the paper "Adapting Failure Mode And Effects Analysis (FMEA) To Select Hazard Mitigation Measures," by Marcelo E. Valdes[2]. The ANSI Z10 hierarchy and author's examples of arc flash control measures appear in **Figure 1**. A detailed description of FMEA and the example used in this guide are available in the paper[2].

As illustrated, the hierarchy in **Figure 1** places greater value on measures that automatically reduce or eliminate hazards versus measures that require human activity or interpretation. This is consistent with an expectation that any human activity is subject to possible error and is inherently less reliable than automatic measures. The hierarchy does not prevent the simultaneous use of multiple solutions. In fact, an engineer can evaluate the use of multiple hazard control measures on the lower end of the hierarchy, since these measures are typically 'additive' and not exclusive.

Effectiveness		Hierarchy of Hazard Control Measures (ANSI Z10)	Examples of Arc Flash Incident Energy Control Measures
Most	1	Elimination of the hazard	Secured & verified de-energization
	2	Substitution of less hazardous equipment or materials	Smaller transformers, lower voltage, insulated bus bars, internal barriers
	3	Engineering control to reduce exposure or severity	Faster over-current protection, energy shunting devices
	4	Warnings, signs, and other communications	Signage, training, indicating lights
	5	Administrative control, including safe work practices	Maintenance switch, specific work practices
Least	6	Personal protective equipment	PPE per applicable standards, temporary barriers

Fig. 1 Hierarchy of Hazard Control Measures

With that background, let's explore the details of the FMEA methodology and, in particular, apply the methodology to a practical example.

5-Step FMEA Process Overview

Outlined below are the FMEA steps for optimizing arc flash mitigation strategies:

1. Identify activities performed that pose risks
2. Assess and assign frequency of activity, probability of incident and potential severity
3. Calculate base risk priority number (BRPN)
4. Identify options to mitigate or reduce BRPN
5. Assign an effect co-efficient based on an expected change in frequency, probability and/or severity for each activity by each option to quantify BRPN reduction and rank potential solutions

Description of Failure Mode and Effects Analysis (FMEA) Model

FMEA was initially used for military applications in the 1940s to evaluate risk management options for mitigating known threat vulnerabilities. It has evolved for use in industrial settings to efficiently select remedial actions from multiple options and reduce frequency or impact from system, subsystem or component failures. **Figure 2** identifies the key steps in a typical FMEA analysis.

Step 1: Detect failure mode
Identify the failure that produces an undesirable outcome.

Step 2: Severity assignation
Assign a degree, preferably measurable, of severity to that outcome.

Step 3: Probability assignation
Determine the probability of the failure mode.

Step 4: Detection assignation
Assign a probability of not detecting the failure mode before consequences occur.

A high value in steps two through four indicates the least desirable state: high severity, high probability of occurrence and/or low probability of detection prior to the failure having an effect. The multiplication of each of these factors together yields a risk priority number (RPN) that is used to select the most important design changes or corrective actions. To determine the effects of any improvements to the system, an engineer must first calculate the base RPN (BRPN) of the system. Changes applied to mitigate failures can then be compared to the BRPN to identify those with the best outcome.

To quantify the key elements of the FMEA activity model—frequency of opportunity (OPP), probability of an incident during the activity (PROB) and the level of severity (SEV)—an engineer creates a table that identifies each of these elements and assigns a numerical value as shown in **Figure 3**.

Fig. 2 FMEA Activity Model

Figure 3 lists numerical assignments to opportunity, probability and severity for an example activity related to arc flash mitigation; each can take on values between one and 15. Specific numeric values within this range are further identified as being high, moderate or low, as shown at the bottom of the figure. For example, high values for frequency and probability are assigned a 15, while moderate and low values are nine and three, respectively. Severity also receives numerical values between one and 15, based on the incident energy of an arc flash event, with 30 cal/cm^2 being the most severe and 1.2 cal/cm^2 being of low severity (as a point of reference, 1.2cal/cm^2 results in 2nd degree burns to bare skin and 8 cal/cm^2 in 3rd degree burns). An engineer can assign these metrics to individual activities, as shown in the entries at the middle of the figure.

Activity that creates incident opportunity	Frequency of activity (opportunity)		Risk (activity's incident probability)		Severity of consequence		Hazard RPN
Activity A	15	X	15	X	12	=	2700
Activity B	15		9		15		2025
Activity C	9		9		15		1215
Activity D	6		9		3		162
Activity E	3		3		3		27
Activity F	3		3		1		9
					Base RPN (BRPN) before hazard mitigation activity =		6138.0

opportunity probability severity scale:
1, 3, 6, 9,12, 15. 1= lowest, 15= highest

Frequency	Probability	Severity
High =15	High =15	>30 cal/cm^2 =15
Moderate =9	Moderate =9	>8 cal/cm^2 =12
Low =3	Low =3	>1.2 cal/cm^2 =3
		≤1.2 cal/cm^2 =1

Fig. 3 FMEA Activities to Establish Base RPN

Once the individual activity metrics have assigned values, they are multiplied together to determine the hazard RPN. Activity A is determined to have an RPN of 2700, by multiplying together the values for opportunity frequency (15), probability (15) and severity (12). The baseline RPN is the sum of the RPN for the group of activities. In the example shown in **Figure 3**, the BRPN is 6138. Any mitigation strategies an engineer may employ should reduce the BRPN, and mitigation strategies that reduce the BRPN the most should be prioritized for a more detailed analysis. In some cases, a mitigation strategy can be applied to multiple activities, creating a significant overall mitigation result.

In order to analyze the mitigation for a particular action, an engineer estimates the changes in the opportunity, probability or severity of the activity by applying an effect coefficient. For example, in **Figure 4** there are three possible mitigation solutions under analysis. If the solution has no effect on the opportunity, probability or severity, the effect coefficient is set to 1. If there is an effect, the engineer scales the associated coefficient to measure the likely reduction in the factor. For example, in Solution 1 the probability of an arc flash event during Activity A is judged to fall to 10%, and thus the effect coefficient is set to 0.1. Note that Solution 1 also reduces the probability of arc flash events in Activities D and E, so the coefficient factors are set to 0.1 for these factors as well. The resulting reduction from the BRPN of 6138 appears at the bottom of each individual solution sub-matrix. This process is often described in technical literature as 'filtering' the hazard FMEA through the mitigation solution coefficient matrix to arrive at the BRPN reductions.

		Opportunity		Probability		Severity		All
		Effect coefficient	Affected factor	Effect coefficient	Affected factor	Effect coefficient	Affected factor	Affected RPN
Solution 1	Activity A	1	x 15	x 0.1	x 1.5	x 1	x 12	270
	Activity B	1	15	1	9	1	15	2025
	Activity C	1	9	1	9	1	15	1215
	Activity D	1	6	0.1	0.9	1	3	16
	Activity E	1	3	0.1	0.3	1	3	3
	Activity F	1	3	1	3	1	1	9
	Net reduction provided by solution 1 from BRPN=							2600
Solution 2	Activity A	0.1	1.5	1	15	1	12	270
	Activity B	0.1	1.5	1	9	1	15	203
	Activity C	0.1	0.9	1	9	1	15	122
	Activity D	1	6	1	9	1	3	162
	Activity E	1	3	1	3	1	3	27
	Activity F	1	3	1	3	1	1	9
	Net reduction provided by solution 2 from BRPN=							5346
Solution 3	Activity A	1	15	0.5	7.5	1	12	1350
	Activity B	1	15	0.5	4.5	1	15	1013
	Activity C	1	9	0.5	4.5	1	15	608
	Activity D	1	6	0.5	4.5	1	3	81
	Activity E	1	3	0.5	1.5	1	3	14
	Activity F	1	3	0.5	1.5	1	1	5
	Net reduction provided by solution 3 from BRPN=							3069

Scale: 0, 0.1, 0.5, 1. 0 = complete mitigation, 1 = no effect

Fig. 4 RPN Reductions by Applying Mitigation Coeffecients

It is important for the above process to leverage the experience and knowledge of the engineer and not be viewed as a purely mechanical process. In particular, the engineer should assign values for the effect coefficients only after detailed evaluation of all the activity and mitigation strategies. It may be that secondary effects come in to play that keep the coefficient from being too low (or zero) due to the possibility of human error or incorrectly following complex procedures. The tool is best used when it incorporates the detailed knowledge the user has of the entire system under analysis.

Applying FMEA to Arc Flash Mitigation: A Real-World Example

To better understand the FMEA process in sufficient detail to be able to apply it to your own system, it is useful to take a familiar, practical example and go through each step of the process. Additionally, the example analysis becomes a good starting point for an engineer's analysis of a new or existing facility. The following example considers several typical activities listed as having some level of arc flash hazard or shock hazard within NFPA 70E[3]. Against these activities the example analyzes the effect of a small sample group of arc flash hazard mitigation solutions. (Note that the values assigned for this example are selected for purposes of illustration and are **not reflective of actual values** for a specific facility or electrical system. Users must carefully select each metric based on their experiences and knowledge or from recognized industry standards when available.)

The activities to be considered are these:

- Insertion or removal of a low-voltage power circuit breaker (LVPCB) from draw-out switchgear with the doors closed. Fault current available 50-55kA at 480V.
- Removal of bolted cover from the same switchgear for purposes of an infrared survey.
- Troubleshooting of control wiring in the same switchgear with doors to live conductors open.
- Insertion or removal of starter buckets from a 480V motor control center (MCC) with 50-55kA available, protected by conventional switchgear low voltage power circuit breakers.
- Removal of bolted covers from the same MCC for purposes of an infrared survey.

ArcWatch-Based Mitigation Solutions Address Multiple Activities

As is seen in the example design, 'point solution' mitigation strategies that attack a single activity provide BRPN reductions for a single entry (or line) in the effect coefficient matrix. If a single activity is a very large contributor to the overall BRPN, a point solution can be an effective mitigation approach. More typically, multiple activities are involved, so the engineer should look for approaches that address multiple activities. Reductions made on several entries of the coefficient matrix reduce the overall PBRPN much more than a single solution. For example, both GE ArcWatch Circuit Breaker and ArcVault Containment System technologies provide reductions for all the activities shown in the example design.

ArcWatch technology, found in specific low-voltage GE trip units and circuit breakers, gives engineers the ability to improve arc flash protection without sacrificing selective coordination. An engineer can set the instantaneous pick-up value on a circuit breaker sufficiently below the predicted arcing current, permitting the circuit breaker to clear arcing faults using the circuit breaker's fastest speed. The selective coordination may also minimize incident energy, which also contributes to lower results in the BRPN. Furthermore, ArcWatch technology is full-time, always-on so it doesn't require potentially error-prone human intervention to operate.

ArcVault is a shunt device that redirects and contains the arc flash away from the operator into a protected dome. This shunt device provides high-risk reduction to minimize PPE damage. ArcVault is a system that requires strong administrative procedure guidance and adherence to realize the maximum benefit.

The arc flash hazard mitigation solutions evaluated are these:

- Arc resistant (AR) switchgear for the low-voltage switchgear, reducing incident energy to < 8 cal/cm^2
- Use of infrared scanning windows in the switchgear
- Use of infrared scanning windows in the MCC
- Use of a permanently installed thermal monitoring system within the switchgear
- Use of a permanently installed thermal monitoring system within the MCC
- Use of more optimized circuit breaker settings to reduce incident energy to <8 cal/cm^2
- Use of a shunt energy absorption device operated by a maintenance switch at the main switchgear providing incident energy <1.2 cal/cm^2

Figure 5 shows the example BRPN matrix with values assigned for opportunity frequency, risk probability and potential severity. Note the consequence severities are all high or moderate based on the incident energy available during an activity-associated arc fault event. Switchgear-related activities, with incident energy > 30 cal/cm^2, have high severity and activities related to the MCC, with incident energy >8 cal/cm^2, have moderate severity. The resulting BRPN metric adds up to 4347, with the switchgear (SWGR) cover removal for IR scan being the largest contributor to the BRPN result. In many cases one or two activities appear to be major contributors (key risks) and will receive higher priorities for a mitigation strategy.

Activity that creates incident opportunity (exposure)	Activity frequency (opportunity)	Freq. X effect	Risk (probability of incident during activity)	Risk X effect	Severity of consequence	Severity X effect	Hazard RPN
SWGR CB removal/insertion	9	X	3	X	15	=	405
SWGR cover removal for IR Scan	9		15		15		2025
Troubleshooting wiring in SWGR	3		9		15		405
MCC starter removal/insertion	15		3		12		540
MCC cover removal for IR Scan	9		9		12		972
						Base RPN =	4347

Fig. 5 **BRPN Matrix for Arc Flash Examples for Five Activities**

Figure 6 shows the effect coefficient matrix assigned to each arc flash mitigation measure for each hazard producing activity. These coefficients would contain the practitioner's assessment of the effect of each arc flash mitigation solution on reducing the opportunity frequency, risk probability or severity for each activity. Note that some mitigation strategies apply to a single activity while others can apply to multiple activities and factors. It is important for these coefficients to be based on the user's experience and knowledge and should, whenever possible, include quantifiable factors such as incident energy, voltage level exposure, distance, the hierarchy of hazard control measures, known reliability data and other similar factors.

Once the effect coefficients are all identified, the engineer may filter the hazard FMEA through the mitigation solution coefficient matrix to arrive at the BRPN reductions. **Figure 7** shows the details of the calculations for each activity and mitigation strategy on the associated RPN. Typically there is a wide range of potential RPN reductions that result from the analysis. In fact, if the ranges are too similar, the strategies analyzed may be too narrowly focused and the engineer should consider additional strategies.

	AR Swgr	IR windows SWGR	IR windows MCC	7x24 thermal mntr Swgr	7x24 thermal monitoring MCC	Faster CB	Shunt Dev. Main. Switch
Opportunity	**Effect on need to engage in activity**						
SWGR CB removal/insertion	1	1	1	1	1	1	1
SWGR cover removal for IR Scan	1	0.1	1	0.1	1	1	1
Troubleshooting wiring in SWGR	1	1	1	1	1	1	1
MCC starter removal/insertion	1	1	1	1	1	1	1
MCC cover removal for IR Scan	1	1	0.1	1	0.1	1	1
Risk	**Effect on probability of incident during activity**						
SWGR CB removal/insertion	1	1	1	1	1	1	1
SWGR cover removal for IR Scan	1	1	1	1	1	1	1
Troubleshooting wiring in SWGR	1	1	1	1	1	1	1
MCC starter removal/insertion	1	1	1	1	1	1	1
MCC cover removal for IR Scan	1	1	1	1	1	1	1
Severity	**Effect on seriousness of incident**						
SWGR CB removal/insertion	0.1	1	1	1	1	0.5	0.1
SWGR cover removal for IR Scan	1	1	1	1	1	0.5	0.1
Troubleshooting wiring in SWGR	1	1	1	1	1	0.5	0.1
MCC starter removal/insertion	1	1	1	1	1	0.5	0.1
MCC cover removal for IR Scan	1	1	1	1	1	0.5	0.1

Notes: Perceived effect may vary by user and situation

1 AR SWGR has no effect on opportunity but has effect on severity for some activity in the AR equipment.

2 IR windows and thermal monitoring significantly diminish need for cover removal, expected that some cover removal may still be required hence it's not "0".

3 Faster CB settings reduce Ei during all activity but has no effect on severity or risk of incident during activity. Reduction is not expected to be to minimum level.

4 Shunt device typically reduces Ei to minimum levels. However, maintenance switch requires administrative procedure while 7x24 offers continuous protection. Risk modified to reflect "probability" associated with administrative procedure though it does not affect probability of incident.

Fig. 6 Effect Coefficients for Arc Flash Mitigation Solutions

The results range shown in the example analysis in **Figure 7** is typical and illustrates the effect that point solution strategies may have on the outcome.

Studying the details produced by the analysis provides a useful sanity check and should be done to insure that the results are logical and consistent. This weeds out possible entry errors and misapplication of the process. Organizing the BRPN reduction results in a table, sorted by most effective to least effective, as done in Table 1 below can assist in evaluation of the results. The ranking of results for the example system seems logical, since strategies that mitigate arc flash events on multiple activities are more effective. Results that seem inconsistent or illogical should be looked at in more detail and could be the result of an error in the process or could provide new insight into the nature of the underlying system.

Analyzing Combined Hazard Mitigation Measures

This analysis does not take into account combinations of hazard control measures. These could be analyzed similarly by combining the hazard reduction measures that are complementary and do not address the same hazard in a

Fig. 7 Detailed BRPN Reduction Matrix for Example Arc Flash Mitigation Strategies

Activity that creates incident opportunity (exposure)	Activity frequency (opportunity)	Freq. X effect	Risk (probability of incident during activity)	Risk X effect	Severity of consequence	Severity X effect	Hazard RPN
SWGR CB removal/insertion	9		3		15		405
SWGR cover removal for IR Scan	9		15		15		2025
Troubleshooting wiring in SWGR	3		9		15		405
MCC starter removal/insertion	15		3		12		540
MCC cover removal for IR Scan	9		9		12		972
						Base RPN=	4347
AR SWGR							
SWGR CB removal/insertion	1	9	1	3	0.1	1.5	41
SWGR cover removal for IR Scan	1	9	1	15	1	15	2025
Troubleshooting wiring in SWGR	1	3	1	9	1	15	405
MCC starter removal/insertion	1	15	1	3	1	12	540
MCC cover removal for IR Scan	1	9	1	9	1	12	972
						Base RPN reduction =	365
IR windows in SWGR							
SWGR CB removal/insertion	1	9	1	3	1	15	405
SWGR cover removal for IR Scan	0.1	0.9	1	15	1	15	203
Troubleshooting wiring in SWGR	1	3	1	9	1	15	405
MCC starter removal/insertion	1	15	1	3	1	12	540
MCC cover removal for IR Scan	1	9	1	9	1	12	972
						Base RPN reduction =	1823
IR windows in MCC							
SWGR CB removal/insertion	1	9	1	3	1	15	405
SWGR cover removal for IR Scan	1	9	1	15	1	15	2025
Troubleshooting wiring in SWGR	1	3	1	9	1	15	405
MCC starter removal/insertion	1	15	1	3	1	12	540
MCC cover removal for IR Scan	0.1	0.9	1	9	1	12	97
						Base RPN reduction =	875
7x24 thermal monitoring SWGR							
SWGR CB removal/insertion	1	9	1	3	1	15	405
SWGR cover removal for IR Scan	0.1	0.9	1	15	1	15	203
Troubleshooting wiring in SWGR	1	3	1	9	1	15	405
MCC starter removal/insertion	1	15	1	3	1	12	540
MCC cover removal for IR Scan	1	9	1	9	1	12	972
						Base RPN reduction =	1823
7x24 thermal monitoring MCC							
SWGR CB removal/insertion	1	9	1	3	1	15	405
SWGR cover removal for IR Scan	1	9	1	15	1	15	2025
Troubleshooting wiring in SWGR	1	3	1	9	1	15	405
MCC starter removal/insertion	1	15	1	3	1	12	540
MCC cover removal for IR Scan	0.1	0.9	1	9	1	12	97
						Base RPN reduction =	875
Faster CB tripping							
SWGR CB removal/insertion	1	9	1	3	0.5	7.5	203
SWGR cover removal for IR Scan	1	9	1	15	0.5	7.5	1013
Troubleshooting wiring in SWGR	1	3	1	9	0.5	7.5	203
MCC starter removal/insertion	1	15	1	3	0.5	6	270
MCC cover removal for IR Scan	1	9	1	9	0.5	6	486
						Base RPN reduction =	2174
Maintenance sw operated shunt dev.							
SWGR CB removal/insertion	1	9	1	3	0.1	1.5	41
SWGR cover removal for IR Scan	1	9	1	15	0.1	1.5	203
Troubleshooting wiring in SWGR	1	3	1	9	0.1	1.5	41
MCC starter removal/insertion	1	15	1	3	0.1	1.2	54
MCC cover removal for IR Scan	1	9	1	9	0.1	1.2	97
						Base RPN reduction =	3912

Scale: 0, 0.1, 0.5, 1.
0 = complete mitigation, 1 = no effect

mutually exclusive manner. For example, an engineer may combine the use of arc resistant (AR) switchgear with either infrared windows or permanent thermal monitoring, or the use of one of the shunt energy device solutions and AR switchgear. Combination of one or more measures that provide limited value in isolation may provide a synergistic cumulative benefit for specific hazard combinations.

Summary

The FMEA methodology demonstrated on an example system shows how to evaluate a variety of arc flash mitigation strategies over a range of tasks that could be impacted by an arc flash event. This methodology is a useful process for facilities managers who are considering an upgrade or for consulting engineers considering a new design. The analysis provides a framework within which the user can include unique, specific knowledge and experience with the facility or design combined with the expected activities that could be affected by arc flash events. The careful use of the FMEA methodology results in a prioritized list of the considered mitigation strategies and an associated metric that can be used in a cost/benefit analysis to determine an optimal strategy deployment.

References

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