Starting Small – a Hierarchy of Mitigation for Industrial Arc Flash

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***Abstract*— Arc flash studies and mitigation are critical for worker safety, but navigating modeling techniques and mitigation strategies can be confusing and expensive. Before installing upgraded relays, fiber optic sensors, or differential protection schemes, it is useful to work through an established hierarchy of less intensive solutions.**

Easily overlooked system modeling details -- specifically electrode configuration, bus isolation, and fuse sizing – can greatly change arc flash analysis results. New to IEEE 1584-2018 standard, electrode configuration selection takes into account physical layout of the energized bus components. Bus isolation pertains to if the main protective device can be relied on to clear a fault on the bus it is protecting. Fuse sizing can also mitigate arc flash incident energies, but fuses must be able to handle normal system currents without sustaining damage.

Two common protection solutions, which are relatively simple to model and analyze, should also be considered before upgrading relay devices. These solutions are Maintenance Mode (also known as hot line/hot bus tag) and fiber optic arc flash sensing. Fiber optic sensing is now state of the art. A direct comparison of these schemes using calculations from IEEE 1584-2018 is necessary to show which is more effective at lowering arc flash incident energy.

This paper proposes solutions to industrial arc flash mitigation, starting with simpler and less expensive options and working up to enhanced protective relaying schemes. This paper will also present some common "gotchas" that have been addressed while working in the industry. Unlike many mitigation references, arc flash calculation methodology and modeling strategies for accurate arc flash risk modeling are taken into consideration before moving to settings changes. In an example system, both Maintenance Mode and fiber optic sensing mitigation techniques are then modeled and presented as a data-based comparison of these solutions.

Keywords—Arc Flash, IEEE 1584, incident energy, light sensor, maintenance mode

I. INTRODUCTION

Arcing currents are a phenomenon that occur when an electrical current path arcs through the air from conductor to conductor or to ground. The heat and pressure caused by an Arc Flash can cause significant damage to electrical equipment and can be dangerous and sometimes even fatal to personnel working on or near live equipment. Taking extra precaution to analyze existing or future electrical equipment installations to determine incident energy levels is applicable to almost any electrical service and pertinent to worker safety.

Arc flash standards give guidance on how to perform a study and interpret the results, but when mitigation is required, it can be difficult to know where to start. Techniques presented here have been used successfully by the authors in real-world arc flash studies and mitigation. In this paper we discuss processes to mitigate excessive incident energy levels starting with inexpensive and relatively easy to implement options and moving up the hierarchy to more expensive or complicated to implement options.

The simple one-line diagram shown in Figure 1 is used to quantify the results of proposed mitigation strategies throughout this paper. It is nominally 5 kV unless otherwise stated. A source capable of producing 70 kA of three phase short circuit current, which can represent a utility source or a generator, feeds a main distribution bus and several feeders. Arc flash analysis is performed on the main bus and one downstream feeder bus.

All three relays – F1 Feeder Relay, Main Relay, and Remote Relay – have a single 51P phase time overcurrent element enabled. These overcurrent elements are coordinated and set to protect downstream elements, such as cables and breakers. This is an extremely simple system, but by making incremental changes and directly comparing arc flash incident energy results actual modeled effects described in this paper can be quantified.

Appendix A lists all test conditions and results from this example model.

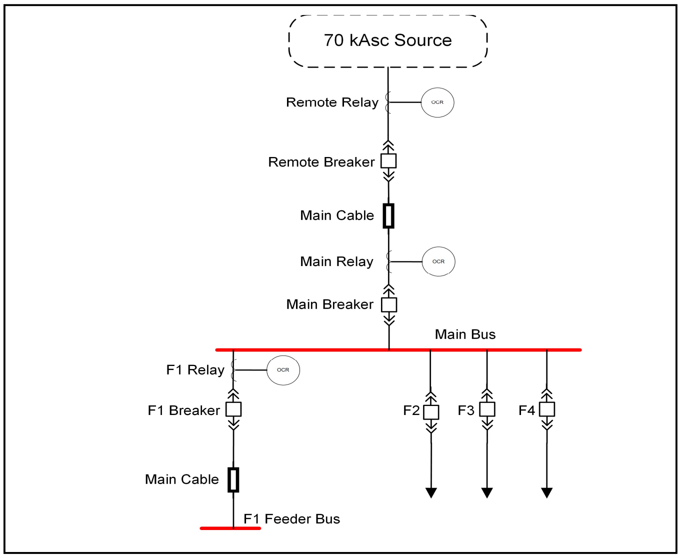

Fig. 1. Test system configuration

II. ACCURATE SYSTEM MODELING

Accurately modeling the electrical system for an arc flash study is crucial for worker and equipment safety. If the calculated incident energy exposure risk is lower than actual, proper care may not be taken by workers maintaining energized equipment. It is tempting to make conservative assumptions in the model when data is not readily available to minimize risk, but higher-than-actual results will also have drawbacks. PPE designed for higher incident energies is heavy, hot, and clumsy - the wearer is exposed to unnecessary discomfort and may take longer to finish a dangerous task. Over-conservative assumptions can also lead to unnecessary costly mitigations, such as upgrading switchgear or requiring process shutdowns before work can begin. A more accurate model may raise or lower your calculated incident energies and is always best practice.

Data collection and modeling, or verification of data in an older system model, is a complex and time-consuming task that will not be covered here. However, some system attributes that factor into arc flash calculations are easy to overlook in the revised IEEE 1584-2018 standard. These factors should be taken into consideration before costly system upgrades or even relaying changes are proposed.

A. IEEE 1584-2018

The IEEE 1584 standard for performing Arc Flash calculations was first released in 2002, based on empirical testing and physics knowledge. It is now referenced in NFPA 70E, the OSHA approved standard for industrial arc flash safety. Most arc flash software programs use calculations specified in IEEE 1584; be sure to check the software manual and settings to ensure this is the case. Another calculation method, called the Lee method, was developed by Dr. Ralph Lee in 1982. The Lee method is theoretically derived and produces conservative results. It should be used for voltages over 15 kV, which are currently not covered by IEEE 1584 [1].

In 2018, IEEE released an updated standard after performing more than 2000 additional tests. These updates include additional variables and calculation adjustments to better align the calculations with actual test results [1]. The parameters discussed below were not part of IEEE 1584-2002, but will impact results when using the 1584-2018 guidance. In addition, the following calculation methods have changed which will impact results:

- **Continuous Voltage Spectrum** - Arcing short circuit current is now determined through mathematical interpolation between three tested voltage levels, instead of using two blanket equations across a wide voltage range.
- **Arcing Current Variation Correction Factor** - An equation is provided to more accurately determine the lower bound of arcing current, instead of assuming 85% of maximum arcing current.

Cases D, E, and F in Appendix A give IEEE 1584-2002 results at three different voltage levels (480V, 5 kV, and 13 kV). These cases can be compared to J, K, and L, in which all variables are identical but IEEE 1584-2018 calculations are used. Incident energy on the main bus decreased by 37% at 480 V, 20% at 5 kV, and 16% at 13 kV. However, there is no guarantee that using IEEE 1584-2018 equations will lower incident energy – especially if electrode configuration is not vertical (VCB).

B. Bus Electrode Configuration

The direction of the arc blast will vary the amount of energy a worker is exposed to. IEEE-2018 now takes into account electrode configuration, which describes how the three phase bus is physically situated with respect to the worker. Acronyms and descriptions of the possible configurations are listed below:

- **VCB** - Vertical Conductors in Metal Box
- **VCBB** - Vertical Conductors in Metal Box terminating in an insulated Barrier
- **HCB** - Horizontal Conductors in a Metal Box
- **VOA** - Vertical Conductors in Open Air
- **HOA** - Horizontal Conductors in Open Air

Horizontal conductors (HCB, HOA) produce higher incident energy values, since arc blasts are typically emitted along the plane of the bus. The insulating barrier in VCBB configurations leads to higher incident energies than VCB, because more of the arc energy deflects forwards towards the person [2]. Open air conductors (VOA, HOA) are typically rare below 15 kV on industrial distribution. It may be necessary to take photos or look in equipment manuals to determine which configuration to select, but this step is important if using IEEE 1584-2018. Assuming the worst case HOA or HCB will definitely lead to elevated incident energy levels.

In Appendix A, Case I shows results for an HCB configured main bus and feeder bus; in Case J all other parameters are the same, but both busses are VCB configured. When VCB configured, the main bus incident energy decreases by 58% and the feeder by 56%. These results show that electrode configuration has a large impact on calculated arc flash incident energy. It should also be noted that VCB results are lower than the closest equivalent IEEE 1584-2002 model, but HCB results are almost double.

C. Enclosure Type

The IEEE 1584-2018 standard is normalized for a “typical” box which is 20”x20”x20”. A calculated correction factor (CF) is applied for enclosures larger or smaller than the “typical” box; this correction factor modifies incident energy to account for how much the enclosure concentrates blast energy toward a worker. Generally larger enclosures allow arc energy to disperse and cool more, producing lower incident energy values at the worker [3].

“Shallow” enclosures are a notable exception to this generality. In IEEE 1584-2018, a separate equation for “shallow” enclosures with depth eight inches or less is defined. The following three factors must be true for the enclosure to be considered shallow:

- Height and width both less than 20 inches
- Depth less than 8”
- System voltage less than 600V

Shallow enclosures produce a lower incident energy, because a larger percentage of blast energy escapes around the short sides of the enclosure [1]. Direction of the arc blast can considerably change the amount of energy a worker is exposed to.

If an enclosure has atypical dimensions, they should be entered directly. However, the IEEE 1584-2018 and 2002 standards provide a chart of accepted default dimensions for different enclosure types, such as Switchgear (SWGR), Motor Control Centers (MCCs), Panelboards, and Junction Boxes. Most Arc Flash software programs allow these descriptors to be entered directly and will modify the enclosure dimensions according to the standard. The gap between conductors can also be defined in relation to one of these default enclosure type – larger conductor gaps allow for longer arcs, which release more incident energy [1].

Case C in Appendix A gives IEEE 1584-2002 incident energies when the enclosure types are set to “other”, meaning an unknown conservative value. At this setting, the gap between conductors is 104 mm and the enclosure size is a 20” box. When the main bus is defined as “Switchgear” in Case D, the conductor gap changes to 32 mm and the enclosure to a 36” box. When defined as “Switchgear”, the main bus incident energy decreases by 52%.

Low voltage (480V) Cases K and M are used to demonstrate shallow enclosures. A shallow enclosure decreases Main incident energy by 28% and feeder incident energy by 33%.

D. Bus Isolation

Bus isolation refers to whether or not the main protective device directly upstream of a given bus is physically separated from arc flash damage on that bus. If the main protective device is not isolated faults can arc from the bus to the protective device, damaging and disabling it. In this case the main protective device can no longer reliably protect the bus from arcing faults, so the next upstream protective device is relied on to clear the fault. This leads to longer clearing times and thus, higher incident energy levels. If the main protective device is isolated from the bus, such as metal-clad switchgear conforming to IEEE Standard C37.20.2, then there is little risk of an arcing fault and the main protective device will trip for the fault.

Cases B and H in Appendix A give results for both IEEE 1584-2002 and 2018 revisions, without an isolated main protective device. Cases D and J are identical except for their main protective devices are isolated. For the 2002 revision case, incident energy decreased by 37% when the main was isolated. For the 2018 case it decreased by 38%. In neither calculation method did the feeder incident energy change, because the protective device is remote to the bus and is by definition isolated.

E. Other Modeling Considerations

There are several common errors to check for before finalizing a model. These cases should be checked for any modeled bus producing an extremely high or low incident energy values. In addition, it is good practice to perform hand calculations for bolted fault current, arcing current, clearing time, and incident energy at a few busses to check for general software or case setup errors.

1) Relay Trip Output

If a modeled relay is not set up to trip the correct breaker, the fault will not be interrupted. Slower upstream elements may clear the fault, but this will produce a longer fault clearing time which raises incident energies. Ensure all relays trip the correct breaker. Appendix A Cases J and N show main bus incident energy increasing by 60% when the main relay was not assigned to trip any breaker. Essentially, the upstream line end relay/breaker cleared the fault after a longer time.

2) Outdated Relay Settings

If working with an older model, verify relay settings are up to date. Protective device time-current curves are used to determine clearing time for a calculated arcing fault current, so missing or incorrect setting elements will change the incident energy at downstream busses. It is common for field changes or even large projects to not be reflected in the model. Incorrect current transformer ratios will also cause errors.

3) Maximum Fault Clearing Time

High incident energies result from long clearing times. In the model study settings, be sure a maximum clearing time is set. This value should represent the time it takes a worker to move away from the arc blast, or more realistically to be blasted away. Two seconds is suggested as a reasonable assumption by IEEE 1584, but should only be used if the area is open enough for the worker to get away. Enclosed spaces and suspended platforms may require longer maximum clearing times. Setting the maximum clearing time will reduce incident energy for clearing times over two seconds, but results will likely remain very high.

4) *Differential Schemes*

Bus, line, and transformer differential schemes can be easily overlooked in arc flash studies, even though they dramatically improve results. Look through drawings and photos to be sure all differential elements are modeled. Some software programs allow direct modeling of differential relays, but care must be taken to correctly model CT ratio and polarity. It can be easier to calculate the clearing time of a differential element by summing the relay and breaker operate times, then setting this as the clearing time for the protection elements. Differential scheme clearing times usually will not apply to the high side of the main bus protective device. This is important to keep in mind, as a separate label must be printed for the main cabinet.

For Case P in Appendix A, a 0.083 second clearing time was used to simulate a bus differential relay. This is the same value used by the software for all instantaneous elements, automatically accounting for relay and breaker operate time. Adding this differential relay decreased the main bus incident energy compared to Case I by 67%.

III. PROTECTION MODIFICATIONS

An accurate model may still result in unacceptable arc flash incident energy values, meaning mitigation is necessary. Arc flash mitigation can be costly and complicated, especially if older switchgear needs to be upgraded or protection devices replaced [5]. The mitigation strategies described in this section are relatively easy and low-cost and should be considered first if mitigation is called for. It is worth noting that any changes to relay settings will likely change arc flash results – solutions covered here are specific to arc flash. If relay trip times can be decreased while maintaining coordination and reliability this should be considered.

Before starting work on any mitigation plan, remember the main purpose of studying arc flash is to keep people safe. Prohibiting live work on equipment with high incident energy values accomplishes this goal but may not be possible if the equipment is non-redundant or supplies critical processes that are rarely shutdown. In addition, this method will not prevent costly equipment damage from arc blasts.

A. *Fuse Sizing & Replacement*

Fuses are usually inexpensive, reliable, and easily replaced for a sizing change. Decreasing the fuse size can lower the incident energy levels at a bus but this must be done cautiously. The fuse can't be so small that it blows or is damaged during normal system cold-load pickup, transformer inrush, or high-inertia large motor starts.

Dual-element current Limiting Fuses (CLFs) can also be installed to quickly extinguish arcs. CLFs typically open a faulted circuit in less than half a cycle [3] whereas most breakers take 3-5 cycles. As can be seen in Appendix A Cases I and O, adding a CLF upstream of the F1 feeder bus reduced the feeder incident energy from 23 to less than 2 cal/cm^2. Note that no fuse or CLF existed in the model prior to this addition.

Care must be taken to only install CLFs in areas with high arcing current. CLFs follow a time-delayed element fuse curve for fault magnitudes below current-limiting element operation, at which point they will limit high fault current by operating almost instantaneously. If an arc occurs below the current-limiting pickup the fuse will take longer to open and may actually increase arc flash energy [4].

B. *Maintenance Mode*

Maintenance Mode (MM) is a function that can be utilized in a feeder relay to protect workers during energized maintenance or while racking in or out a breaker. MM is an instantaneous overcurrent element with a pickup often set the same as the phase time overcurrent (51P) pickup. Before beginning work downstream of the feeder breaker, the relay must be put into MM manually, usually with a pushbutton or panel mounted switch. However, the worker must remember to take the relay out of MM once they are finished working. For added security against inadvertent operation, Arc Flash tripping is usually supervised by a high current condition.

A major benefit of MM is cost - if programmable relays with programmable pushbuttons are already installed no additional equipment is necessary. Due to the low current pickup, MM also provides an extra layer of protection against non-arcing faults. For instance, MM could limit a person's exposure to an electrocution or trip on a high-impedance, lower current fault before it develops into an arcing fault.

When enabled, MM is also very effective. Cases I and Q in Appendix A show a decrease in incident energy of 60%, from 23 cal/cm^2 to 9 cal/cm^2 on the feeder bus.

There are two main drawbacks of MM. It does not protect equipment during normal operation, when MM is not enabled. It also relies on human operators to enable and disable, and failure to do either at the right time can have consequences. Working near live equipment without enabling MM will expose workers to an arc flash hazard, while walking away without disabling MM will likely cause protection miscoordination and unwanted tripping. Thorough training along with incorporating a MM in-service alarm will lower these risks, but human error can never be eliminated.

It is important to consider Arc Flash labeling on MM capable equipment. It can be tempting to add a MM element to the model and print labels for only this best-case scenario, but these labels will be incorrect whenever MM is disabled. A second model case must be run, with the original hazardous incident energy values, so both normal and MM incident energies can be reported to workers. Even placing Arc Flash labels with both values in the field can be confusing, so consider labeling equipment with normal operation incident energy values and keeping the safer MM values in an engineering report or safety manual.

C. *Arc Flash Light Sensors*

Arc flash sensors are fiber optic strands connected directly into a relay with arc flash sensing capabilities. They are placed in the back of the breaker cabinet, where light from a switchgear arc will radiate. A pickup higher than ambient light is set in the relay along with an overcurrent supervision setting, and when these values are exceeded the relay will initiate a trip within seven milliseconds [4]. This significantly decreases worker exposure to any arc flash, lowering incident energy. For added security, Arc Flash tripping may be supervised by a high current condition.

Unlike Maintenance Mode, arc flash sensors protect equipment from extended arc damage even when nobody is working on the system. This scheme does not need to be enabled or disabled manually, which eliminates human error. Another huge benefit of arc flash sensors is expanded zones of protection - maintenance mode typically only reduces incident energy downstream of feeder breakers, while sensors can be used to quickly clear arcing faults on the switchgear bus as well as feeders.

In terms of performance, light sensors in the feeder cabinet which trip the feeder breaker have a nearly identical effect to Maintenance Mode applied on the feeder, when fixed clearing time is set to 0.083 seconds, the software calculated sum of relay and breaker operate times. The main bus is also equipped with light sensors set to trip the main breaker – in this case incident energy is reduced 67% from 40 to 13 cal/cm^2, as can be seen in Appendix A cases I and R.

There are downsides to arc flash tripping, mainly cost and complexity. If the installed relaying is not capable of arc flash sensing it must be upgraded; a specialized arc flash sensing system or auxiliary sensors could also be installed [5]. The sensors must be installed correctly in suitable locations, and they can be easily broken if pinched or bent.

Additionally, care must be taken to route arc sensors to relays with the ability to clear a fault in that area; it is common to see bus-side feeder breaker stabs monitored by a feeder relay, when the feeder breaker would be unable to clear this arc. For example, if a fault occurred on the high side of “F1 Breaker” in Figure 1, the arc flash would be physically located in the F1 Breaker switchgear cabinet. It would be easiest to connect this sensor to the F1 relay when installing the sensing system, but unless the F1 relay can trip the Main Breaker this fault will not be cleared.

Improper design or broken sensors can lead to a worst-case scenario. Workers could believe the arc flash danger is low, when in fact incident energy is high. Because arc flash tripping is always enabled it is permissible to display this lowered value on arc flash labeling, but be sure to verify correct setup. If the sensing relay provides any alarm points, such as sensor trouble, monitor these and fix any problems before working near the switchgear.

Arc Flash tripping is typically modeled by setting a fixed clearing time on all busses protected by the scheme. Use the sum of the relay and breaker operating times for this value. If performing an arc flash study on a system that appears to use arc flash sensors, it is important to verify the scheme and sensors are set up and in working order before assuming they will operate for an arc.

IV. CONCLUSIONS

The intent of this paper is to provide the reader with a hierarchy of mitigation applications to reduce arc flash incident energy. As can be seen in the modeled results comparison in Appendix A, both modeling approaches and protection changes can be applied to effectively reduce arc flash hazards. Accurate modeling using IEEE 1584-2018 variables, such as electrode configuration, plus enclosure size an main protective device isolation, should be considered before any physical updates. If accurate modeling does not produce more acceptable incident energy values, simple protection changes such as Maintenance Mode can be implemented. Arc Flash light sensors and Current Limiting Fuses can be installed, possibly at higher cost and effort, for around-the-clock protection. Care must be taken when implementing all arc flash specific protection schemes, as certain engineering decisions and human errors can render them ineffective and provide a false sense of security.

Correctly modeling and mitigating arc flash hazards is important for human safety and equipment protection, but it can be difficult to know where to start. This paper, plus the test results on a sample system shown in Appendix A, gives an overview of possible mitigation strategies at no cost, or relatively low cost. These strategies can be attempted or studied before more invasive system overhauls are proposed.

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APPENDIX A – ARC FLASH SAMPLE RESULTS

	Case Parameters						Incident Energy (cal/cm^2)	
Case	IEEE 1584 Revision Year	Nominal Bus Voltage	Isolated Main	Enclosure Type (Main, Feeder)	Electrode Configuration	Notes	Main Bus	Feeder Bus
A	2002	5 kV	No	Other, Other	n/a		69.315	23.822
B	2002	5 kV	No	SWGR, MCC	n/a		32.895	22.191
C	2002	5 kV	Yes	Other, Other	n/a		43.865	23.822
D	2002	5 kV	Yes	SWGR, MCC	n/a		20.817	22.191
E	2002	0.48 kV	Yes	SWGR, MCC	n/a		31.311	32.156
F	2002	13 kV	Yes	SWGR, MCC	n/a		12.954	13.97
G	2018	5 kV	No	SWGR, MCC	HCB		64.524	23.141
H	2018	5 kV	No	SWGR, MCC	VCB		26.58	10.144
I	2018	5 kV	Yes	SWGR, MCC	HCB		39.971	23.141
J	2018	5 kV	Yes	SWGR, MCC	VCB		16.553	10.144
K	2018	0.48 kV	Yes	SWGR, MCC	VCB		19.643	14.547
L	2018	13 kV	Yes	SWGR, MCC	VCB		10.808	5.988
M	2018	0.48 kV	Yes	SWGR, MCC	VCB	Shallow Enclosure (8 inch depth)	14.136	9.666
N	2018	5 kV	Yes	SWGR, MCC	VCB	Main Breaker not tripped by relay	26.58	10.144
O	2018	5 kV	Yes	SWGR, MCC	HCB	200A CLF installed on Feeder	39.971	1.112
P	2018	5 kV	Yes	SWGR, MCC	HCB	Bus Differential (0.083 seconds)	13.306	23.141
Q	2018	5 kV	Yes	SWGR, MCC	HCB	Maintenance Mode	39.971	9.268
R	2018	5 kV	Yes	SWGR, MCC	HCB	Light Sensor Trip	13.306	9.23

Note: Results cannot be directly compared across voltage levels