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Why arc-resistant drives need to be considered

Aaron H. VanderMeulen
Application Engineer

Stan R. Simms
Design Engineer

Reports have shown fatal injuries related to electrical incidents from 2004 through 2010 resulted in 1,494 fatalities, 29% of which were attributed to contact with wiring, transformers and electrical components. From 2011 to 2013, 43% of fatalities were attributed to indirect contact and 54% attributed to direct contact.[1]

There is a systematic approach to minimizing or mitigating the risk to electrical injury. It is best to select the highest level of control possible. As outlined by the Occupational Safety and Health Administration (OSHA) Hierarchy of Controls & ANSI Z10 (2012): Elimination or substitution, engineering controls, warnings, administrative controls, personal protective equipment (PPE).

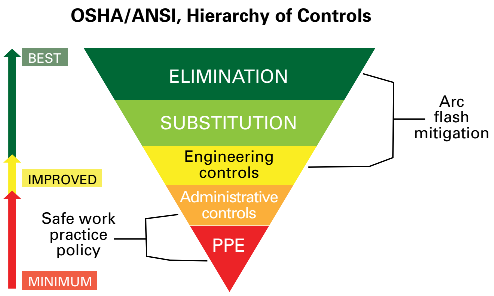

Figure 1. OSHA hierarchy of controls

Ideally, with any electrical equipment, to reduce the risk of injury, the hazard needs to be eliminated. Operating mechanism to disconnect or make power in order to de-energize equipment is in itself a hazard and it is difficult to completely eliminate the hazard.

Substitution allows different equipment to be utilized that reduces the risk of injury. In this case, to reduce the risk of injury, the equipment could be upgraded to arc resistant to protect from arc flash and arc blast injury.

Engineering controls include isolation devices, guards, etc. or administrative controls such as limiting the time of hazard exposure. Engineered controls will be discussed further in this paper. Training and communication are effective tools for awareness.

Many companies are adopting administrative controls such as workplace practices and rules adopting routine training, communication and standard work practices, but this does not eliminate the hazards.

PPE is allowed to be used when engineering controls are not feasible or do not completely eliminate the hazard under the OSHA guidance. Over reliance on PPE as a measure is not the correct approach.

This paper will focus on understanding why arc-resistant equipment needs to be considered when evaluating the risk of arc flash and arc blasts associated with internal arcing faults in medium-voltage adjustable frequency drives.

The three criteria evaluated in this paper include:

1. System architecture
2. System impedance
3. Failure mode and analysis

System architecture

Many different manufacturers build arc-resistant equipment. This equipment includes, but is not limited to, low-voltage metal-enclosed switchgear, motor control centers, medium-voltage motor starters and metal-clad switchgear. Product safety has evolved to incorporate the standard IEEE® C37.20.7-2007, IEEE Guide for Testing Metal-Enclosed Switchgear Rated Up to 38 kV for Internal Arcing Faults. This standard is widely adopted and builds harmony amongst vendors, end users, third-party certifiers and power test labs. Switchgear and motor starter equipment built and certified to this standard are prevalent in facilities worldwide.

Medium-voltage adjustable frequency drives (MV AFDs) are common in large industrial facilities and are often overlooked regarding the hazards associated with operating and maintaining such complex equipment. Medium-voltage drives comprise many interconnect power components operating in tandem. A medium-voltage drive should not be considered a simple add-on piece of equipment or switchgear. A detailed failure mode analysis is presented in several scenarios to illustrate the need for a system evaluation with regards to internal arcing faults.

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[1] Occupational Injuries from Electrical Shock and Arc Flash Events

Manufacturers may provide a fully integrated or non-integrated solution. Non-integrated solutions require the end user to select additional equipment such as feeders, power transformers, reactors or filters. Specific coordination is needed between components to ensure adequate functionality and protection. Feeder options include load-break switches, fused contactors and power circuit breakers.

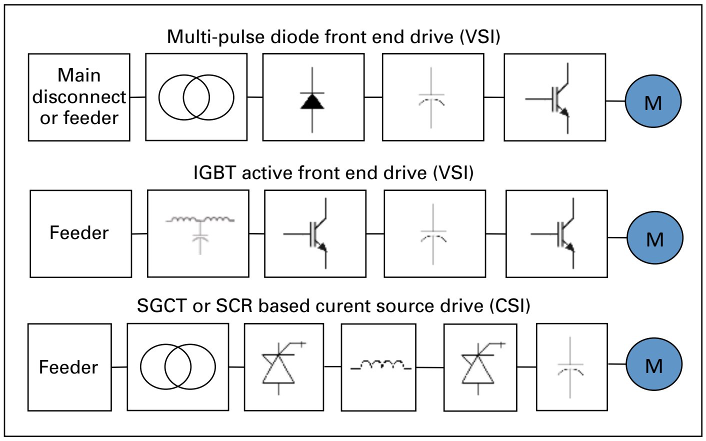

Figure 2. Drive topologies

MV AFD designs utilize different converter topologies, inverter topologies and semiconductor devices (diode, SCR, IGBT, SGCT, etc.). Unlike medium-voltage starters or switchgear, MV AFD power conversion technology is different based on each manufacturer's approach.

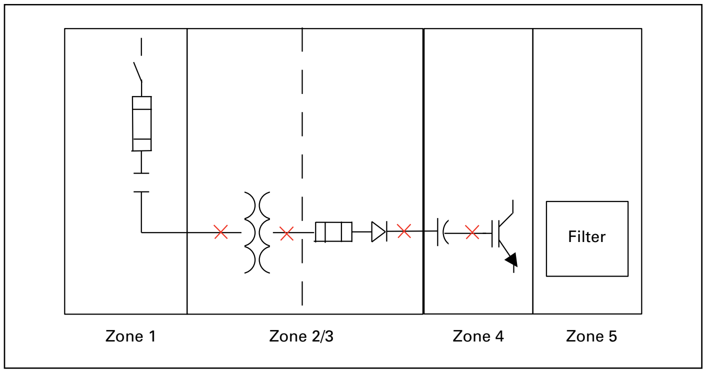

Figure 3. Fully integrated drive

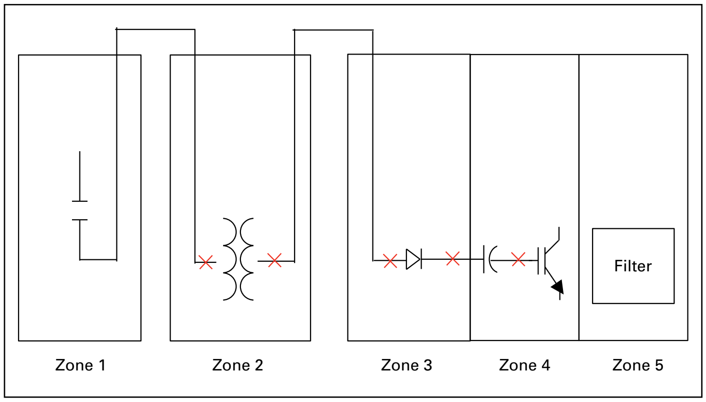

Figure 4. Non-integrated drive

Two drive architectures will be evaluated. **Figure 3** shows a fully integrated drive with a fused, non-load-break disconnect, isolation transformer, converter and inverter with optional output filter. **Figure 4** shows a non-integrated drive with similar components as **Figure 3**. The spacing between zones suggests separate items that could be selected based on end user discretion from manufacturer specification. Each zone represents a power stage typically found in MV AFDs. The red 'x' signifies potential internal arc fault locations of interest. Each has its own associated hazard concerns.

System impedance

Short-circuit currents

With MV AFDs installed in industrial areas with weak or soft utility power systems, it is important to understand how this affects the arcing current magnitude and duration. Equipment is type tested and rated at a specific short-circuit current magnitude and duration. In many installations, the actual available short-circuit is a fraction of the equipment rating. Also, arc-resistant equipment is given a third rating based on the arc-fault duration tested.

As an example, a natural gas compression station with a 20 MVA unit substation 13.8 kV / 4160 V DY of 8.5% impedance has a rated secondary current of 2779 A and a maximum short circuit of 32.7 kA (235 MVA). However, if the utility available short circuit is only 10 kA (238 MVA), the transformer secondary short-circuit current is reduced to 16.4 kA (118 MVA); the utility impedance has limited the overall short-circuit current.

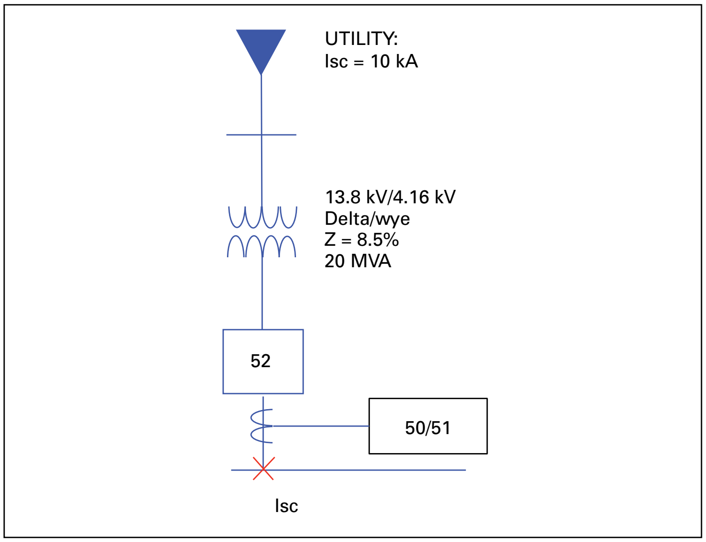

Figure 5. System one-line diagram

Arcing fault currents

Given most MV AFDs must comply with the IEEE 519 harmonic limits, manufacturers address this need with an isolation transformer or line reactance in the converter. Similar to the example above, which is examined with a power system study, this added converter impedance affects the system; however, its effect is not well known.

The available bolted fault current is reduced with every additional impedance as you move from the utility to the drive converter. This perspective fault current is further reduced with arcing impedance, which can lead to increased fault clearing time and increased incident energy.

Examples of arcing fault current with respect to bolted fault current are illustrated in **Table 1**. This table will be referenced in the next sections.

Table 1. IEEE 1584 (2002) arcing current

kA	Ibf (A)	log (Ia)	Ia (A)	% Ia/Ibf
50	50000	4.623	42003.7	84%
40	40000	4.528	33730.7	84%
30	30000	4.405	25422.0	85%
20	20000	4.232	17065.2	85%
10	10000	3.936	8633.8	86%
5	5000	3.640	4368.0	87%
1	1000	2.953	897.8	90%

Legend:
Ibf = bolted fault (amperes)
Ia = arcing fault (amperes)

Failure mode and analysis

Primary faults (Zone 1, Figure 3 and Figure 4)

Primary faults would be localized to the input equipment. The input equipment, ideally, is constructed to the C37.20.7 standard. Many papers discuss the construction of arc-resistant medium-voltage motor starters and switchgear, and this paper does not explore this topic in detail. Care should be taken on understanding the perspective arcing current magnitude and upstream clearing times of the protection equipment. A system study is paramount. It is important that proper coordination is achieved while reducing the likelihood that the arcing fault duration does not exceed the equipment rating. Special consideration should be taken with a weak power system or source.

Transformer secondary faults (Zone 2)

An example was given with a 20 MVA substation transformer and evaluated the secondary short-circuit current of 16.4 kA. This is a relatively straight-forward calculation with a two-winding transformer. However, with MV AFD isolation transformers, it is not easy to calculate the secondary short-circuit current because of their given variations and complexities. It is not unusual for these types of transformers to have four to twelve secondary circuits or more to address converter harmonics. A complex model is required that is typically outside the capability of traditional power system analysis software. An approach is used in the following example that may help with future drive system studies.

A 4160 V, 6000 hp drive utilizing a five-winding, 5750 kVA transformer is used in this example. The primary to secondary impedance is 6% with all secondary circuits shorted. With only one secondary circuit shorted, the secondary impedance is 11%, but 44% is reflected to the primary, based on empirical data.

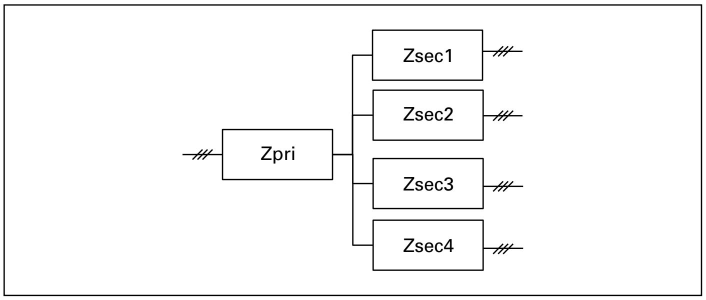

Figure 6. Transformer impedance model

Each secondary circuit has a rated current of 704 A and 1000 V. The estimated secondary bolted fault circuit current is calculated as:

$$I_{bf,sec1} = \frac{I_{sec}}{Z_{sec}} = \frac{704\text{ A}}{0.11} = 6400\text{ A}$$

Equation 1

Assuming the arcing fault current is 85% of the bolted fault current per the IEEE 1584 table:

$$I_{a,sec1} = 0.85 \text{ x } 6400\text{ A} = 5440\text{ A}$$

Equation 2

The arcing current as reflected to the primary:

$$I_{a,pri} = \frac{I_{pri}}{Z_{pri}} \text{ x } 0.85 = \frac{704\text{ A}}{0.44} \text{ x } 0.85 = 1360\text{ A}$$

Equation 3

Using a 750E primary fuse for transformer protection, the total clearing time, without additional engineering controls, is beyond 600 seconds. The fuse opens in the time overcurrent region. Significant damage due to the arcing fault is possible because the duration exceeds the design rating. If a breaker and protective relay were used in place of the fuse, the breaker would open based on the time overcurrent region, resulting in similar damage.

It is critical to coordinate upstream protection to clear faults within the downstream equipment arcing fault duration rating.

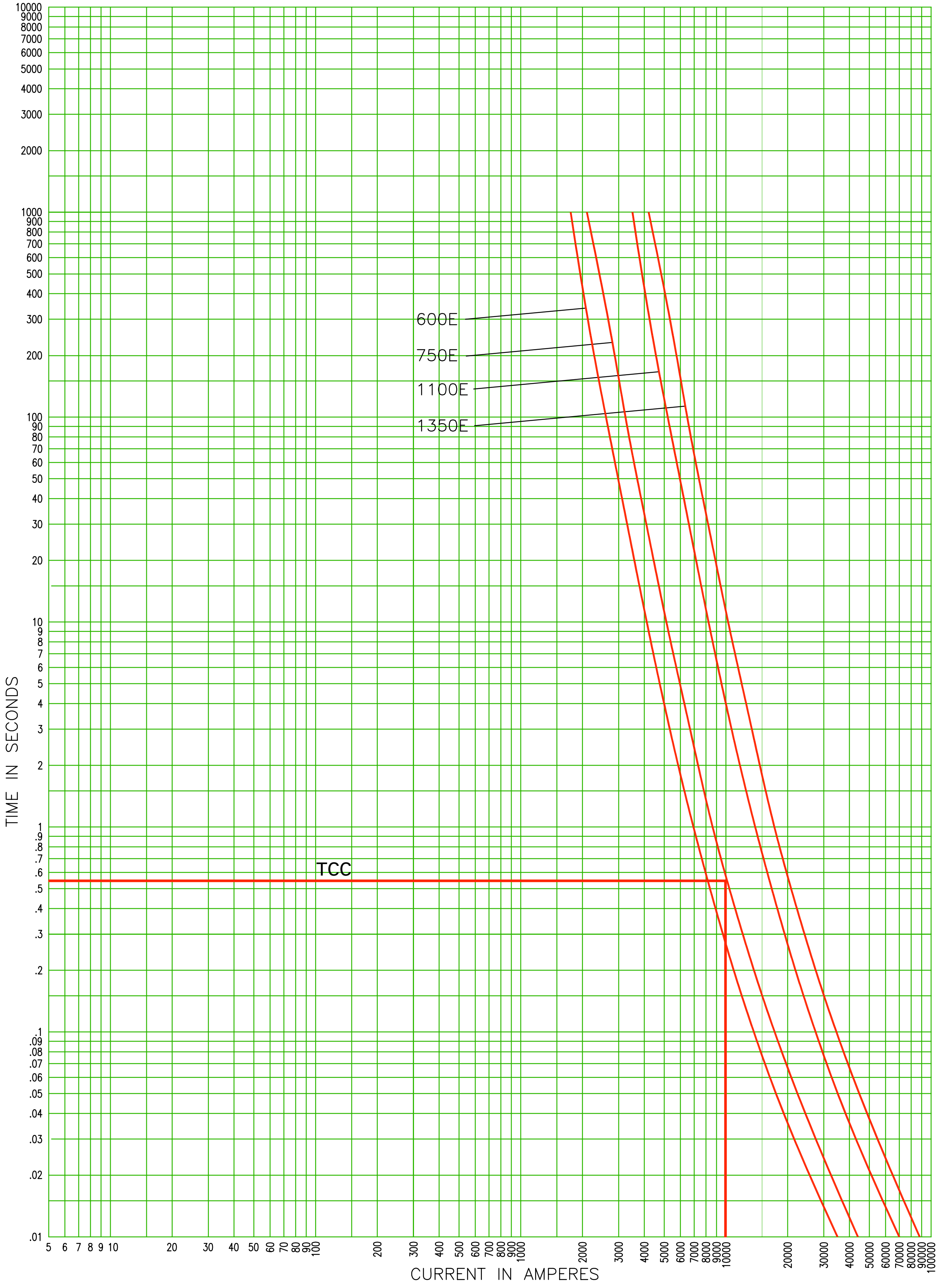

Figure 7. Fuse time current curve (TCC)

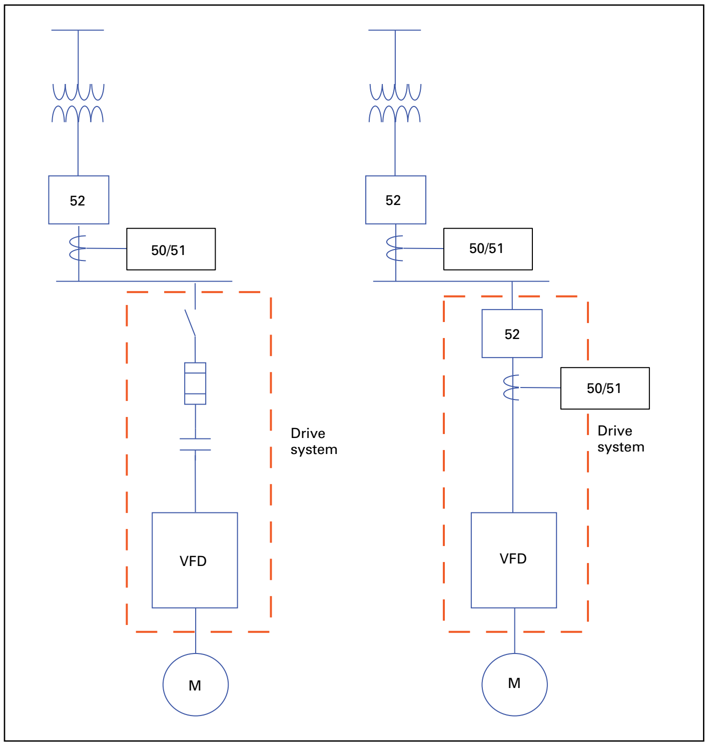

Figure 8. MV AFD feeder

Based on the Lee method[2], the unaddressed theoretical available incident energy is well above 40 cal/cm² at a working distance of 36 inches even if the clearing time is limited to 1 second, posing a problem.

$$E = 5.12 \times 10^5 V I_{bf} \left(\frac{t}{D^2}\right)$$

Equation 4

$$E = 5.12 \times 10^5 (1.0)(6400\ A)\left(\frac{1.0\ s}{(914\ mm)^2}\right) = 3919\ \frac{cal}{cm^2}$$

Equation 5

Rectifier faults (Zone 3)

Designs in which some manufacturers do not incorporate semiconductor fuses into the converter are known as fuse-less designs.

When semiconductor fuses are provided and properly coordinated, these engineering controls have the potential to reduce the available incident energy, as compared to the previous example. For a secondary bolted fault from the working example above, the semiconductor fuses open in approximately 34.2 milliseconds.[3] Arcing fault current of 85% of bolted fault magnitude results in a clearing time of approximately 47.3 milliseconds.

$$I^2t = 1{,}400{,}000\ A^2s = \frac{1{,}400{,}000}{(6400\ A)^2} = 0.0342\ sec$$

Equation 6 (Bolted fault clearing time)

$$I^2t = 1{,}400{,}000\ A^2s = \frac{1{,}400{,}000}{(5440\ A)^2} = 0.0473\ sec$$

Equation 7 (Arcing fault clearing time)

With the addition of this engineering control, the theoretical available incident energy has been significantly reduced. Note the outcome is still a cause for concern. The hazard is not yet completely eliminated.

$$E = 5.12 \times 10^5 (1.0)(6400\ A)\left(\frac{0.047\ s}{914^2}\right) = 185\ \frac{cal}{cm^2}$$

Equation 8

It should be noted that this single winding fault scenario does not include arcing faults that dynamically propagate to multiple secondary circuits.

Arc back failure

One failure mode of power converters is the diode arc back failure mode outlined in IEEE 551 Violet Book, section 8.7. When a diode (valve) loses its semiconducting properties (diode short), the current magnitude exceeds that of typical three-phase bolted faults by up to 2.73 times. This short-circuit peak current, if not accounted for in the design of the drive, can result in catastrophic transformer failure and arcing faults with significant enclosure damage. In some cases, enclosure doors have bowed or blown off. There is a need for semiconductor fuses as an engineering control.

DC bus faults (Zone 4)

An arcing fault on the DC bus is difficult to model but can be estimated as a three-phase bolted fault on the secondary with an 85% factor from **Table 1**. In a distributed multi-pulse rectifier design, a fault may begin at a single module, but then dynamically propagate to subsequent locations. **Figure 9** shows a vertical or horizontal module arrangement for rectifiers or inverters.

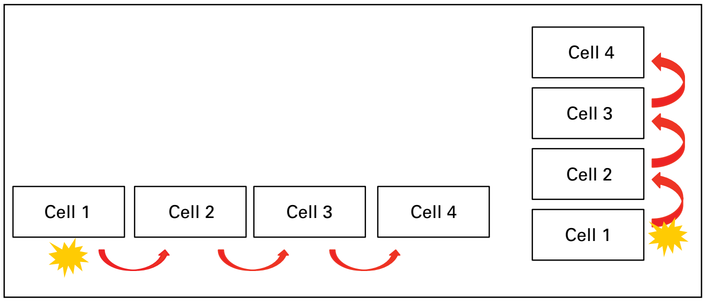

Figure 9. Module layout

$$I_{bf,pri} = \frac{I_{pri}}{Z} = \frac{704\ A}{0.06} = 11{,}733\ A \times 0.85 = 9973\ A$$

Equation 9

The transformer primary current of 10 kA would open the primary fuse in approximately 0.55 seconds (**Figure 7**). The semiconductor fuses would open in approximately 0.0141 seconds. This results in an incident energy of 101.3 cal/cm² at a working distance of 36 inches.

$$E = 5.12 \times 10^5 (1.0)(11{,}733\ A)\left(\frac{0.0141}{914^2}\right) = 101.3\ \frac{cal}{cm^2}$$

Equation 10

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[2] IEEE 1584-2002

[3] SIBA SBQ3 semiconductor fuse, 1100 A

Ionized gasses

Ionized gas from an arc fault is the source for dynamic propagation. With medium-voltage motor starters or switches, segregation barriers are implemented as engineering controls to reduce propagation and allow fuses to clear the fault as intended. This is especially important to consider in medium-voltage drive design. Some designs incorporate stacked converter and inverter cells/modules. As mentioned previously, an arcing fault in the module can easily propagate to an adjacent cell without barriers. In **Figure 10**, diode and semiconductor fuse barriers are implemented.

Figure 10. Phase segregation barriers

Pressure wave

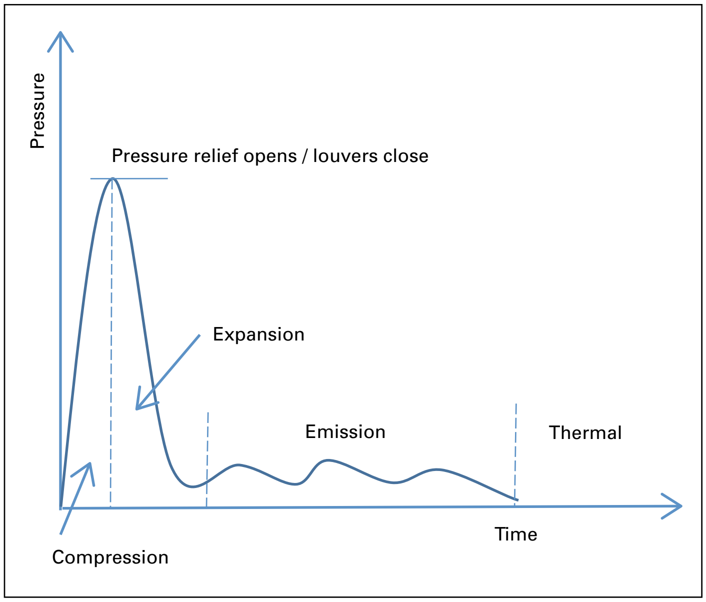

Figure 11. Pressure wave

An arcing fault heats and expands copper metal rapidly, producing a pressure wave that has to be contained and directed away from personnel. The peak pressure wave occurs between 8 and 10 milliseconds after arc initiation. With drive configurations using forced air-cooling, a deflection means is necessary to prevent pressurized gases from exiting the intake vents, possibly toward a user. An additional engineering control (shown in **Figure 12**) closes a louver upon internal high pressure. In this approach, the pressure wave is engineered to redirect away from the user.

External view

Internal view

Figure 12. Louver

The heated and expanded gasses can reach temperatures of 35,000 degrees F. The type test as required by IEEE C37.20.7 has measures that detect non-complying internal arc fault containment. **Figure 14** is an example of an additional engineering control that quenches exhaust arc flames in air-cooled enclosures. **Figure 13** represents a type test setup with cotton indicators to observe the effects of possible escaping arc gasses.

Figure 13. Cotton indicators

Figure 14. Arc flame quencher

Active engineering controls (preventative)

Pre-charge system

Many drives utilize a DC bus pre-charge system to limit capacitor inrush current. An engineering control to reduce arc flash risk can be in the form of a limited energy pilot circuit that additionally soft magnetizes the transformer. This circuit would include sensors and a detection method to determine if there is a short circuit within Zone 1, 2 and 3 (**Figure 3**) such as a misplaced tool left after maintenance.

This approach detects a short circuit prior to closure of the main contactor and is the highest level of engineering control.

Active Engineering controls (reactive)

Light detection system

Fiber optic light detection sensors have been utilized in switchgear as a means to protect equipment by limiting the arcing fault duration. There is no governing body that has created a set of standards that provides guaranteed integration of the detection circuits and equipment without type testing to evaluate the efficacy of these systems. At best, this active engineering control provides a backup to passive arc-resistant construction. It does not eliminate the localized pressure wave caused by an arcing fault because the relatively slow reaction time of upstream coordination.

Differential protection

Transformer differential protection schemes, utilized widely in industrial facilities to reduce arcing duration, are difficult to implement with drive isolation transformers. Bus differential schemes could be implemented but would be limited to protection up to the transformer primary. Application on the output of the inverter would cause protection relay misoperation due to the change in line/load kVA and base frequency.

These last two active engineered controls do not eliminate the hazard nor do they protect against the initial arc blast or pressure wave. The philosophy behind these engineered controls is to decrease the upstream clearing time to limit equipment damage.

Summary

The failure mode analysis in this paper has highlighted the need for arc-resistant engineering controls for the entire drive system, particularly Zone 2. It is suggested that a comparable evaluation be performed on the internal failure modes of other vendors' medium-voltage drives not shown in this paper.

The outcome of a thorough system analysis, with regards to MV AFD internal arcing faults, results in the both active and passive engineering controls to protect personnel and minimize equipment damage.

Although active engineering controls have the potential to reduce arc incident energy, they are likely defeated to type test the passive construction when evaluating to the commonly accepted IEEE standard.

The following is a checklist of requirements to include when specifying an arc-resistant medium-voltage adjustable frequency drive:

Arc equipment considerations

Design	Requirement
Passive construction	✓
Short-circuit protection	✓
Arc rating	✓
Fully integrated	✓
Fused converter	✓
Gas segregation barriers	✓
System FMEA	✓
Third-party certification (UL/CSA)	✓

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Eaton
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United States
Eaton.com

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