PERFORMANCE OF AN ARC-RESISTANT MEDIUM-VOLTAGE MOTOR CONTROL CENTER FOR AN IN-SERVICE FAULT

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Mark A. Metzdorf, P.E.
Senior Member, IEEE
BP Products North America Inc.
150 W. Warrenville Road
Naperville, IL 60563
USA
mark.metzdorf@bp.com

Douglas BeCraft
Member, IEEE
BP Products North America Inc.
2815 Indianapolis Blvd.
Whiting, IN 46394
USA
douglas.becraft@bp.com

Richard Bhalla, M.S.
Member, IEEE
Eaton
221 Heywood Road
Arden, NC 28704
USA
richardbhalla@eaton.com

Adam E. Fabrici
BP Products North America Inc.
2815 Indianapolis Blvd.
Whiting, IN 46394
USA
adam.fabrici@bp.com

Abstract – Since the introduction of the IEEE C37.20.7 standard and predecessor documents for testing switchgear under arcing fault conditions, the use of arc-resistant equipment has increased and is now the standard in many companies in the petrochemical and oil industries. Equipment designs have evolved to be more robust under fault conditions to meet the testing criteria, but there is limited knowledge of how such equipment performs if a fault occurs while in service at an end-user facility.

This paper discusses an actual fault sustained on an arc-resistant 5kV motor control center lineup at a large oil refinery and lessons learned from the incident. The paper discusses the background of the installation, provides an overview of the fault incident and discusses the causes of the incident. The considerations for proper coordination of protective relays to achieve both the desired selectivity for faults to ensure continuity of service to critical refinery processes and to properly protect the equipment in accordance with its arc rating are discussed. The testing protocol and passing criteria for arc-resistant equipment is explored, with an emphasis on providing a comparison between how a manufacturer tests the equipment and how it performs during the test versus the perception that end-users may have. Potential recommendations are offered to enhance the testing protocol and testing criteria to better align with end-user expectations. Additionally, the paper will highlight other considerations that should be part of the application, installation and maintenance of arc-resistant equipment.

Index Terms — Arc-resistant equipment, medium-voltage switchgear, medium-voltage motor control, electrical fault, arcing fault.

I. INTRODUCTION

As part of a facility project, several substations were installed that include medium-voltage arc-resistant switchgear and motor control centers (MCCs). The medium-voltage MCCs were supplied as Type 2B per IEEE C37.20.7 - 2007 [1] and were commissioned and placed in service in 2012. In early 2016, an arc-fault incident took place in one of the medium-voltage MCCs during the attempted start of a 1250 horsepower (hp) induction motor.

After this fault incident, electrical personnel at the facility expressed concern over the extent of external “damage” and the possibility of injury within close proximity of the faulted equipment, in particular, the low voltage controls compartment recessed within the main compartment door.

Some electrical personnel have the perception that arc-resistant equipment eliminates arc flash hazards. Arc-resistant switchgear is instead designed to divert the arc fault energy and gases away from the user and, depending on the rated construction, prevent or minimize damage to adjacent sections of the equipment. Protective devices and schemes can also be used to minimize the duration, and consequently the energy magnitude, of arcing faults to further reduce equipment damage.

This paper will discuss the fault incident, what end users in the oil, gas and petrochemical industry may typically expect, what might be provided by an original equipment manufacturer (OEM) and what lessons can be taken from the fault incident to improve understanding and application of arc-resistant equipment and its design.

II. 5KV FAULT INCIDENT

In early 2016, a 1250 hp cooling water pump motor was intentionally stopped by operations. About one week later, the pump was ready to be put back into service and the motor was started. Approximately 1 second after the 4160 V contactor was closed, the multi-function solid-state relay on the upstream MCC bus main breaker detected phase time overcurrent and bus under-voltage conditions. Approximately 0.9 seconds later, the main breaker relay initiated a trip and the breaker subsequently opened. The starter isolation switch had not been operated between the time the motor was stopped and the attempted start that led to the fault.

The substation smoke alarm was activated and onsite emergency services and electrical maintenance personnel responded to investigate. Upon arrival, the MCC and surrounding area were found covered in a layer of soot, the low voltage compartment door of the affected starter was mechanically damaged (bowed), and the substation external arc exhaust discharge dampers for the MCC were open. A photo of the MCC as-found after the incident is shown in Fig. 1. The arrow identifies the compartment where the fault occurred.

The area was secured and an assessment of the substation electrical equipment was conducted. The affected MCC bus was isolated and locked out and other downstream low voltage loads that had been automatically tripped during the fault were restarted. Damage to the starter was extensive, including the

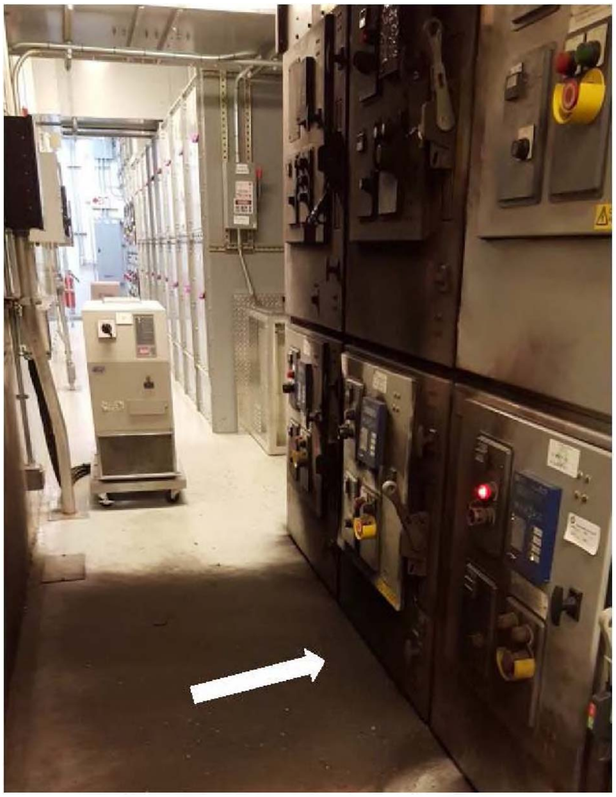

Fig. 1 Motor control center after fault

interior of the door-mounted low voltage controls compartment. Soot was also found in adjacent starter cubicles. The diagram in Fig. 2 shows the damage sustained by the MCC. The starter protective relaying did not indicate any fault conditions, but motor testing was performed to rule out a problem with the motor and/or leads that might have initiated the fault. No problems were identified. In the days that followed the incident, numerous covers of the affected MCC were removed for inspection and cleaning. Soot was also found in the vertical and horizontal bus compartments (as shown in the MCC physical construction diagram in Fig. 3). After CO_2 (dry ice) and hand cleaning, insulation resistance of the bus exceeded 1 teraohm and the equipment was re-energized.

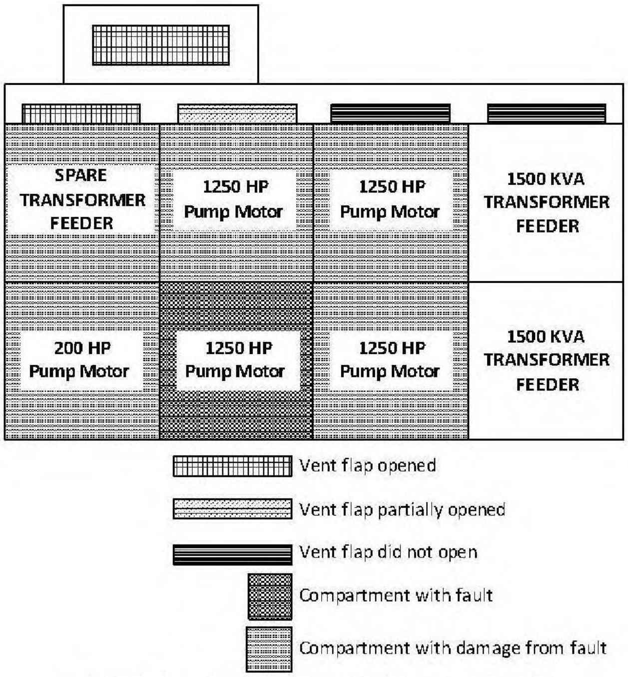

Fig. 2 Elevation Diagram of Damage to MCC

After ruling out several other potential sources of the fault, it was determined that the most likely cause of the fault was an unidentified breakdown in the dielectric properties of the air inside the starter compartment in the area of the line side of the medium voltage fuses. The fault likely started on A-phase, based on the extent of damage in the starter, and propagated into a phase-to-phase and phase-to-ground fault. The main breaker tripped on phase time-overcurrent. Ground fault current was present, but was below the relay pickup level.

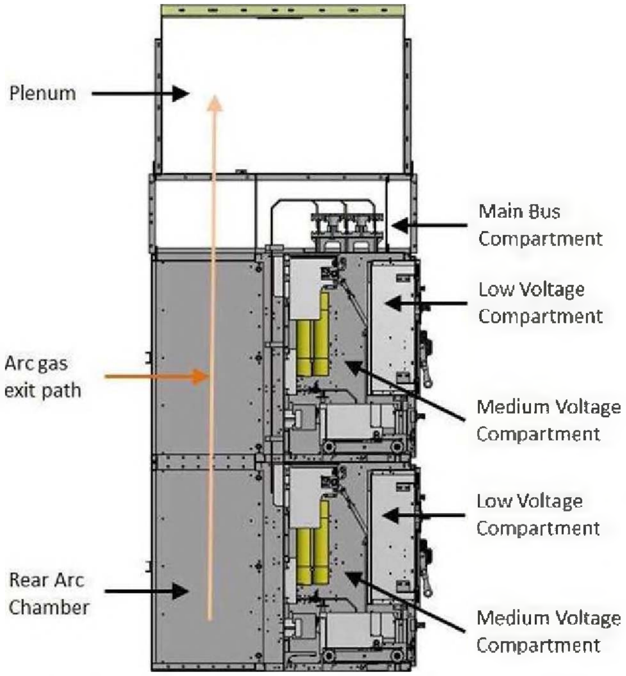

Fig. 3: Arc-Resistant Equipment Typical Compartments

III. USER DESIGN PHILOSOHPY AND EXPECTATIONS

End users typically have protection design philosophies for existing installations and new equipment, often based on standard industry practices. Additionally, those who operate or maintain arc-resistant equipment have certain perceptions about how the equipment is designed and tested. These design philosophies and perceptions may lead to particular practices around application of the equipment and upstream protective devices and also certain expectations of how the equipment will perform in the event of a fault. These philosophies, perceptions, and expectations will be explored further within the context of the performance of the entire installed system, with the view that many users have a basic understanding of arc-resistant equipment, but often are not experts.

A. Relay Coordination and Settings

1) Engineering Approach: The protective relaying scheme for this installation follows a standard design philosophy used by the facility that is based on the best practices of IEEE 242 (Buff Book) [2] and is implemented using multifunction microprocessor based relays. Each medium-voltage motor starter uses medium voltage R-Type fuses for short-circuit protection and a multifunction microprocessor protection relay, which provides thermal overload, definite time delay phase overcurrent, current imbalance, and definite time delay neutral overcurrent protective functions. The motor control center main and tie (normally open) circuit breakers each have multifunction microprocessor protective relays that provide phase time overcurrent and residual ground overcurrent protective functions. The transformers feeding the line-up are low resistance grounded.

A one-line diagram, including the protective relaying scheme is shown in Fig. 4 below. The protective functions on the motor starter are set based upon the load equipment ratings. The motor control center main and tie circuit breakers have phase time overcurrent set points selected based upon the rated ampacity of the system components in order to provide maximum load flexibility over the life of the system and properly coordinate with the downstream devices in the overload region. The ground fault element settings on the main and tie breakers are set to rapidly clear a ground fault while still providing adequate coordinating time intervals with the downstream medium-voltage contactor definite time delay neutral overcurrent protective functions.

2) Selectivity and Continuity of Service: The device coordination for the system is shown in the time-current coordination curves (for phase currents) in Fig. 5. Point "A" represents the actual pickup during the fault at 17 kA and 0.9 seconds. Point "B" represents the point of 50 kA and 0.5 seconds (matching the MCC arc-resistant ratings), which was evaluated to determine the relay settings during the coordination study. The phase time overcurrent relay functions on this system use a typical inverse-time characteristic, which was selected to mimic the characteristics of existing electro-mechanical relays in the upstream substation. The coordination philosophy at this facility is to clear faults to individual utilization loads quickly while intentionally having a time delay for system buses to maintain a high degree of continuity of service. This continuity is desired for buses that feed multiple pieces of utilization equipment in order to minimize the potential for a process upset due to a nuisance trip of a large quantity of equipment. As a result, a large coordinating time interval margin between motor starter protection elements and upstream phase overcurrent devices is used, which is common in the oil, gas and chemical industry to provide service continuity. Likewise, instantaneous phase overcurrent elements are not included on the main circuit breakers for the motor control centers.

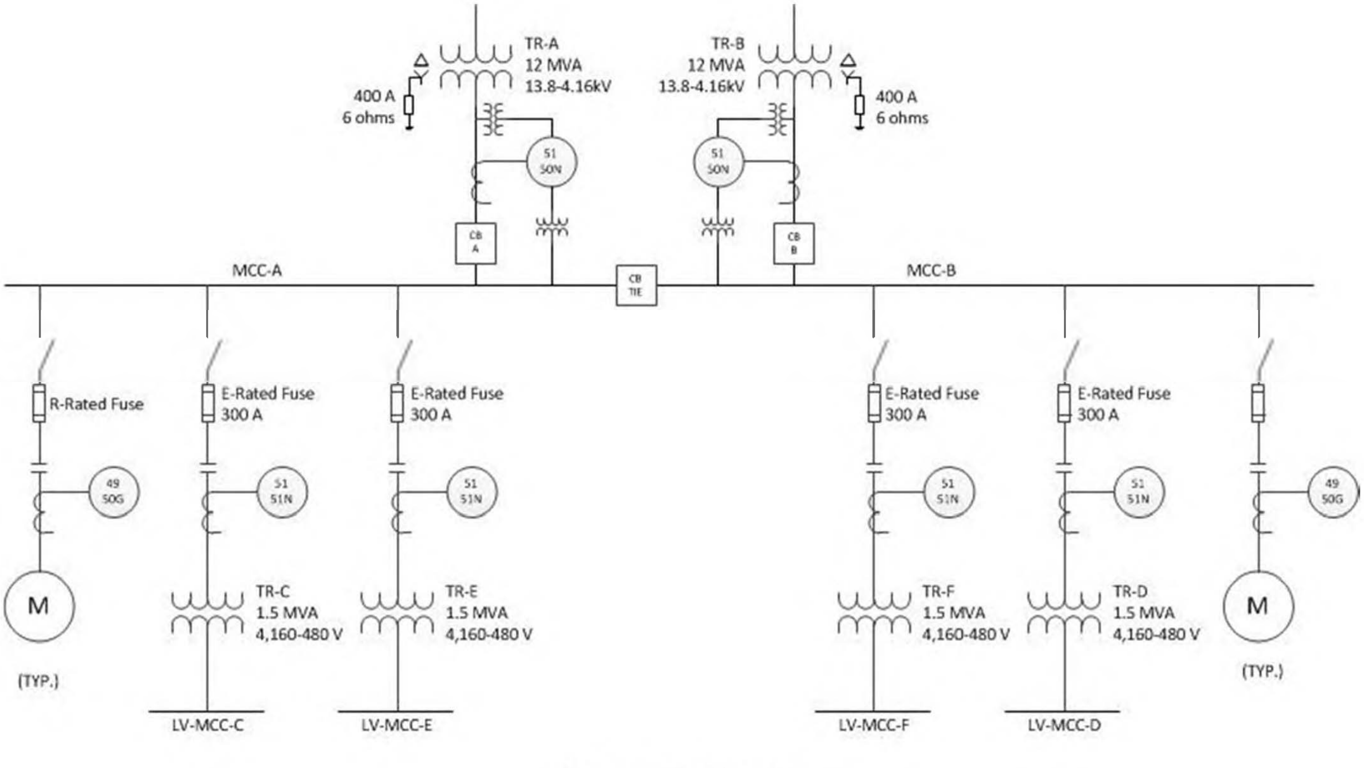

Fig. 4 One Line Diagram

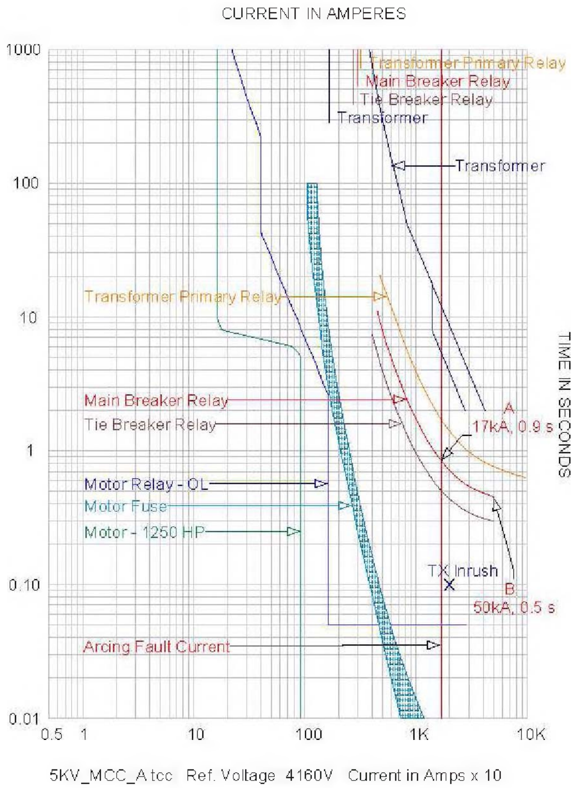

Fig. 5 Time-current Coordination Curves

B. *Equipment Design and Testing*

1) *Location of Fault Initiation*: End users routinely make important assumptions regarding equipment design. The location of fault initiation that is used during product certification is likely assumed to be in a "worst-case" location. That is, the locations that produce both the (1) most severe fault energy that may impact the pass/fail criteria as well as (2) the fault location(s) that are most likely to be encountered during end-user interface with the equipment. For a medium-voltage MCC, the most severe fault energy would likely be located on the line side of the protective fuse in the motor starter medium voltage compartment since this is where the longest clearing time would be in that compartment. Whereas the most likely location for a fault is expected to be at the fixed portion of the motor starter isolation switch.

The fault discussed in this paper occurred on the line side of the fuses and stayed within the main medium voltage compartment (see Fig. 3). Since the fault did not propagate to the vertical bus in the rear arc chamber, the pressure relief system was not effective in exhausting the pressure build-up and fault products out of the equipment. This resulted in pressure build-up and some of the fault products exiting the equipment through the front, including the low voltage control compartment of the MCC.

2) *Fault Magnitude and Duration*: The end user's expectations for equipment performance are straightforward for faults at the maximum fault rating of the equipment, in this case 50kA, being sustained for the duration up to the equipment arc resistance rating. However, achieving the required clearing time for fault magnitudes below the maximum arcing fault current rating requires additional evaluation when protective relaying using an inverse-time overcurrent function is applied. The end user may make an incorrect assumption of the required fault clearing time when applying inverse-time relaying if only considering the clearing time at the maximum arc fault current rating and not fully considering arc fault current magnitudes less than the maximum value.

3) *Passing Criteria*: When discussing the end user's expectations with regard to arc-resistant equipment, it is important to also understand the perspective of the electrician who is often in the closest proximity to the arc flash hazard. From the electrician's perspective, the expectation is that equipment tested and rated as arc-resistant will not pose an arc flash hazard when properly applied and operated, such as panels and doors properly secured. Further, they expect that the equipment is tested to the worst case conditions applicable to operation and the application. In the fault event described in this paper, the site electricians were surprised by the amount of physical damage to the equipment. While it is generally understood at the facility that "arc-resistant" does not translate into damage free, the examples of faults on arc-resistant equipment available to end users are primarily from manufacturer's testing rather than in-service cases that would more directly relate to the electrician's operating environment.

C. *PPE Selection for Arc-Resistant Equipment*

The event discussed in this paper prompted evaluation of arc flash hazard PPE selection methodology as it relates to arc-resistant equipment at the facility. Three primary options were considered: (1) arc-resistant equipment is applied and operates within the parameters of IEEE C37.20.7, which results in minimum additional PPE requirements relative to standard oil, gas and petrochemical facility PPE when reviewed according to industry standards, (2) consider the arc rated PPE selection as if the equipment is not arc-resistant, or (3) utilize task or risk based application of the arc-resistant rating within the requirements of the governing electrical safety standards, which may require arc rated PPE for some tasks but not others.

All three of these selection methods can be found across our industry. As a result, at facilities that use the first option, there is a minimal amount of PPE required in addition to standard oil and gas facility flame retardant clothing or arc-resistant clothing. This can lead the end user to having a high level of personal security and the perception that there is not an arc flash hazard when working around this equipment. However, IEEE C37.20.7 provides guidance that "adequate personal protective equipment is required, as all hazards associated with an internal arcing fault are not eliminated when equipment tested to this guide is used" [1]. Therefore, options (2) and (3) provide a greater degree of protection to the worker for all arc flash hazards in the event that a component of the protection system does not function as designed or if the system is not properly applied either initially or throughout the life of the equipment.

IV. OEM PERSPECTIVE

IEEE C37.20.7 *Guide for Testing Metal-Enclosed Switchgear Up to 38 kV for Internal Arcing Faults* defines criteria for testing switchgear that is considered arc-resistant and was initially released in 2001. It was primarily based on Annex AA (introduced in 1981) to IEC 298 (redesignated in 2003 as IEC 62271-200) [1]. IEEE C37.20.7, in addition to the IEC and EEMAC standards, were written for testing switchgear for internal arcing faults [1]. IEEE C37.20.7 has also been used as the basis for testing other types of similar equipment, such as motor control centers. With guidance from the certifier for a satisfactory test plan, OEMs have followed the guide to develop a motor control center design that passes the arc fault tests per the test plan.

A. Equipment Ratings

The equipment ratings are the actual values measured from the successful arc testing carried out per the test plan developed in conjunction with a certifier to meet the intent of the IEEE guide. Equipment that performs per the guide will have a nameplate that shows its ratings. For example, the equipment will have a rating similar to as shown below:

Accessibility Level: Type 2B
Internal Arcing Short-Circuit Current: 50 kA
Arcing Duration: 0.5 second.

What do these ratings mean?

1) *Accessibility type (Type)*: There are two levels of accessibility. Type 1 equipment with arc-resistant designs or features is freely accessible from the front only. Type 2 equipment with arc-resistant designs or features is freely accessible from all four sides (back, front, left, and right).

Further, a suffix is added to provide more information regarding the level of protection provided. Suffix A is used (i.e. Type 1A or Type 2A) to identify the basic rating. Suffix B is used (i.e. Type 1B or Type 2B) to indicate that the arc fault in the equipment does not cause holes in the freely accessible enclosure or in the walls isolating the low voltage control or instrument compartment(s). There are also suffixes C & D, but they are not as common and will not be covered in this paper [1].

2) *Internal Arcing Short-Circuit Current*: The value of the internal arcing short-circuit current (given in kA) is the maximum value of the RMS symmetrical prospective current applied to the equipment during qualification testing.

3) *Arcing Duration*: The rated arcing duration *(given in seconds*) is the period of time the equipment experienced the effects of an internal arcing fault during the qualification testing. Per the IEEE guide, the preferred rated arcing duration is 0.5 s [1], which is normally sufficient time for the upstream protective device to clear the fault.

B. Equipment Design

Arc-resistant design features are intended to provide an additional degree of protection to the personnel performing the normal operating duties in close proximity to the equipment while the equipment is operating under normal conditions. The normal operations include opening or closing switching devices, connecting and disconnecting withdrawable parts, reading of measuring instruments, and monitoring the equipment.

One misconception is that arc-resistant equipment prevents an arc from occurring. In reality, arc-resistant equipment simply provides an additional degree of protection during a fault for the operator. This is obtained by the arc-resistant design features, such as a stronger frame, stronger doors and hinges, arc chamber, plenum, and exhaust ducts.

An arc fault can be initiated by many factors, including improper installation, rodents, dust, corrosion, or other impurities on the surface of the conductor(s). An arc flash is the uncontrolled conduction of electrical current from phase to ground and/or phase to phase. The arc rapidly heats the surrounding air and vaporizes the metallic components in its path. These two effects contribute to a rapid overpressure of the faulted compartment. Arc-resistant equipment is designed to mitigate these hazards for a specified period of time, as indicated by the rated arcing duration, by releasing the pressure in a controlled way. Many equipment designs do this through a combination of a plenum and exhaust ducts. By doing so, the effects of the fault should be controlled within the equipment ratings. Fig. 3 shows compartments that are typical of arc-resistant equipment designs.

To properly apply the arc-resistant equipment, the electrical protective devices must be coordinated with the ratings of the arc-resistant equipment. The rated arcing duration of the equipment must exceed the clearing time for the protective system.

C. Equipment Testing

To test equipment per the IEEE C37.20.7 guide, black cotton indicators (section 5.4.1) are placed vertically and horizontally around the equipment in accordance with the rated accessibility type (Type 1 or 2) specified by the manufacturer [1]. The vertical indicators are located from floor level to a height of 2 m (79 in.) and a distance of 100 mm +/- 15 mm (4 in.) from the surface of the equipment, facing all points where fault products are likely to be emitted. The horizontal indicators are located at a height of 2 m (79 in.) from the floor and horizontally covering the whole area between 100 mm +/- 15 mm (4 in.) and 800 mm (31 in.) from the equipment, around the perimeter of the equipment to evaluate hazards from falling debris. The values of the internal arcing short circuit current and arcing duration to be used during the test are provided by the manufacturer and if the equipment performs per the guide, these values will be specified on the rating nameplate.

Due to the lack of prescriptive location where an arc should be initiated within the guide, an agreement on the placement of the wire must be reached between the manufacturer and the certifier to create a test plan that meets the requirements of the guide. IEEE C37.20.7-2007, section 5.3 requires that "The point of initiation shall be located at the furthest accessible point from the supply within the compartment being tested", but then also references Table B.1 (column 1), which provides a list of the most likely arc fault locations [1]. Table B.1 is reproduced in Appendix A.

With all of the doors closed and the plenum and exhaust duct assemblies properly installed, an arc is initiated using a 24 AWG metal wire. The gases released by the arc fault are intended to be released into the plenum and are vented by the exhaust ducts into a designated safe area.

A successful test is needed at each designated arc test location in order to obtain an arc-resistant label. For example, for a medium-voltage motor control center test locations may include the starter medium voltage compartment, main bus compartment, and incoming cable compartment.

According to IEEE C37.20.7, the following criterion is used to assess the capability of the equipment to withstand arcing faults. The equipment must meet all criteria to qualify as arc-resistant [1]:

1) That properly latched or secured doors, covers, and so on, do not open. Bowing or other distortion is permitted provided no part comes as far as the position of the indicator mounting racks or walls (whichever is closest) on any assessed surface.

2) No fragmentation of the enclosure occurs within the time specified for the test. The ejection of small parts, up to an individual mass of 60 g, from any assessed external surface above a height of 2 m and from any external surface not under assessment, is accepted. No restriction is placed on the number of parts allowed to eject.

3) It is assumed that any opening in the equipment caused by direct contact with an arc will also ignite an indicator mounted outside of the equipment at that same point. Since it is not possible to cover the entire area under assessment with indicators, any opening in the area under assessment that results from direct contact with an arc is considered cause for failure. Openings above the indicator mounting rack height (2 m) that do not cause ignition of the horizontally mounted indicators are ignored.

4) That no indicators ignite as a result of escaping gases.

5) That all the grounding connections remain effective.

V. LESSONS LEARNED AND RECOMMENDATIONS

Arc-resistant standards primarily date back to the 1980s and equipment has been widely available in the marketplace since the early 1990s. Since this time, arc-resistant equipment has gained acceptance and is widely used within the oil, gas and petrochemicals industries. However, despite the relatively large installed base of arc-resistant equipment, there is very little published information on how this equipment performs under real-world fault conditions. This may be due to the combination of the improved design of arc-resistant equipment, which is based on lessons learned in laboratory testing, along with other advances in construction (such as insulated bus and compartment sectionalizing). While this is obviously a benefit since there is less exposure to personnel and improved availability of the equipment in the field, it also potentially slows the learning process since there is less real world data publicly available. Thus, this paper offers several lessons learned from the fault event and recommendations that apply to manufacturers, engineers who specify equipment and protection, and end-users.

A. Relay Coordination

The short-time withstand current rating of medium-voltage equipment needs to exceed the duration that a fault will exist on the power system due to the normal settings and coordination of protective relays. As such, historically it has not been a primary concern of protection engineers to consider these times (which is typically 2 seconds for medium-voltage metal-clad switchgear [3]) when determining relay settings. This rating represents a mechanical limit, beyond which the equipment may start to physically come apart.

Arc-resistant equipment has a second rating in the form of the internal arcing short-circuit current and maximum arcing duration. The rated arcing current is often the same as the short-time withstand current rating and thus does not need to be separately considered (beyond ensuring that the equipment rating exceeds the system short-circuit current). However, the maximum arcing duration requires special consideration by the protection engineer. This rating does not necessarily represent a physical or defined limit like the short-time withstand current rating, but instead is the duration that the manufacturer has tested the equipment. After this time is exceeded, the equipment cannot be expected to continue to perform per its design as arc-resistant equipment.

Currently, the practices for setting the parameters of protective relays (or other protective devices) varies, and in some cases, as was the case for the equipment discussed in this paper, the protection may not be designed to clear the fault within this time. However, it is important that this is the case to ensure that arc-resistant equipment performs as designed. IEEE C37.20.7 states this in Appendix B, Application Guide: "The coordination of the arc-resistant switchgear rated arcing duration with the clearing time of the protective scheme is essential." [1]

In order to assist protection engineers with ensuring faults are cleared within the maximum arcing duration, a simple and visual method of plotting the "arc-resistant design region" on time current coordination (TCC) curves is suggested. This region can be shown by plotting a horizontal line at the maximum arcing duration and a vertical line at the internal arcing short-circuit current rating. The upstream protection should be designed to clear a fault within the region bounded by these lines. In other words, the protection device curve should intersect a line representing the arcing fault current of the electrical system within the bounded region (note the reaction time of protective relays and delay time of any circuit breakers also needs to be considered).

A simplified TCC illustrating this method is shown in Fig. 6. A horizontal line is drawn at 0.5 seconds to match the rated maximum arcing duration of the arc-resistant equipment. A vertical line is drawn at 50 kA to match the rated internal arcing short-circuit current of the equipment. These two lines are drawn from the axis to the point of their intersection. The region bounded by these lines (shaded in the figure) represents the "arc-resistant design region" of the equipment, or the time-current region that the equipment is designed to safely withstand an arcing fault. A second vertical line (typically plotted for all time values on the TCC) is drawn at the value of electrical system arcing current seen by the upstream protection device, which is 25 kA for this example. The figure shows three sample protective device (PD) curves that could potentially be part of the electrical system. For this example, it can be seen that only PD #3 would adequately protect the arc-resistant equipment, since it is the only device that intersects the arcing fault current within the "arc-resistant design region." The clearing time for PD #1 and PD #2 at the system arcing fault current level exceed the maximum arcing duration of the equipment. PD #2 may appear to provide adequate protection since it enters the "arc-resistant design region," but it intersects the system arcing current outside the region, so it will not provide the necessary protection. A more detailed example TCC is given in Appendix B.

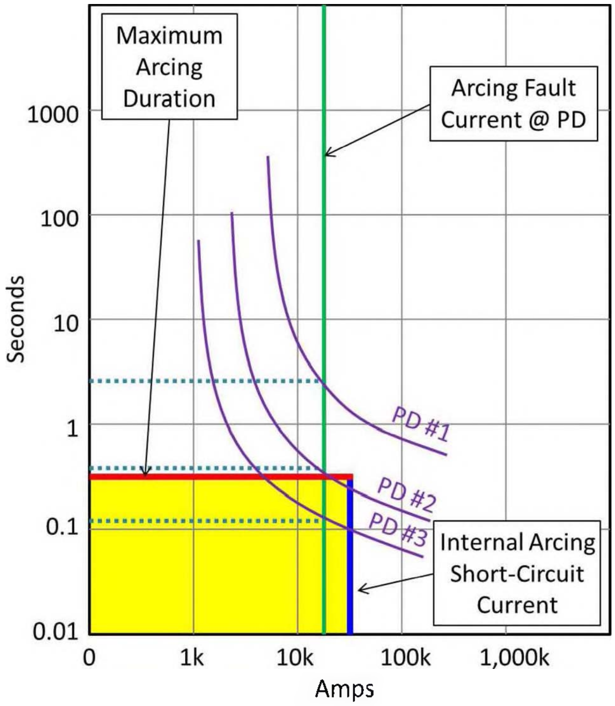

Fig. 6 TCC with Equipment Arc Rating Plotted

Currently, this can be done manually within most power system analysis software packages. It would be ideal if such packages would incorporate this functionality so that equipment buses could have associated parameters such as a "checkbox" input to identify that a particular bus is part of a piece of arc-resistant equipment with inputs for the internal arcing short-circuit current and maximum arcing duration. This information could then be selected to be automatically plotted on the TCC.

B. Equipment Design - Pressure Relief

Most MV arc-resistant equipment designs use some form of pressure relief, typically in the form of vent flaps or plates. Since the equipment is tested using the rated fault current for the rated arcing duration, the equipment pressure relief system is nominally subjected to the maximum pressure build-up that will occur given the rated arcing duration. However, faults that occur in equipment installed in an industrial power system will likely not experience faults at the rated time and current (based on upstream protection relay settings and protection device clearing time). Thus, the pressure profile in the equipment during an in-service fault could be different than that observed during the certification testing. This could lead to uncertain operation of the equipment pressure relief system.

C. Equipment Design - Type 2B

Type 2B equipment is often specified for oil, gas and petrochemical facilities since it provides added safety to personnel that may be working in the low voltage control compartment during a fault. However, equipment designs vary and the effects of the fault experienced during testing cannot be taken as representative of all faults that the equipment may experience over its lifetime. This testing is intended only to be representative of faults the equipment is likely to experience, but is not intended to encompass all types of faults or fault locations.

End users should have a high level of awareness of what the Type 2B designation actually means and the associated limitations. Consistent with IEEE C37.20.7, arc-resistant equipment is not designed to prevent a fault, but to minimize the effects of a fault from impacting personnel near the equipment. Type 2B equipment provides an added level of protection, but does not provide absolute protection.

It is suggested that, to enhance the protection of Type 2B equipment, equipment designs include complete isolation of low voltage control compartments from the medium voltage compartments. While this may be inherent in some equipment designs, such as metal enclosed and metal clad switchgear, it may not be part of the normal design for motor control centers. Since most current arc-resistant equipment designs have been adopted from their predecessor non-arc-resistant designs, isolation of these compartments may require special attention. In particular, for medium-voltage MCCs, sealing of all openings between the low voltage and medium voltage compartments is likely the only effective way to prevent arc products from entering the low voltage compartment. While this sealing could be seen as a de facto requirement due to the testing criteria in IEEE C37.20.7, the only stated requirement is that the indicators used in testing do not ignite and that the fault does not result in holes in the compartment wall(s). The location of the fault initiation during testing also has an impact on where the fault propagates to and thus where the pressure and arc products go. Furthermore, when equipment is applied beyond its rating the enclosure withstand capability, including the Type 2B arc-resistant rating, cannot be predicted.

D. PPE Selection

As discussed previously there are several approaches to selecting arc rated PPE when working on arc-resistant equipment. While there are advantages and disadvantages of each approach, the conservative approach is to treat arc-resistant equipment as if it is not arc-resistant and select arc rated PPE for invasive tasks based on the available arc flash incident energy (or the task if arc flash incident energy calculations are not available).

The facility where this incident occurred elected to select arc rated PPE for arc-resistant equipment applications using the same methodology as is used for non-arc-resistant equipment applications at the facility. That is, the arc-resistant equipment is treated as if it is not arc-resistant. While this often requires the worker to wear more PPE than is required by electrical safety standards for arc-resistant installations, this allows for a clear approach and standardization of PPE selection across the facility, which has a large installed base of both arc-resistant and non-arc-resistant equipment. Additionally, this approach provides the worker with an additional layer of protection from arc flash hazards when working on arc-resistant equipment in the event of a fault.

While this can result in additional PPE being used for many tasks, this approach provides the best level of protection for personnel. Many users, including electricians who routinely work on the equipment, do not realize what the acceptable passing criteria for arc-resistant equipment is, which can create a 'false sense of security' that arc-resistant equipment is "safe." Even if equipment meets the test criteria, pressure, hot gasses, acoustic waves, and particles can still be emitted from the equipment under fault conditions. While PPE can help to protect personnel from some of these hazards, electrical personnel should also be trained to understand the hazards that are still present with arc-resistant equipment.

E. Commissioning and Maintenance Inspections

Most EPC firms and end-users are well aware of the various aspects of the lifecycle of electrical equipment and how to effectively perform them: specification, purchase, installation, commissioning and maintenance. While arc-resistant equipment does not require different treatment from equipment that is not arc-resistant over this lifecycle for most of these aspects, there are two aspects that should receive special consideration due to the design of arc-resistant equipment.

Most arc-resistant equipment designs incorporate some form of metal flap or plate used to relieve the pressure in a controlled manner that is built-up during an arc fault. For equipment that exhausts into the room, these are typically found on the top of the equipment. For equipment that vents outside the room via ducts or a plenum, there are typically two sets: on the top of the equipment and at the termination of the exhaust duct (often at the substation exterior wall).

During installation and commissioning, it is suggested that these arc vents be inspected to ensure the following:

- Free of shipping materials.
- No signs of damage, moisture or corrosion.
- Flaps (where present) move freely along their entire intended path of travel.
- Plates (where present) are properly attached.
- Retaining clips or screws (where specified by the manufacturer) are in place.
- No loose or missing hardware.

Similar inspections should also be performed throughout the life of the equipment during routine maintenance. It is suggested that arc vents be inspected routinely to ensure the following:

- No signs of damage, moisture or corrosion.
- Flaps (where present and not attached by retaining clips or screws) move freely along their entire intended path of travel.
- Plates (where present) are properly attached.
- Retaining clips or screws (where specified by the manufacturer) are in place.
- No missing hardware.
- Gaskets (where present) are in good condition and not deteriorated.
- Dust, dirt and debris are removed from the area around arc vents and (where present) ducts or plenums.
- No visible gaps at joints of ducts or plenums (where used).
- Air filter (if present) is in good condition.

These checks can be performed by simple visual inspection although, depending on the equipment design, this may require removal of access plates or panels (especially where ducts or plenums are used). Additional, more invasive, inspection or testing could be performed, but these items are suggested as a simple way to check the condition of arc vents while minimizing the amount of additional work and reducing the potential for introducing errors or damage.

F. Spare Parts

The need for spare parts is typically evaluated during any project installing new equipment, so it is likely assumed that the recommended spare parts list provided by an EPC or equipment manufacturer contains all the necessary parts. However, some items that are unique to arc-resistant equipment may not be included in spare parts lists or specifically referenced in the manufacturer's operation and maintenance instructions. Additionally, while projects almost always provide a spare parts list, it is often left up to the owner or end-user to actually purchase the parts. For existing facilities, the process for doing so may not be clearly defined, it may be assumed that existing spare parts for similar equipment are adequate or limited spare parts may only be held on-site (e.g. trip and close coils, indicating lamps, etc.) based on experience of failures.

If a fault occurs at oil, gas and chemical facilities, this often means that production is impacted, resulting in a desire to quickly restore the equipment to service (without compromising safety of personnel and operations). Typically, individual components that have been damaged can be removed or replaced, structural items (such as sheet metal and insulating materials) can be cleaned on-site and portions of equipment damaged "beyond repair" can be isolated. Arc-resistant equipment is no different from equipment that is not arc-resistant in this respect, but arc-resistant equipment often has 'specialty' components required to properly function.

It is suggested that end users review each arc-resistant equipment installation to determine what 'specialty' components are part of the equipment design.

1) Arc vent plates: As discussed previously, some arc-resistant equipment designs utilize a specially designed plate to relieve the pressure from a fault. The plate is designed to burst open above a certain pressure and thus cannot be reused. The plate and associated hardware (such as screws or bolts) need to be replaced after a fault.

2) Arc vent flaps: Other arc-resistant equipment designs may use flaps. Some designs rely on the flap weight to stay closed and typically do not need to be replaced after a fault, unless there is physical damage. The flap can simply be closed and reused. However, other flaps are held in place with retaining clips or screws and the flap may be damaged when it breaks away from the retaining mechanism, or if the flap can be reused, the retaining device(s) needs to be replaced.

3) Retaining clips or screws: Additional retaining clips or screws are often used on external exhaust flaps at the end of ducts or plenums. These ducts are used to exhaust fault products outside of the substation and so a flap is used primarily to keep moisture and other contaminants out of the duct. After a fault, or anytime the flap is opened, the retaining device(s) needs to be replaced.

Once the components that are part of an arc-resistant equipment installation have been identified, consideration should be given to holding a suitable quantity of spares on-site to facilitate quick replacement in the event of a fault.

VI. CONCLUSIONS

Arc-resistant equipment is one of many advances to the design and construction of electrical distribution equipment over the past several decades that have contributed to increased safety of personnel who operate and maintain the equipment. The testing criteria defined in IEEE C37.20.7 and other global standards provides a framework that allows manufacturers to design and test equipment and should give end users confidence that equipment meeting the criteria incorporates these advances. However, everyone should also be aware of the limitations of equipment that has been designed and tested to be arc-resistant. The current revision of IEEE C37.20.7 has room for improvement, which has been recognized by the working group and manufacturers. These improvements will be addressed in the upcoming revision. Although arc-resistant equipment will sustain damage during a fault, which could be significant, the primary purpose of arc-resistant designs is to protect personnel. One example of equipment that sustained an actual fault while in-service at an end user substation largely performed as designed and the as-found condition of the equipment meets the passing criteria defined in IEEE C37.20.7.

It is important for those who specify and apply arc-resistant equipment to have an understanding of the way it is designed and tested so that they can appreciate the limitations. For arc-resistant equipment to perform as designed, the internal arcing short-circuit current rating needs to be properly specified based on the electrical power system the equipment will be applied on and the upstream protection device(s) need to clear arcing faults within the equipment maximum arcing duration. One way to help protection engineers visualize the equipment ratings in relation to protection settings is to plot the internal arcing short-circuit and current maximum arcing duration on the TCC. The protection needs to clear arcing faults within the region bounded by these parameters to ensure the equipment is properly applied within its ratings. The application of protection methods, such as high-speed relaying using arc flash detection sensors, differential protection, zone selective interlocking, or definite time elements, can help in achieving this objective.

It is equally important that end users, including operators and electricians that routinely interact with arc-resistant equipment, have a basic understanding of what "arc-resistant" equipment means in terms of the testing and passing criteria. This creates a foundation for the correct expectations, which can also inform decisions around work practices. It is suggested that where arc-resistant equipment is installed training be provided to site personnel, with a focus on electricians. The training might cover topics such as the various types of arc-resistant equipment (as defined by IEEE C37.20.7), similarities and differences between arc-resistant equipment and non-arc-resistant equipment, the requirements for testing arc-resistant equipment (including the passing criteria), and how to properly interact with arc-resistant equipment (e.g. PPE required, opening and re-securing doors, maintenance and inspection of equipment).

Lastly, it is the expectation of the electrical community that industry continue to improve equipment standards, which will lead to better designs and development of innovative solutions to further enhance personnel safety. One opportunity, which should be addressed in the next revision of IEEE C37.20.7, is to provide more specific criteria on where arc faults are to be initiated in each type of equipment (since the location of likely faults varies between switchgear and motor control centers). Further, faults that occur in the real world are inevitably unpredictable, so more rigorous testing, including better understanding the effects at fault currents less than the rated value, is necessary to ensure that the equipment meets the expectations of end users. Most people that specify, purchase, install and use arc-resistant equipment are not experts in switchgear or motor control equipment design and rely on manufacturers to provide safe solutions. The methods used by manufacturers to pass arc-resistant testing vary, but when the details of equipment designs are considered there are some best practices used that should be adopted across the industry.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

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IX. VITAE

Mark A. Metzdorf (M'06, SM '15) graduated from Purdue University in 2007 with a BSEE degree. He currently works for BP as a Principal Electrical Engineer in the Refining Technology & Engineering group based in Naperville, IL. In this role, he provides electrical power system technical support to BP's eight refineries in the US, Europe and Australia along with other parts of the Downstream business. Prior to joining BP in 2013, Mark was the Electrical Engineer for the Olefins and Hydrocarbons portion of the LyondellBasell manufacturing complex in Channelview, TX, responsible for designing and implementing small projects, participating in capital improvement projects, planning and coordinating electrical maintenance and project work during major unit outages and supporting the daily maintenance activities of the electrical distribution system. Mark is an IEEE Senior member, is the lead author of a previous PCIC paper and co-presented a previous PCIC tutorial. He represents BP on the API Subcommittee on Electrical Equipment and on the API 541/546/547 motors task force. He is a registered professional engineer in the state of Texas.

Douglas BeCraft (M'08) received a Bachelor of Engineering in Electrical Engineering from Vanderbilt University in 2008. He has been employed at the BP Whiting Refinery since 2012 and is currently the Instrumentation and Electrical Engineering Superintendent in the Maintenance and Reliability Department. He has previously held roles as Electrical Engineer and Electrical Engineering Superintendent. Prior to joining BP, he was employed at Marathon Petroleum Company working in maintenance and major capital project electrical engineering roles at multiple refineries.

Richard Bhalla (M'17) received his B.E.M.E from T.I.E.T, Punjab, India in 1999 and M.S.M.E degree from Wayne State University, MI, USA in 2002. Since 2013, he has been a Medium-Voltage Control Assemblies Lead Design Engineer with Eaton. From the very beginning of his tenure with Eaton, he has been working on the arc-resistant medium-voltage control center. From 2003 through 2013, he was an engineer and a senior engineer for light and medium duty emergency vehicle manufacturers.

Adam E. Fabrici received his BSEE from Purdue University Calumet in 1987. He is currently a Reliability Engineer for BP. Over a career spanning 30 years he has held a variety of positions in projects, procurement and maintenance related to refinery electrical systems and equipment.

IEEE C37.20.7 Table B.1—ARC FAULT LOCATIONS, CAUSES, AND PREVENTATIVE MEASURES [1]

Locations where internal faults are more likely to occur	Possible causes of internal faults	Possible preventative measures
Cable terminations	Inadequate design	—Selection of adequate dimensions
	Faulty installation	—Avoidance of crossed cable connections —Checking of workmanship on site —Correct torque
	Failure of insulation (defective or missing)	—Checking of workmanship and/or dielectric test on site —On-line partial discharge monitoring
Disconnects Switches Grounding switches	Misoperation	—Interlocks —Delayed reopening —Independent manual operation —Making capacity for switches and grounding switches —Instructions to personnel
Bolted connections and contacts	Corrosion	—Use of plating, corrosion inhibiting coatings, and/or greases —Encapsulation, where possible
	Faulty assembly	—Checking of workmanship by suitable means —Correct torque
Instrument transformers	Ferroresonance	—Avoidance of these electrical influences by suitable design of the circuit
Circuit breakers	Insufficient maintenance	—Regular programmed maintenance —Instructions to personnel
All locations	Error by personnel	—Limitation of access by compartmentalization —Insulation embedded live parts —Instructions to personnel
	Aging under electric stresses	—Partial discharge tests (periodic or online)
	Pollution, moisture, entrance of dust, vermin, etc.	—Measures to ensure that the specified service conditions are achieved
	Overvoltages	—Surge protection. —Adequate insulation coordination —Dielectric tests on site

APPENDIX B

EXAMPLE TCC WITH ARC-RESISTANT EQUIPMENT RATING PLOTTED