ELECTRIC POWER RESEARCH INSTITUTE

CRITICAL MAINTENANCE INSIGHTS ON PREVENTING HIGH-ENERGY ARCING FAULTS

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Executive Summary

High-energy arcing faults (HEAFs) can occur, and when combined with latent protective device issues or switchgear issues, can escalate and cause significant equipment damage and impact on generation. An analysis of industry data demonstrates that an effective preventive maintenance program is important in minimizing the likelihood and/or severity of an HEAF event. Sixty-four percent of HEAF events were considered preventable, and the most prevalent cause of failure was inadequate maintenance. These data demonstrate that proper maintenance can prevent most HEAF events. Effective maintenance practices and strategies are summarized in this report by equipment type, including circuit breakers, bus ducts, protective relays, and cables. These maintenance practices include the following:

- *Periodic circuit breaker maintenance including routine preventive maintenance and overhaul, considering the following:*
  - Particularly important is maintenance of the unit auxiliary transformer (UAT) breaker, which, if it fails, could lead to an extended duration un-isolatable generator-fed fault at the first switchgear bus.
  - For critical switchgear, such as the UAT breaker, feeder circuit breakers that carry higher currents, and switchgear that is part of a bus transfer scheme, the proper maintenance of primary connections to both the bus and the circuit breaker is especially important.
- *Timing tests on circuit breakers associated with fast bus transfer schemes*
- *Bus duct visual inspections, torque checks, or re-torqueing, of bolted connections (Particularly important are bus ducts that connect the UAT to the source breaker of the first switchgear bus because there is no breaker to isolate the HEAF from the generator during coast-down.)*
- *Connection resistance measurements on bolted bus duct connections*
- *Periodic calibration of protective relays, as well as inspections, electrical tests, and functional testing (Protective relay calibration should include dual verification techniques and/or engineering work order/procedure review for alignment to engineering calculations.)*
- *Periodic visual inspection of cable terminations and cable insulation*
- *Periodic infrared thermography of cable terminations and splices*
- *Periodic very low frequency tan delta (or dielectric spectroscopy) testing to monitor insulation degradation*
- *Periodic partial discharge testing on cables rated 8 kV and higher*
- *Periodic power frequency or very low frequency withstand test to IEEE 400.2 levels following successful tan delta testing, or after cable replacement is performed*

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This white paper was prepared by EPRI.

Insights on High-Energy Arcing Faults

The Nuclear Regulatory Commission (NRC) has identified a potential generic issue (PRE GI-018) for stations with aluminum in electrical distribution equipment (load centers, switchgear, bus ducts, and so forth) where high-energy arcing faults (HEAFs) can occur. The NRC has developed an assessment plan with an associated timeline and milestones. Industry operating experience suggests that arc faults can occur, and when combined with latent issues with protective devices, bus ducts, switchgear or circuit breakers, these arc faults can escalate and cause significant equipment damage (See NRC Information Notice 2017-04, High Energy Arcing Faults in Electrical Equipment Containing Aluminum, Components.)

The Electric Power Research Institute (EPRI) is assisting the industry in addressing this issue and has produced two white papers:

- EPRI 3002011922, *Characterization of Testing and Event Experience for High-Energy Arcing Fault Events*
- EPRI 3002011923, *Nuclear Station Electrical Distribution Systems and High-Energy Arcing Fault Events*

This report communicates some critical insights provided in EPRI report 3002011923, *Nuclear Station Electrical Distribution Systems and High-Energy Arcing Fault Events*, as well as other EPRI reports that are referenced below. Industry guidance below is broken down into the areas of circuit breakers and switchgear, bus duct, protective relays, and cables. Collectively, this guidance identifies industry practices that help ensure that electrical distribution systems perform properly to help reduce either the likelihood and/or severity of an HEAF event.

- Sixty-four percent of HEAF events were considered preventable.
- The most prevalent cause of failure was inadequate maintenance.
- Proper maintenance can prevent most HEAF events.
- An effective preventive maintenance program is important in minimizing the likelihood and/or severity of an HEAF event.
- Effective maintenance practices and strategies are summarized in this report by equipment type (that is, circuit breakers, bus ducts, protective relays, and cables).

According to EPRI report 3002011922, a review of HEAF events discovered that 64% of the events were considered to be preventable and the most prevalent cause of failure was inadequate maintenance. These data demonstrate that proper maintenance can prevent most HEAF events. A strong preventive maintenance and testing program is an important element in minimizing the likelihood and/or severity of an HEAF event.

Circuit Breakers

Several significant HEAFs were caused by failed fast bus transfer events where the unit auxiliary transformer (UAT) breaker was either slow to open, or stuck, allowing the fault to either continue to be fed by the generator during coast-down or closure of the startup transformer (SUT) breaker, paralleling the bus to a new source to feed the fault. Timing tests on medium-voltage circuit breakers are part of periodic maintenance program (see EPRI TR-112783). Although circuit breaker timing tests are not a comprehensive assessment of the overall condition of a circuit breaker, these tests provide some indication of the condition of a circuit breaker's subcomponents.

Particularly important is maintenance of the UAT breaker, which, if it fails, could lead to an extended duration fault resulting from a generator-fed fault at the first switchgear bus. Operating experience has shown this breaker to fail during automatic bus transfers.

In several HEAF events, faults were fed from the generator as the generator field collapsed following a generator trip. This can occur in a unit-connected design configuration where the main generator and UAT have no in-line generator circuit breaker and, therefore, no backup circuit breaker(s) to isolate the transformer and the downstream bus from a generator-fed fault if any of the following occur (see below):

- The UAT secondary side breaker fails to open
- The UAT secondary side breaker is slow to open
- A fault exists anywhere between the UAT and the first load-side bus feed circuit breakers

In the unit-connected design, it is especially critical for circuit breakers immediately downstream of the UATs to be properly maintained, or any other scenario where there is a possibility of a generator-fed fault affecting a plant bus.

Operating Experience Example

A grid disturbance caused the main generator protection to actuate. Fast transfer failed for one bus, thereby allowing the main generator to be paralleled with the SUT through the UAT. Overcurrent protection initiated a trip of the UAT breaker, but out-of-phase condition exceeded breaker interrupting rating, causing the breaker to fail. No interlock existed to prevent paralleling main generator with the SUT.

Based on industry experience, proper maintenance includes the connection between the primary connections (stabs) on the circuit breaker and the connections (fingers) where the circuit breaker is inserted into the switchgear bus. Industry operating experience and the EPRI Fire Events Database include events where the lack of proper maintenance of primary connections, including the bus and circuit breaker connections, have resulted in electrical faults, some of which were HEAF events. Stations typically have periodic preventive maintenance and refurbishment frequencies for medium-voltage circuit breakers, but switchgear maintenance outages are not frequently available as a result of outage scheduling restrictions. The switchgear contains connections to the circuit breaker, which might not be maintained as often as the connection on the circuit breaker. For critical switchgear, such as feeder circuit breakers that carry higher currents, and switchgear that is part of a bus transfer scheme, proper maintenance of connections on both the bus side and the circuit breaker side is especially important. Inspections should be performed to ensure that proper silver plating exists on breaker-to-bus connection locations. Maintenance should also verify the spring tension of the springs used on the primary connections. Also, proper alignment of the circuit breaker into the switchgear cubicle should be verified periodically.

Circuit breaker maintenance program fundamentals are contained in EPRI report 1000014, *Circuit Breaker Maintenance Programmatic Considerations.* Circuit breaker maintenance includes periodic routine preventive maintenance and refurbishment. Because of the mechanical complexity of most switchgear circuit breakers, maintenance is mostly time-based, with condition-based maintenance being used when appropriate. Maintenance frequencies are modified by stations based on the circuit breaker environment, economic and safety significance, manufacturer's recommendations, type of lubricant, maintenance history, industry operating experience, and operational history. Routine preventive maintenance includes as-found checks, visual inspection and cleaning, mechanical checks and adjustments, electrical tests, lubrication, main and secondary contact inspections and testing, primary current injection testing (trip device testing), cubicle and primary stab inspections, and breaker timing. Circuit breakers need to be periodically refurbished (overhauled), which encompasses a complete disassembly and re-lubrication to restore the circuit breaker to like-new condition. EPRI report 3002005428, *Preventive Maintenance Basis Database (PMBD)*, provides switchgear maintenance tasks and frequencies that serve as a baseline that nuclear stations can modify based on station-specific conditions and experience.

EPRI Guidance:

- EPRI 1000014, *Circuit Breaker Maintenance Programmatic Considerations*
- EPRI TR-112783, *Circuit Breaker Timing and Travel Analysis*
- EPRI 3002005428, *Preventive Maintenance Basis Database (PMBD)*

Operating Experience Example

A nuclear power plant experienced a reactor scram and main turbine trip. The plant trip was partially caused by an electrical fault in the 6.9-kV electrical distribution system. The non-segregated bus's flex connections overheated and failed catastrophically. All three bus conductors melted and resulted in a fire and significant damage. The most likely cause of the failure was a combination of overheating of the flex connection and torque relaxation because of thermal cycling over time. Contributing causes to the failure included a lack of torque checks on the connection bolting and insufficient temperature monitoring. One of the more significant lessons learned from this event was that the torque (tightness) of bolted connections on a non-segregated bus should be periodically checked.

Bus Duct

A number of HEAF events that were initiated in bus duct locations were a direct result of inadequate maintenance. Bolted bus bar connections need to be periodically checked for proper torque. When connections are being re-taped, the proper (voltage class) tapes should be used.

Manufacturers generally specify torqueing specifications (and, in some cases, lubrication requirements) for bolted electrical connections, and these should be used. However, there are many bolted electrical connections in power plants for which no manufacturer torque specification is available. As a result, many plants have developed their own torque requirements to be used when no manufacturer specification is available.

According to EPRI report 3002011484, *Reliability and Maintenance of Bolted Bus Bar Connections*, the most reliable way to determine the condition of a bolted connection is to measure its contact resistance (joint contact resistance for a bolted bus bar connection). A major advantage of this measurement is that it can be used on booted and taped joints. EPRI report 3002011484 further states that the actual area of contact is a function of the contact load (bolt torque) and the material's hardness. It does not depend on the total area of the contact face.

EPRI report 1013457, *Nuclear Maintenance Applications Center: Switchgear and Bus Maintenance Guide*, describes improved arc flash protection that can mitigate switchgear faults, minimizing impact to personnel and equipment.

The EPRI reports listed below provide maintenance guidance on bus duct visual inspections, checking the torque (re-torqueing) of bolted connections, performing connection resistance measurements, and so forth.

EPRI Guidance:

- EPRI 3002011484, *Reliability and Maintenance of Bolted Bus Bar Connections*
- EPRI 3002000707, *Lessons Learned from Exelon's Non-Segregated Bus Inspections*
- EPRI 1013457, *Nuclear Maintenance Applications Center: Switchgear and Bus Maintenance Guide*
- EPRI 1015057, *Nuclear Maintenance Applications Center: Isolated Phase Bus Maintenance Guide*

Protective Relays

HEAF events have occurred where protective relays were left with their trip contacts disabled after maintenance (that is, leads not landed). One point beyond functional testing logic testing would have identified this configuration control issue.

Maintenance practices have resulted in incorrect or non-optimum setpoints. Maintenance practices should include dual verification techniques and/or engineering work order/procedure review for acceptance and alignment to engineering calculations.

Relay settings need to be periodically calibrated to offset age-related setpoint drift. The EPRI reports listed below provide maintenance guidance for protective relays that include visual inspections, mechanical adjustments, electrical tests, calibration, and functional testing.

EPRI Guidance:

- EPRI NP-7216, *Protective Relay Maintenance and Application Guide*
- EPRI 3002005359, *Industry Practices Related to the Application of Protective Relaying for Large Power Transformers at Nuclear Power Stations: Transformer Protective Relay Guide*

Cables

Cable-related failures that could result in an HEAF would most likely result from cable insulation degradation, an accessory failure (termination kit or splice kit), ohmic heating or a high-resistance mechanical connection of a termination or splice.

In cables rated less than 1000 volts, an insulation failure, whether it be the cable, a splice, or termination insulation, would typically only occur as the result of long-term ohmic heating or insulation wear from cyclic vibration. High-resistance bolted connections can generate significant heat that also could result in insulation failure. Maintenance tasks such as periodic visual examination for signs of wear or overheating, infrared thermography of terminations and splices, and insulation-resistance testing are the recommended maintenance tasks found in EPRI's cable aging management implementation guide (3002010641).

Cables rated 5 kV and higher are operated at higher levels of electrical stress that could exceed the capabilities of the insulation of a degraded cable. Insulation degradation can result from thermal stress (rare), because of water treeing, external partial discharge/corona related insulation wear caused by poor splice or termination workmanship, partial discharge internal to a splice or termination resulting from poor design (rare) or poor workmanship (likely), or a single, large manufacturing defect.

EPRI's medium-voltage cable testing guidance in report 3002000557 recommends the following testing to monitor cable condition:

- Periodic visual inspection of cable terminations and cable insulation for signs of mechanical wear, overheating caused by high ohmic loading or a high resistance connection, signs of corona, or tracking
- Periodic infrared thermography of terminations and splices to detect high resistance connections
- Periodic very low frequency tan delta (or dielectric spectroscopy) to monitor for insulation degradation
- Periodic partial discharge (cables rated 8 kV and higher) to detect degraded terminations or splices
- Periodic power frequency or very low frequency withstand test to IEEE 400.2 levels to fail severely degraded cable insulation resulting from widespread degradation or a large, single defect

EPRI Guidance:

- EPRI 3002010641, *Low-Voltage and Instrumentation and Control Cable Aging Management Guide, Revision 1*
- EPRI 3002000557, *Plant Engineering, Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants, Revision 1*

EPRI RESOURCES

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