



U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

DRAFT BRANCH TECHNICAL POSITION (BTP) 8-9

OPEN PHASE CONDITIONS IN ELECTRIC POWER SYSTEM

REVIEW RESPONSIBILITIES

Primary - Organization responsible for electrical engineering

Secondary - None

A. BACKGROUND

On January 30, 2012, Byron Station, Unit 2 experienced an automatic reactor trip from full power because the reactor protection scheme detected an undervoltage condition on the 6.9-kV buses that power reactor coolant pumps (RCPs). The undervoltage condition was caused by a broken insulator stack of the Phase C conductor for the 345 kV power circuit that supplies both station auxiliary transformers (SATs). The insulator failure resulted in a high impedance fault through the fallen Phase C conductor and a sustained open phase condition on the high voltage side of the SAT. The open circuit created an unbalanced voltage condition on the two 6.9-kV nonsafety-related RCP buses and the two 4.16-kV engineered safety features (ESF) buses. ESF loads remained energized momentarily, relying on equipment protective devices to prevent damage from an unbalanced overcurrent condition. The overload condition caused several ESF loads to trip.

Approximately 8 minutes after the reactor trip, the control room operators diagnosed the loss of Phase C condition and manually tripped breakers to separate the unit buses from the offsite power source. When the operators opened the SAT feeder breakers to the two 4.16-kV ESF buses, the loss of ESF bus voltage resulted in the emergency diesel generators (EDGs) automatically starting and restoring power to the ESF buses. In the event that the operators failed to diagnose the condition in a timely manner, a potential damage to the RCP seals due to loss of seal cooling water may have resulted in a loss-of-coolant event within a few more minutes.

A second event also occurred at Byron Station Unit 1 on February 28, 2012. This event was also initiated by a failed inverted porcelain insulator which resulted in an open phase as well as a phase to ground fault on the line side of the circuit. In this event, the fault current was high enough to actuate protective relaying on the 345 kV system. The 4.16-kV ESF buses experienced an undervoltage condition due to the opening of 345 kV system breakers, which resulted in separation of SATs from the 4.16-kV buses. The 1A and 1B EDGs started and energized the 4.16-kV ESF buses as designed.

Past operating experience has identified design vulnerabilities associated with single-phase open circuit conditions at South Texas, Unit 2; Beaver Valley Power Station, Unit 1; James A. Fitzpatrick Nuclear Power Plant; and Nine Mile Point, Unit 1. These events involved offsite power circuits that were rendered inoperable by an open-circuited phase. In each

instance (except South Texas, Unit 2), the condition went undetected for several weeks because offsite power was not aligned to ESF buses during normal operation and the surveillance procedures, which recorded phase-to-phase voltage, did not identify the loss of the single phase. At South Texas, Unit 2, offsite power was normally aligned to ESF and nonsafety plant buses and the reactor was manually tripped by the operator when circulation water pump was tripped by the open phase condition. Recently, two related international events occurred. First, the Bruce Power Plant in Canada identified that the protective relaying scheme is vulnerable to open-phase, or loss-of-phase events based on an event that occurred on December 22, 2012, where one of the 3-phases of 230 kV overhead line connections was broken. Second, the Forsmark, Unit 3 in Sweden reported that protective relaying scheme is vulnerable to open phase events based on an event that occurred on May 30, 2013 (circuit breaker to the 400 kV grid was disconnected in two phases, when power source to the safety buses were in the process of realigning to an alternate 70 KV source). In both events, EDGs did not automatically connect to the safety buses because the plant design did not have features to address open phase conditions.

Based on the Byron Station operating event, the staff issued U.S. Nuclear Regulatory Commission (NRC), Information Notice 2012-03, "Design Vulnerability in Electric Power System," dated March 1, 2012 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML120480170). On July 27, 2012, the staff issued NRC Bulletin 2012-01, "Design Vulnerability in Electric Power System," to confirm that licensees comply with Title 10 of the *Code of Federal Regulations* (10 CFR) 50.55a(h)(2), 10 CFR 50.55a(h)(3), and Appendix A to 10 CFR Part 50, General Design Criteria (GDC) 17, or principal design criteria specified in the updated final safety analysis report. Specifically, the NRC requested licensees to provide information by October 25, 2012, (1) regarding the protection scheme to detect and automatically respond to a single phase open circuit condition or high impedance ground fault condition on GDC 17 power circuits, and (2) operating configuration of engineered safety features buses at power. The Electrical Engineering Branch staff has reviewed the information that NRC licensees provided and the detail of this review is documented in a Summary Report dated February 26, 2013 (ADAMS Accession No. ML13052A711).

Safety Significance of open phase condition: At Byron, both offsite and onsite electric power systems were not able to perform their intended safety functions due to the design vulnerability. Manual actions were necessary to restore ESF safety functions. A design-basis event concurrent with this open phase condition could have resulted in the plant exceeding the guidance contained in 10 CFR 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors." The accident sequence precursor analyses conducted by the staff calculated a conditional core damage probability of 1×10^{-4} .

The purpose of this BTP is to provide guidance to the staff in reviewing various licensing actions related to electric power system design vulnerability due to open phase conditions in offsite electric power system in accordance with Appendix A to 10 CFR Part 50, GDC 17 or principal design criteria specified in the updated final safety analysis report, and 10 CFR 50.36(c)(2) and (c)(3).

B. BRANCH TECHNICAL POSITION

The design of the electrical system should address the following open phase conditions:

- (i) Electric power from the transmission network to the onsite electric distribution system is supplied by two physically independent circuits. The system should address loss of one of the three phases of the independent circuits on the high

voltage side of a transformer connecting an offsite power circuit to the transmission system under all operating electrical system configurations and loading conditions:

- a. with a high impedance ground fault condition; and
 - b. without a high impedance ground fault condition; and
- (ii) loss of two of the three phases of the either offsite power circuit on the high voltage side of a transformer connecting an offsite power circuit to the transmission system under all operating electrical system configurations and loading conditions.

1. Nuclear Power Plants with Active Safety Features

For performing licensing reviews for operating reactors and new reactors with active safety features plant designs under 10 CFR Part 50 and 10 CFR Part 52, the following criteria should be satisfied:

I. Detection and Alarms

An open phase condition should be automatically detected and alarmed in the control room unless it can be shown that the open phase condition does not prevent functioning of important-to-safety SSCs.

Detection circuits for the open phase condition, which prevents the functioning of important-to-safety SSCs, should be sensitive enough to identify an open phase condition under all operating electrical system configurations and loading conditions for which they are required to be operable.

II. Actuation circuits

The design of actuation circuit should minimize misoperation, maloperation, and spurious actuation of an operable off-site power source by providing independent dual sensors and coincidence logics. Additionally, the protective scheme should not separate the operable off-site power source in the range of voltage perturbations such as switching surges, load or generation variations etc., normally expected in the transmission system.

Licensees/applicants should perform failure modes analysis to demonstrate that the additional actuation circuit design does not result in lower overall plant operation reliability. These devices must be coordinated with other protective devices in both the transmission system and the plant's electrical system (e.g., fault protection, overcurrent, etc.).

III. Circuit Classification

Class 1E detection and actuation circuits at the ESF bus level meet the applicable requirements of GDC 17. A non-Class-1E detection and actuation circuit at the non-Class1E level may be acceptable if the following is satisfied:

A detection/protection scheme providing equivalent function at the high voltage circuit (non-Class-1E) is acceptable to the NRC if the licensee can demonstrate compliance with NRC regulations in 10 CFR 50.55a (h)(2) or 10 CFR 50.55a(h)(3), "Protection Systems,"

otherwise, an alternative to the requirements of 10 CFR 50.55a (h)(2) or 10 CFR 50.55a(h)(3) should be submitted and authorized prior to implementation in accordance with 10 CFR 50.55a(a)(3) or an exemption to these requirements in accordance with 10 CFR 50.12, "Specific exemptions," must be processed.

IV. Updated Final Safety Analysis Report

The Updated Final Safety Analysis Report (UFSAR) should be updated to discuss the design features and analyses related to the effects of, and protection for, any open phase condition design vulnerability. This update would typically be to Chapter 8 of the UFSAR and completed in conjunction with the 10 CFR 50.71(e) requirements.

V. Protective Actions

For an open phase condition, the staff finds the following method for meeting the design requirements acceptable:

- (1) With no accident condition signal present, the licensee/applicant should demonstrate that:
 - a. The condition does not adversely affect the function of important-to-safety structures, systems and components; and
 - b. Abnormal operating occurrence, transients, events, and accidents (e.g., RCP seal failure) would not be created as a result of the condition;
 - c. Important-to-safety equipment is neither prevented from operating because protective devices are actuated nor damaged by the condition; and
 - d. Safe Shutdown capability is not compromised for all operating and anticipated operational occurrences.
- (2) With an accident condition signal present, the licensee/applicant should demonstrate that:
 - a. Automatic detection and actuation will transfer loads required to mitigate postulated accidents to an alternate source and ensure that safety functions are preserved, as required by the current licensing bases.
 - b. Alternatively, a licensee/applicant may demonstrate by analytical analyses and actual testing that all design basis accident acceptance criteria and GDC17 or equivalent criterion are met with the open phase condition, given other plant design features. The analyses should include all design and licensing basis assumptions including single failure criterion.
- (3) Following protection system requirements should be met for the open phase condition:

The voltage or current sensors should be designed to satisfy the following applicable requirements 10 CFR 50.55a(h)(2) or (h)(3) derived from IEEE Std. 279 and/or IEEE Std. 603, as endorsed by RG 1.153:

- i. Class 1E equipment should be used and should be physically located at and electrically connected to the Class 1E switchgear.
- ii. An independent scheme should be provided for each division of the Class 1E power system.
- iii. The open phase protection should include coincidence logic on a per bus basis to preclude spurious trips of the offsite power source.
- iv. The open phase protective devices should automatically initiate the disconnection of offsite power sources whenever the setpoints and time delay limits have been exceeded.
- v. Capability for test and calibration during power operation should be provided.
- vi. Annunciation must be provided in the control room for any bypasses incorporated in the design.

If the non-Class 1E open phase circuit protection schemes are installed on the offsite power system, the following equivalent protection system requirements specified in 10 CFR 50.55a (h)(2) or 10 CFR 50.55a(h)(3) should be met as a minimum:

Justifications for complying with NRC regulations 10 CFR 50.55a (h)(2) or 10 CFR 50.55a(h)(3), "Protection Systems," should be provided. Otherwise, an alternative to the requirements of 10 CFR 50.55a (h)(2) or 10 CFR 50.55a(h)(3) must be submitted and authorized prior to implementation in accordance with 10 CFR 50.55a(a)(3) or an exemption to these requirements in accordance with 10 CFR 50.12, "Specific exemptions," must be processed.

- i. Non-Class 1E equipment should satisfy separation requirements if interface with safety busses is required.
- ii. An independent dual detection scheme should be provided at the non-Class 1E level for each circuit that feeds the division of the Class 1E power system.
- iii. The open phase protection should include coincidence logic on a per train/per phase basis to preclude spurious trips of the offsite power source.
- iv. The open phase protective devices should automatically disconnect the offsite power sources when the setpoints and any time delay limits have been satisfied.
- v. Capability for test and calibration during power operation should be provided.
- vi. Annunciation must be provided in the control room for any bypasses incorporated in the design.

VI. Surveillances and Limiting Conditions for Operation

The technical specifications should include requirements in accordance with 10 CFR 50.36(c)(2) and (c)(3) for limiting conditions for operations, surveillance requirements, trip setpoints, alarm set points, and maximum and minimum allowable values for the open phase conditions relays and associated time delay devices.

2. Nuclear Power Plants with Passive Safety Features

New reactor licensees, COL applicants, and design centers for passive safety features plant designs under 10 CFR Part 52 should address the following design criteria:

I. Detection and Alarms

If the open phase condition prevents important-to-safety functions:

An open phase condition should be automatically detected and alarmed in the control room unless it can be shown that the open phase condition does not prevent functioning of important-to-safety SSCs.

Detection circuits for the open phase condition, which prevents the functioning of important-to-safety SSCs, should be sensitive enough to identify an open phase condition under all operating electrical system configurations and loading conditions for which they are required to be operable.

II. Actuation circuits

If open phase condition actuation circuits are required, the design should minimize misoperation, maloperation, and spurious actuation by providing independent dual sensors and actuation logics that could cause separation from an operable off-site power source. Additionally, the protective scheme should not separate the operable off-site offsite source in the range of voltage unbalance normally expected in the transmission system. Licensees/applicants should perform failure modes analysis to demonstrate that the additional actuation circuit design does not result in lower overall plant operation reliability. These devices should be coordinated with other protective devices in both the transmission system and the plant's electrical system (e.g., fault protection, overcurrent, etc.).

III. Restoration of preferred or Onsite AC Power

Following detection of an open phase condition and alarm in the control room, plant procedures should specify operator actions to ensure the standby diesel generators are connected to the auxiliary alternating current buses if they are not automatically connected in accordance with the design basis requirements or restore the offsite power source to a functional condition.

IV. Surveillances

Periodic tests, calibrations, setpoint verifications or inspections (as applicable) should be established for any new detection and alarm circuits to ensure their reliability to perform its intended design functions.

3. Considerations for Protective Devices for Alarm and Trip Functions

The following guidelines provide an overview of the analyses that should be performed:

- a. Commercially available software packages that have been adequately verified and validated for safety related applications may be used to analyze and model open phase and unbalanced fault conditions. The software should have capabilities to perform the unbalance load flow study for a steady-state solution with opening a single phase at a time. For transformers, the effects of an embedded winding, no-load current and losses, transformer type (core and shell), and inter-phase A, B, C mutual coupling, including zero-sequence shall be included.
- b. Establish the capability of the major important-to-safety components to withstand unbalanced voltage/current conditions expected during various operating and loading conditions. The manufacturer provided parameters maybe acceptable if specified during the procurement process. Industry standards such as NEMA MG 1-2011 (Motors and Generators), Section 20.24, titled, "Effects of Unbalanced Voltages on the Performance of Polyphase Squirrel-Cage Induction Motors", and IEEE Std. C37.96-2012 (Guide for AC Motor Protection), Section 5.7.2.6, "Unbalanced protection and phase failures" may be used for general guidance.
- c. Establish the limitations of existing protective devices for various operating and loading conditions with open phase conditions on each phase.
- d. The magnitude of expected unbalance voltage and current for different open phase or high impedance fault currents may dictate the operating characteristics of proposed protective devices. As an example, a protective device with two settings may be used for (a) alarm only when a low unbalanced voltage/current is detected, (b) trip when higher unbalanced voltage/current that is deemed unacceptable for plant equipment is detected. A time delay may be incorporated in both settings to avoid actuations during transient conditions. Any time delay provided must always meet the accident analysis assumptions.

C. REFERENCES

1. RG 1.153, "Criteria for Power, Instrumentation, and Control Portions of Safety Systems."
2. NRC Information Notice 2012-03, "Design Vulnerability in Electric Power System," dated March 1, 2012, ADAMS Accession No. ML120480170.
3. NRC Bulletin 2012-01, "Design Vulnerability in Electric Power System," dated July 27, 2012, ADAMS Accession No. ML12074A115.
4. IEEE Std. 279-1971, "Criteria for Protection Systems for Nuclear Power Stations."

5. IEEE Std. 603-1991, "Criteria for Safety Systems for Nuclear Power Generating Stations."
7. NRC Bulletin 2012-01 Summary Report dated July 2, 2013, ADAMS Accession No. ML13052A711.
8. Industry Initiative on Open Phase Condition - Functioning of Important-to-Safety Structures, Systems and Components, ADAMS Accession No. ML13333A142.
9. SECY-13-0107, Status of the Accident Sequence Precursor Program and the Standardized Plant Analysis Risk Models," dated October 4, 2013, ADAMS Accession No. ML13232A062.

PAPERWORK REDUCTION ACT STATEMENT

The information collections contained in the Standard Review Plan are covered by the requirements of 10 CFR Part 50, and 10 CFR Part 52, and were approved by the Office of Management and Budget, approval numbers 3150-0011, 3150-0151.

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