NUREG-0800

U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

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

Byron Station is a two-unit pressurized water reactor plant. The electrical distribution system for each unit consists of four nonsafety 6.9-kilo Volt (kV) buses, two nonsafety 4-kV buses, and two engineered safety features (ESF) 4-kV station buses. Both the ESF 4-kV and the two nonsafety 6.9-kV station buses that power the two reactor coolant pumps (RCPs) are normally supplied by station auxiliary transformers (SATs) connected to the 345-kV offsite power switchyard. On January 30, 2012, 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 the RCPs. The undervoltage condition was caused by a broken inverted porcelain insulator stack of the Phase C conductor for the 345-kV power circuit that supplies both 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 ESF buses. Some ESF loads that were energized relied on equipment protective devices to prevent damage from an unbalanced overcurrent condition. The phase overcurrent condition actuated relays to trip several ESF loads.

Approximately 8 minutes after the reactor trip, the control room operators diagnosed the loss of Phase C condition and manually tripped circuit 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 voltage relays started the emergency diesel generators (EDGs) and restored power to the ESF buses. If the condition had been allowed to persist for an additional few minutes, damage to the RCP seals could have occurred due to loss of RCP seal cooling water. This in turn could have resulted in a loss of coolant from the RCP seals in the containment building.

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 that 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 a loss of voltage due to the opening of 345-kV system breakers, which resulted in separation of the SATs from the 4.16-kV buses. The two EDGs started and energized the 4.16-kV ESF buses as designed.

A review of other operating experience identified design vulnerabilities associated with single-phase open circuit conditions at South Texas, Unit 2 (See Licensee Event Report (LER) 50-499/2001-001, ADAMS Accession No. ML011010017); Beaver Valley Power Station, Unit 1 (See LER 50-334/2007-002, ADAMS Accession No. ML080280592); and a single event that affected Nine Mile Point, Unit 1 (See LER 50-220/2005-04, ADAMS Accession No. ML060620519) and the neighboring James A. Fitzpatrick Power Plant (See LER 50-333/2005-06, ADAMS Accession No. ML060610079.)

These events involved offsite power circuits that were rendered inoperable due to an open circuit in one phase. In each instance (except South Texas, Unit 2), the condition went undetected for several weeks because offsite power was not aligned to the 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 the three Circulating Water Pumps were tripped by the open phase condition. Operating experience has identified three similar international events:

1. On December 22, 2012, Unit 1 at Bruce Power Plant in Canada was in shutdown condition when a maintenance cooling system pump (P1) tripped. Operators tried to manually start pumps P1 and P2 but both failed to start due to the electrical protection schemes. Field operators identified a loss-of-phase condition caused by a break in one of the 3 phases of the 230 kV overhead line connection.

2. On May 30, 2013, Forsmark Unit 3 in Sweden reported an event resulting from human error. The plant was in a refueling outage with one of the two 400-kV offsite power circuit breakers and a 70-kV back-up power supply breaker open due to maintenance work. While testing the protective relaying for the main generator, an erroneous trip

signal was sent to the remaining 400-kV offsite power source circuit breaker. One of the three phases in the circuit breaker failed to open, resulting in a double open phase condition in the power circuit (i.e., two open phases). Some of the operating loads tripped due to phase unbalance, while some safety-related and nonsafety-related loads overheated and failed. The undervoltage relays on the safety buses did not detect the degraded voltage conditions because the induced voltage was higher than the trip setpoint of the relays.

3. On April 27, 2014, the Dungeness B power plant in United Kingdom experienced random tripping of large loads resulting from the loss of one of three phases in the 400kV electrical supply to the site. The open phase condition was the result of inadequate contact in one pole of the circuit breaker.

In the events discussed above, the protective relaying schemes did not detect the open phase(s) conditions due to inadequate detection schemes. As a result, degraded power sources continued to supply plant safety-related and nonsafety-related loads. In addition, the emergency diesel generators (onsite power system) did not automatically connect to the safety buses because the plant design did not have features to detect and automatically isolate the open phase conditions in the offsite power source.

Based on the Byron Station operating event, the staff issued NRC, Information Notice 2012-03, “Design Vulnerability in Electric Power System,” dated March 1, 2012 (ADAMS Accession No. ML120480170). On July 27, 2012, the staff issued NRC Bulletin 2012-01, “Design Vulnerability in Electric Power System,” (ADAMS Accession No. ML12074A115) 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, **“**General Design Criteria for Nuclear Power Plants**,”** to 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities,” General Design Criterion (GDC) 17, “Electric Power Systems,” or principal design criteria specified in the updated final safety analysis report. Specifically, the NRC requested licensees to provide information by October 25, 2012, regarding (1) 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) the operating configuration of engineered safety features buses at power. The Electrical Engineering Branch staff has reviewed the information that NRC licensees provided and the details of this review are documented in a NRC Bulletin 2012-01, “Design Vulnerability in Electric Power System,” Summary Report dated February 26, 2013 (ADAMS Accession No. ML13052A711).

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 systems in accordance with Appendix A to 10 CFR Part 50, GDC 17 or principal design criteria specified in the updated final safety analysis report, 10 CFR 50.55a(h)(2), 10 CFR 50.55a(h)(3), and 10 CFR 50.36(c)(2) and 10 CFR 50.36(c)(3).

B. BRANCH TECHNICAL POSITION

1. Electric power from the transmission network to the onsite electric distribution system is supplied by two physically independent circuits. The design of the electrical system and the protective relaying system should address the following open phase conditions (OPCs):

(i) 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. The protection scheme should consider 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 offsite power circuit (without ground) 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.

Notes:

i. The staff should ensure that licensees have considered all potential OPCs on the high voltage and low voltage side of transformers and interconnecting onsite auxiliary power circuits. Any connections that are not evaluated should be documented with an adequate justification. If there is a potential for OPCs in the intervening power path, the licensee should have analyses to show that the above open phase conditions are the limiting conditions.

ii. For AP 1000 plants, electric power from the transmission network to the onsite electric distribution system is supplied by only one circuit.

iii. For the purpose of OPC evaluation, high impedance ground faults are ground faults that produce fault currents below the ground fault relay setting.

2. For operating reactors and new reactors with active design safety features, reviewed under 10 CFR Part 50 and 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants,” the following criteria should be satisfied when evaluating OPCs:

   a. The OPC should be automatically detected and alarmed in the main control room under all operating electrical system configurations and plant loading conditions. The detection circuits should be sensitive enough to identify OPCs under all operating electrical system configurations and plant loading conditions for which the offsite power supplies are required to be operable in accordance with plant technical specifications (TSs) for safe shutdown.

   The detection circuit should minimize spurious indications for an operable offsite power source in the range of voltage perturbations such as switching surges, transformer inrush currents, load or generation variations, lightning strikes, etc., normally expected in the transmission system. If the plant auxiliaries are supplied from the main generator and the offsite power circuit to the ESF bus is configured as a standby power source, then any failure (i.e., OPC) should be alarmed in the main control room for operators to take corrective action within a reasonable time. In such cases, the consequences of not immediately isolating the degraded power source should be evaluated to demonstrate that any subsequent design bases conditions that rely on offsite power circuit(s) for safe shutdown do not create plant transients or abnormal operating conditions. Also, the remaining power source(s) can be connected to the ESF buses within the time assumed in the accident analysis.

b. If offsite power circuit(s) is (are) functionally degraded due to OPCs, and safe shutdown capability is not assured, then the ESF buses should be designed to be transferred automatically to the alternate reliable offsite power source or onsite standby power system within the time assumed in the accident analysis and without actuating any protective devices, given a concurrent design basis event.

c. The design of protection features for OPCs should address the following:

(i) Power quality issues caused by OPCs such as unbalanced voltages and currents, sequence voltages and currents, phase angle shifts, and harmonic distortion that could affect redundant ESF buses. The ESF loads should not be subjected to power quality conditions specified in industry standards such as Institute of Electrical and Electronic Engineers (IEEE) Standard (Std) 308-2001, "Criteria for Class 1E Power Systems for Nuclear Power Generating Stations," Section 4.5, "Power Quality," with respect to the design and operation of electrical systems as indicated in Regulatory Guide (RG) 1.32 "Criteria for Power Systems for Nuclear Plants."

(ii) Protection scheme should comply with applicable requirements including single failure criteria for ESF systems as specified in 10 CFR Part 50, Appendix A, GDC17, and 10 CFR 50.55a(h)(2) or 10 CFR 50.55a(h)(3), which require compliance with IEEE Std 279-1971 "Criteria for Protection Systems for Nuclear Power Generating Stations" or IEEE Std 603-1991, "Standard Criteria for Safety Systems for Nuclear Power Generating Stations." RG 1.153, "Criteria for Power, Instrumentation, and Control Portions of Safety Systems," provides additional guidance on this topic.

If protective features are provided in a non-Class 1E system only, a failure of the non-Class 1E scheme should not preclude the onsite electrical power system from performing its safety function given a single failure in the onsite power system.

(iii) Protection scheme design should minimize misoperation, maloperation, and spurious actuation of an operable off-site power source. 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.

(iv) The unbalanced voltage/current conditions for ESF components expected during various operating and loading conditions should not exceed motor manufacturer's recommendations. The International Electrotechnical Commission (IEC) Standard IEC 60034-26, National Electrical

Manufacturers Association (NEMA) Standard (MG 1) Parts 14.36 and 20.24, 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.

Technical Specification Surveillance Requirements and Limiting Conditions of Operation for equipment used for mitigation of OPCs should be identified and implemented consistent with the operability requirements specified in the plant TSs and in accordance with 10 CFR 50.36(c)(2) and 10 CFR 50.36(c)(3). RG 1.93 "Availability of Electric Power Sources," provides additional guidance on this topic.

3. For new reactor licensees, COL applicants, and applications for certification of designs incorporating passive safety features reviewed under 10 CFR Part 52, the following criteria should be satisfied when evaluating OPCs:

   a. The OPC should be automatically detected and alarmed in the main control room under all operating electrical system configurations and plant loading conditions. The detection circuits should be sensitive enough to identify OPCs under all operating electrical system configurations and plant loading conditions for which the offsite power source is normally required in accordance with Appendix A to 10 CFR Part 50, GDC 17.

   b. 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 or restore the offsite power source to a functional condition.

   c. Periodic surveillance tests should be established for any new detection and alarm circuits to ensure their reliability to perform their intended design functions.

C. REFERENCES

1. Institute of Electrical and Electronics Engineers, IEEE Std 279-1971, "Criteria for Protection Systems for Nuclear Power Stations."

2. Institute of Electrical and Electronics Engineers, IEEE Std. 603-1991, "Criteria for Safety Systems for Nuclear Power Generating Stations."

3. U.S. Nuclear Regulatory Commission, "Industry Initiative on Open Phase Condition - Functioning of Important-to-Safety Structures, Systems and Components," ADAMS Accession No. ML13333A142.

4. U.S. Nuclear Regulatory Commission, Licensee Event Report, Byron Station, Unit 1 and Unit 2, ADAMS Accession No. ML12272A358.

5. U.S. Nuclear Regulatory Commission, “Design Vulnerability in Electric Power System,” Information Notice 2012-03, dated March 1, 2012, ADAMS Accession No. ML120480170.

6. U.S. Nuclear Regulatory Commission, “Design Vulnerability in Electric Power System,” Bulletin 2012-01, dated July 27, 2012, ADAMS Accession No. ML12074A115.

7. U.S. Nuclear Regulatory Commission, “Design Vulnerability in Electric Power System,” Summary Report, NRC Bulletin 2012-01, dated February 26, 2013, ADAMS Accession No. ML13052A711.

8. U.S. Nuclear Regulatory Commission, NRC letter dated November 25, 2014, from William Dean, Office of Nuclear Reactor Regulation to Anthony Pietrangelo, Nuclear Energy Institute, ADAMS Accession No. ML14120A203.

9. U.S. Nuclear Regulatory Commission, “Criteria for Power, Instrumentation, and Control Portions of Safety Systems,” Regulatory Guide 1.153.

10. U.S. Nuclear Regulatory Commission, “Criteria For Power Systems For Nuclear Plants.” Regulatory Guide 1.32.

11. U.S. Nuclear Regulatory Commission, “Availability of Electric Power Sources.” Regulatory Guide 1.93.

12. U.S. Nuclear Regulatory Commission, “Status of the Accident Sequence Precursor Program and the Standardized Plant Analysis Risk Models,” SECY-13-0107, dated October 4, 2013, ADAMS Accession No. ML13232A062.

13. U.S. Nuclear Regulatory Commission, “Open Phase Conditions in Electric Power System,” Staff’s Response to ACRS letter dated December 17, 2014, regarding BTP 8-9, ADAMS Accession No. ML14364A348.

14. U.S. Nuclear Regulatory Commission, “Open Phase Conditions in Electric Power System,” Advisory Committee on Reactor Safeguards (ACRS) letter dated December 17, 2014, regarding the ACRS review of BTP 8-9, ADAMS Accession No. ML14343A485.

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.

PUBLIC PROTECTION NOTIFICATION

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