Computer Simulation of Complex Power System Faults under various Operating Conditions

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Abstract
A power system is normally treated as a balanced symmetrical three-phase network. When a fault occurs, the symmetry is normally upset, resulting in unbalanced currents and voltages appearing in the network. For the correct application of protection equipment, it is essential to know the fault current distribution throughout the system and the voltages in different parts of the system due to the fault. There may be situations where protection engineers have to analyze faults that are more complex than simple shunt faults. One type of complex fault is an open phase condition that can result from a fallen conductor or failure of a breaker pole. In the former case, the condition is often accompanied by a fault detectable with normal relaying. In the latter case, the condition may be undetected by standard line relaying. The effect on a generator is dependent on the location of the open phase and the load level. If an open phase occurs between the generator terminals and the high-voltage side of the GSU in the switchyard, and the generator is at full load, damaging negative sequence current can be generated. However, for the same operating condition, an open conductor at the incoming transmission lines located in the switchyard can result in minimal negative sequence current. In 2012, a nuclear power generating station (NPGS) suffered series or open phase fault due to insulator mechanical failure in the 345 kV switchyard. This resulted in both reactor units tripping offline in two separate incidents. Series fault on one of the phases resulted in voltage imbalance that was not detected by the degraded voltage relays. These undervoltage relays did not initiate a start signal to the emergency diesel generators (EDG) because they sensed adequate voltage on the remaining phases exposing a design vulnerability. This paper is intended to help protection engineers calculate complex circuit faults like open phase condition using computer program. The impact of this type of fault will be analyzed and for various system operating conditions and possible mitigation methods will be discussed.

1. Introduction

Electric power systems are generally designed to server loads in a safe and reliable manner. One of the major considerations in the design of the power system is determination and adequate protection against short circuits. Uncontrolled short circuits can cause serve outages, interruption of vital services, equipment damage, and possible personnel injury. There are four basic sources of short circuit current contribution in an electrical power system:

- Generators
- Synchronous Motors
- Induction Motors
- Electric Utility Systems

Short-circuit programs provide the equipment voltages and fault currents, in the sequence and phase domain, for simple balanced and unbalanced short circuits in the network under study. The results from short circuit programs are used for selecting power system equipment ratings and for setting and coordinating protective relays. Frequently, protection engineers have to analyze faults that are more complex than simple shunt faults. In many cases, they have to analyze simultaneous shunt and/or series
faults, study systems with unbalanced network elements, and calculate equivalent impedances required to study the stability of a network during system faults and during single-phase open conditions.

Major advances in short-circuit computations in the last 20 years have resulted in new short-circuit computer programs that handle different fault types and very large networks with very small computation times. However most standard short-circuit programs do not handle most complex faults, such as simultaneous shunt and/or series-faults. Engineers have traditionally resorted to complex hand calculations or to more advanced programs such as the Electromagnetic Transient Program (EMTP) to solve protection problems. Though this approach is acceptable, it requires protection engineers to also have expertise on the dynamics of power systems. In addition, for new engineers attempting to solve complex faults under various operating conditions is an overwhelming task. This paper will include an example analysis of open phase fault on system under various operating conditions and include comparison of results against EMTP. The time savings over EMTP modeling will also be highlighted.

2. Short circuit analysis – sequence networks

The classical short-circuit method models the power system network using the bus impedance matrix, $Z_{bus}$. The steps required to calculate the short-circuit voltages and currents are as follows:

1. Compute the sequence network bus impedance matrices.
2. Extract the sequence network single-port Thevenin equivalent impedances of the faulted bus, given by the diagonal terms, $Z_{ii}$, of the respective sequence network $Z_{bus}$ matrices, where $i$ is the index of the faulted bus.
3. Use the sequence equivalent networks to compute the sequence fault currents at the faulted bus.
4. Use the computed sequence fault currents as compensating currents to calculate the network post fault voltages and currents.

3. Complex faults

In a poly-phase system, a fault may affect all phases equally which is a "symmetrical fault". If only some phases are affected, the resulting “unsymmetrical fault" becomes more complicated to analyze due to the simplifying assumption of equal current magnitude in all phases being no longer applicable. The analysis of this type of fault is often simplified by using methods such as symmetrical components.

A symmetric or balanced fault affects each of the three phases equally. In transmission systems, symmetrical faults occur infrequently (roughly 5%). In practice, most faults in power systems are unbalanced or unsymmetrical where the three phases are not affected equally. With this in mind, symmetrical faults can be viewed as somewhat of an abstraction; however, as unsymmetrical faults are difficult to analyze, analysis of asymmetric faults is built up from a thorough understanding of symmetric faults.

Common types of asymmetric faults, and their causes:
- **line-to-line** - a short circuit between lines, caused by ionization of air, or when lines come into physical contact, for example due to a broken insulator.
- **line-to-ground** - a short circuit between one line and ground, very often caused by physical contact, for example due to lightning or other storm damage
- **double line-to-ground** - two lines come into contact with the ground (and each other), also commonly due to storm damage.
An asymmetric fault breaks the underlying assumptions used in three-phase power, namely that the load is balanced on all three phases. Further complication is introduced while modeling simultaneous faults such as open phase or series fault in conjunction with a line to ground fault or shunt fault. Consequently, it has been difficult to directly use software tools such as the one-line diagram, where only one phase is considered. This paper describes a computer simulation program used to model, analyze and report such asymmetric or complex faults.

4. Design vulnerability in electric power system

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-kilovolt (kV) buses that power reactor coolant pumps (RCPs) B and C (two of four RCPs trip initiate a reactor trip). A broken insulator stack of the phase C conductor for the 345-kV power circuit that supplies both station auxiliary transformers (SATs 242-1 and 242-2) caused the undervoltage condition as shown in Fig 2. This insulator stack failure caused the phase C conductor to break off from the power line disconnect switch, resulting in a phase C open circuit and a high impedance ground path. Specifically, the parted phase C connection remained electrically connected on the transformer side, and the loose bus bar conductor end fell to the ground. This ground was a direct result of the broken insulator and not an independent event. The connected loose bus bar provided a path to ground for the transformer high-voltage terminal, but did not result in a detectable ground fault (i.e., neither solid nor impedance) as seen from the source. Since the switchyard (i.e., source side) relaying was electrically isolated from the fault, it did not detect a fault; therefore, it did not operate.

Fig 2. Byron Unit 2 Insulator Failure

After the reactor trip, the two 6.9-kV buses that power RCPs A and D, which were aligned to the unit auxiliary transformers (UATs), automatically transferred to the SATs, as designed.
Because phase C was on an open circuit condition, the flow of current on phases A and B increased because of unbalanced voltage and caused all four RCPs to trip on phase overcurrent. Even though phase C was on an open circuit condition, the SATs continued to provide power to the 4.16-kV ESF buses A and B. 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. 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.

With no RCPs functioning, control room operators performed a natural-circulation cool down of the unit. 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 caused the emergency diesel generators to start automatically and restore power to the ESF buses.

Byron NPGS reviewed the event and identified design vulnerabilities in the protection scheme for the 4.16-kV ESF buses. The loss of power instrumentation protection scheme is designed with two undervoltage relays on each of the two ESF buses. These relays are part of a two-out-of-two trip logic based on the voltages being monitored between phases A–B and B–C of ESF buses. Even though phase C was on open circuit, the voltage between phases A–B was normal; therefore, the situation did not satisfy the trip logic. Because the conditions of the two-out-of-two trip logic were not met, the protection system generated no protective trip signals to automatically separate the ESF buses from the offsite power source.

A second event occurred at Byron Station Unit 1 on February 28, 2012 (approximately a month apart). This event was also initiated by a failed inverted porcelain insulator. In this event, the 4.16-kV ESF buses did sense fault condition and separated SATs from the 4.16-kV buses. The 1A and 1B DGs started and energized the 4.16-kV ESF buses as designed.
At Byron, a failure to design the electric power system’s protection scheme to sense the loss of a single phase between the transmission network and the onsite power distribution system resulted in unbalanced voltage at both ESF buses (degraded offsite power system), trip of several safety-related pieces of equipment such as essential service water pumps, centrifugal charging pumps, and component cooling water pumps and the unavailability of the onsite electric power system. This situation resulted in neither the onsite nor the offsite electric power system being able to perform its intended safety functions (i.e., to provide electric power to the ESF buses with sufficient capacity and capability to permit functioning of structures, systems, and components important to safety).

Since loss of a single phase on the offsite power source can potentially damage both trains of the emergency core cooling system, the protection scheme must automatically initiate isolation of the degraded offsite power source and transfer the safety buses to the emergency power source within the time period assumed in the accident analysis.

The United States Nuclear Regulatory Commission took regulatory actions to require licensees to provide design features to detect and automatically respond to a single-phase open circuit or high impedance fault condition on the high voltage side of a credited offsite circuit. This would ensure that an offsite and an onsite electric power system with adequate capacity and capability will be immediately available to permit the functioning of structures, systems, and components important to safety in the event of anticipated operational occurrences and postulated accidents.

It was determined that evaluations based on the industry guidance are generic assessments cannot be formally credited as a basis for an accurate response.

Hence without formalized engineering calculations the electrical consequences of such an open-phase event, including plant response could not be sufficiently evaluated.

A need for detailed plant-specific models was identified (e.g., transformer magnetic circuit models, electric distribution models, motor models; including positive, negative, and zero sequence impedances, voltage, and currents). Further, the models and calculations were also required to be validated, and analyzed for the plant-specific Class 1E electric distribution system.

5. Open phase fault modeling

INPO Event Reports IER L2-12-14, IER L3-13-13, and NRC Bulletin 2012-01 describe a nuclear safety concern involving an open-phase fault occurring on the offsite power supply of a nuclear plant. This is a previously unanalyzed failure mode for nuclear station offsite power and there has previously been no standard method for analyzing the effects of such faults. An OPF is considered to be an open-phase condition, with or without ground, located on the high-voltage (switchyard) side of each offsite power (OSP) transformer.

It should be noted that there are two aspects to an open-phase fault analysis: “acceptability” and “detectability”. Acceptability involves the ability continue functioning during the open-phase condition without damage and/or spurious operations. Detectability involves the ability of protection systems to detect the open-phase condition. The outcome of OPF analysis is to identify levels of unbalance (voltage and current) during an OPF condition throughout the plant auxiliary power system and determine if existing protective systems will sense the OPF condition. For any cases where the open-phase condition cannot be detected with existing protection systems, this should be identified as a potential vulnerability.

The overall analytical method is a steady-state load flow technique, which of course cannot determine the immediate transient response of the power system to an open-phase fault. However, that is usually not necessary as the steady-state (~30 cycle) voltages and currents (phase and sequence quantities) throughout

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the plant power system (including at load terminals) can typically be used to properly characterize the potential vulnerabilities to an OPF condition. These results, which are indicative of the system’s response to the open-phase condition with all loads remaining in their initial condition (i.e. running or starting) can be compared to a given criteria for either detectability or acceptability. Because it would take an almost unlimited number of simulations to produce “accurate” results for every eventuality (various loading conditions, temperature variations of cable impedance, transformer and machine impedance tolerances, grid voltage variation, grid voltage balance, etc.) bounding techniques can be used to account for the competing conservatism needed to address these variations and tolerances. In addition, margins can be applied to the results when determining the ability of protective devices to detect the open-phase condition.

The OPF analysis should consider all pertinent plant operating scenarios (events/loading), alignments (configurations), and also the amount of potential voltage unbalance in the incoming plant power supplies (grid unbalance).

6. Example of nuclear plant analytical bases for opf study

- Enter additional transformer data\(^1\) (beyond that typically needed):
  - Zero-Sequence Impedances (%Z and X/R), obtained from zero-sequence short-circuit tests, but for transformer with “buried delta” regulating winding, also need zero-sequence open-circuit tests (e.g. Pri-regulating, Sec-regulating, Pri-Sec)
  - Zero Sequence No Load Losses (%FLA and kW)
- Ensure induction motors have all required data to support the OPF analysis, especially negative-sequence reactance (X2). If exact values are not know, this can be approximated as \(X_2 = X_{L,R}\).
- The amount of impedance between open phase and ground (transformer side of the open) can be simulated in ETAP by adding a “phase adapter” and a single phase “infinite load” referenced to ground (see inset). The impedance can be varied to simulate any situation from true open to sold ground.

\[ V_{ab} = \frac{100 \cdot \text{Maximum Deviation From Average}}{\text{Average}} \]

- Determine the motor on each bus with the worst-case current unbalance (use motor with smallest \(X_2\) which is indicative of the largest \(I_x\)) by the formula:

\[^1\text{In most cases, actual data must be used or meaningful OPFA is not possible (it cannot be assumed). It is recommended that each transformer model be validated by simulating the factory short-circuit tests in ETAP, both positive and zero sequence, and comparing to the actual test reports.}\]
\[ I_{ua} = 100 \cdot \frac{I_2}{I_{fl}}, \]  
where \( I_2 \) is the negative sequence current and \( I_{fl} \) is the motor full load current.

- Consider both balanced and unbalanced grid conditions.
- Ensure sufficient study cases are run to bound all combinations of OSP transformers, amount of transformer loading, and amount of open-phase ground impedance. For example:
  - Two offsite power sources
    - Startup/Shutdown Transformer
    - Main Transformer with connected Unit Auxiliary Transformer (consider with and without main generator connected)
  - Three transformer loading scenarios
    - Heaviest (e.g. LOCA loading with any extra plant buses connected)
    - Normal Operation (normal alignment)
    - Lightest (e.g. Refuel loading)
  - Two types of open-phase faults
    - Open
    - Open w/ solid ground
- For detectability, compare the OPF results to existing plant protective device schemes/settings in order to determine if the open-phase condition is adequately detected. This typically involves transformer differential (87T), transformer neutral overcurrent (51N), transmission line negative-sequence, and in-plant bus undervoltage relays. In order to account for various unknowns such as modelling inaccuracy, data inaccuracy, and competing conservatisms (e.g. cable impedance, load diversity, grid voltage level/unbalance) consider application of margins when determining acceptability. Suggested values are:
  - undervoltage detection 10%
  - overcurrent detection 10%
  - differential detection 5%

7. Example results

This table provides an example of an overall summary of the OPF analysis results by identifying areas where detectability is achieved and also highlighting areas of vulnerability.

**OPFA Results for Shutdown Transformer XYZ**

<table>
<thead>
<tr>
<th>OPF Type</th>
<th>Transformer Loading</th>
<th>Light (Refuel)</th>
<th>Normal</th>
<th>Heavy (LOCA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grounded</td>
<td>Detectable</td>
<td>Detectable</td>
<td>Detectable</td>
<td></td>
</tr>
<tr>
<td>Ungrounded(1)</td>
<td>Not Detectable(2)</td>
<td>Not Detectable(3)</td>
<td>Not Detectable(3)</td>
<td></td>
</tr>
</tbody>
</table>

(1) Bus voltage unbalance within NEMA MG-1 allowable values for transformer 13% or less.
(2) Motor current unbalance indicates potential tripping (motors overcurrent).
(3) Motor current unbalance indicates potential motor damage.

\(^2\) Further study can be done as needed to determine the outcome for other amounts of ground impedance.

\(^3\) the ETAP Nuclear Utility User Group determined that similar analytical techniques with ETAP could simulate transformer factory short-circuit test results (positive and zero-sequence) as well as actual results from the open-phase condition at Byron Station with close correlation (within these margins).
Which can be visually displayed as:

However, this two-dimensional view of limited case studies does not fully characterize the outcome of an OPF on a given transformer. A more complete characterization (i.e. all eventualities for both detectability and acceptability) can be thought of as five “dimensions”, which are:

1. Transformer loading (analysis variable)
2. Open-phase grounding (analysis variable)
3. Worst-case bus voltage unbalance (analysis result)
4. Protective device detectability (analysis result)
5. Acceptability of worst-case current unbalance on motor loads (analysis result)

Since ETAP allows quick and efficient simulation of the analysis variables and relatively easy evaluation of the results, multiple OPF simulations can be performed for the analysis variables (transformer loading and open-phase grounding) to allow plotting these five dimensions in sufficient detail to fully characterize the OPF analysis (see example).
8. Comparison of ETAP VS EMTP

Detailed modeling required for open phase fault simulation is possible in EMTP however it is impractical to do so due to a number of reasons:

1. Open phase fault like any other fault has a transient and stead-state component. The transient component only lasts a few cycles as compared to the steady state fault current. It is not necessary to include these transients in the calculation since the protective relaying settings will be based on steady state values in order to avoid nuisance tripping.

2. EMTP requires considerable amount of time to model a complete power electrical system with accurate operating load conditions to fully understand the impact of current and voltage changes in an open phase condition.

3. Most of the electrical systems from HV to LV have already been modeled in ETAP and minimal data entry is need in order to expand the model to perform open phase fault simulation.

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Offsite Power</th>
<th>Xnr Loading</th>
<th>Open-Phase Fault</th>
<th>% Unbalance Acceptable?</th>
<th>Detectable by Voltage?</th>
<th>Detectable by Current?</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Normal</td>
<td>CSST Y/YY (TVA)</td>
<td>Loaded 97%</td>
<td>Open</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>B Normal</td>
<td>CSST Y/YY (TVA)</td>
<td>Loaded 97%</td>
<td>Open with Ground</td>
<td>Yes (80% Vrms, 100% Wb)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C Refueling</td>
<td>CSST Y/YY (TVA)</td>
<td>Loaded 97%</td>
<td>Open</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>D Refueling</td>
<td>CSST Y/YY (TVA)</td>
<td>Loaded 97%</td>
<td>Open with Ground</td>
<td>Yes (80% Vrms, 100% Wb)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>E LOCA</td>
<td>CSST Y/YY (TVA)</td>
<td>Loaded 97%</td>
<td>Open</td>
<td>Yes (80% Vrms, 100% Wb)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>F LOCA</td>
<td>CSST Y/YY (TVA)</td>
<td>Loaded 97%</td>
<td>Open with Ground</td>
<td>Yes (80% Vrms, 100% Wb)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

EMTP analysis was carried out for one of the facilities using simplification of the electrical system as shown in Fig 4. The following simplified test system was derived from one of the nuclear generation facilities and was modeled in EMTP. This particular system took months of simplification and data entry in order to perform transient calculations of the open phase condition. The cost for performing such calculations was over hundreds of thousands of dollars. However, as shown, all MV motors were simplified into lumped motor model. This is not accurate since open phase fault calculations is affected by motor and transformer models as well as the operating load of the system.
It was evident that the entire plant simulation was necessary in order to determine the voltages and currents with high degree of accuracy. Hence the same test system was created in ETAP software once again depicted in Fig 4. The motor circuit parameters were updated in the ETAP model with correct negative sequence impedances and initial loading as shown in Fig 5.

The software simulation was performed in ETAP using Mtr1 at 100% load and the motor terminal line-neutral voltages and currents were compared as shown in Fig 6 and Fig 7 below.
Fig 6. Mtr1 (100% loading) terminal L-N voltages

Fig 7. Mtr1 (100% loading) current
From Fig 6 and 7 it can be see that ETAP simulation is a steady state simulation as compared to EMTP however for determining protection relaying, the transients have to be neglected since they only last for a few cycles. The steady state values from both calculation programs that were used to set the protection relays were identical.

Several other comparison tests were conducted into those with Mtr1 at 50% loading to understand the impact of open phase condition under lightly loaded system. Fig 8 is the comparison of ETAP simulation results versus response from EMTP program.

Fig 8. Mtr1 (50% loading) terminal L-N voltages

9. Computer simulation software requirements

1. **Graphical Placement of the Open-Phase on the One-Line Diagram** – Power system simulation software should allow user to easily place open-phase faults (phase A, B, or C) at any terminal of the three-phase branches, including two-winding and three-winding transformers, cables, transmission lines, impedances, and reactors.

2. **Induction Motor Modeling** – The modeling of induction motors should be capable of handling severe unbalanced system conditions caused by an open-phase fault, including the effects of negative-sequence current.

3. **Transformer Type** - The capability to model various types of transformers, including Shell and Core with 3, 4, and 5 limbs, for both 2-winding and 3-winding transformers should be available.

4. **Transformer Magnetization Coupling** - Based on the no-load data, the magnetizing impedance for positive, negative, and zero sequence couplings should be calculated and taken into account.

5. **Transformer Embedded Winding** - The effects of an embedded (buried) winding, for two and three winding transformers should be included.

6. **Report Current Flows inside Transformer Embedded Winding** - The zero-sequence current circulating inside the embedded delta–connected winding should be calculated and reported.

7. **Ground Impedance** - Simulate open-phase faults with any ground type and with specific values of ground impedance.

10 Findings

Leading to the development of the software module and, as part of the verification and validation (V&V) process, numerous studies and benchmarks were created to simulate open-phase conditions in various networks, including the off-site power supply system of a nuclear power plant. V&V test cases have been created to simulate electrical network behavior with different models and under various operating conditions. The following is a summary of findings:
1. Under low loading, certain transformer configurations, and depending on the amount of impedance between the open transformer phase and ground, detection of an open-phase condition on the primary side of a transformer can be difficult on the secondary side.

2. In some cases, detection of the fault is not possible by monitoring the phase currents and voltages. Under voltage relay schemes are not always able to detect a single open phase.

3. Depending on the location of the relays/monitoring devices, the effects of motor back-emf and voltage drop across cables can be significant for detection.

4. Better accuracy of simulation results is obtained with an actual detailed system model rather than a simplified model.

5. Motor and transformer modeling changes are essential. These expanded models are currently unavailable in other software tools and are essential for obtaining accurate results.

6. The user of the tool must understand that the accuracy of the open phase fault simulation is directly affected by the unavailable, incorrect or incomplete transformer data.

11 Conclusions

In the event of a broken conductor, series or open phase fault, the load currents cannot be neglected, as these are the only currents that are flowing in the network and expanded models are needed for motors and transformers in order to accurately simulate the effect of open phase fault on bus voltages and sequence currents. Without accurate steady state values, it will not be possible to set undervoltage and negative sequence relays properly. The developed software has been validated to perform qualitative analysis of plant response to open phase fault event and provide steady state sequence current and voltages throughout the model. The software was shown to accurately simulate transformer factory impedance tests (positive and zero-sequence short circuit tests) as well as actual open-phase “events”. The software has also been enhanced to calculation asymmetric faults such as LL, LG, LLG on unbalanced systems. Further development is in progress to simulate simultaneous fault such as combination of series and shunt fault.
Computer Analysis of Complex Faults in Power Systems

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Introduction

- A power system is normally treated as a balanced symmetrical three-phase network
- During a fault the symmetry is upset, resulting in unbalanced currents and voltages
- Complex faults include open phase condition
- Open phase may be undetected by standard line relaying
- Damaging negative sequence current can be generated for fault at generator terminals
Short Circuit Analysis

- Compute the sequence network bus impedance matrices.
- Extract the sequence network single-port Thevenin equivalent impedances of the faulted bus.
- Use the sequence equivalent networks to compute the sequence fault currents at the faulted bus.
- Use the computed sequence fault currents as compensating currents to calculate the network post fault voltages and currents.

Fault Types

- Most faults in power systems are unbalanced or unsymmetrical where three phases are not affected equally.
- Assumption of equal current magnitude in all phases being no longer applicable.
- In transmission systems, symmetrical faults occur infrequently (roughly 5%).
- An asymmetric fault breaks the underlying assumptions used in three-phase power that all three phases are balanced.
Fault Types

- **line-to-line** - a short circuit between lines, caused by ionization of air, or when lines come into physical contact, for example due to a broken insulator.
- **line-to-ground** - a short circuit between one line and ground, very often caused by physical contact, for example due to lightning or other storm damage.
- **double line-to-ground** - two lines come into contact with the ground (and each other), also commonly due to storm damage.

Open Phase – Event 1

- On January 30, 2012, Byron Station, Unit 2, experienced an automatic reactor trip.
Design Vulnerability

- A 345-kV phase C insulator stack failed mechanically
- Resulted in a phase C open circuit and a high impedance ground path
- Transformer HV terminal had a ground path, but did not result in a detectable ground fault
- Since the switchyard (i.e., source side) relaying was electrically isolated from the fault, it did not detect a fault; therefore, it did not operate
- Flow of current on phases A and B increased because of unbalanced voltage

Design Vulnerability

- Caused all four Reactor Coolant Pumps (RCPs) to trip on phase overcurrent
- Control room operators performed a natural-circulation cool down of the unit
- Approximately 8 minutes after the reactor trip, the control room operators diagnosed the loss of phase C condition
- Operators manually tripped breakers to separate the unit buses from the offsite power source
- Byron NPGS reviewed the event and identified design vulnerabilities in the protection scheme
Open Phase – Event 2

- A second event occurred at Byron Station Unit 1 on February 28, 2012 (approximately a month apart)
- In this event, the 4.16-kV ESF buses did sense fault condition
- Loss of a single phase on the offsite power source can potentially damage both trains of the emergency core cooling system
- Protection scheme must automatically initiate isolation of the degraded offsite power source and transfer the safety buses to the emergency power source

Event Impact

- The United States Nuclear Regulatory Commission took regulatory actions to require licensees to provide design features to detect and automatically respond to a single-phase open circuit or high impedance fault condition on the high voltage side of a credited offsite circuit
- A need for detailed plant-specific models was identified (e.g., transformer magnetic circuit models, electric distribution models, motor models; including positive, negative, and zero sequence impedances, voltage, and currents)
Open Phase Fault (OPF)

- INPO Event Reports IER L2-12-14, IER L3-13-13, and NRC Bulletin 2012-01 describe a nuclear safety concern involving an open-phase fault occurring on the offsite power supply of a nuclear plant.
- An OPF is considered to be an open-phase condition, with or without ground, located on the high-voltage (switchyard) side of each offsite power (OSP) transformer.

Open Phase Fault (OPF)

- Two aspects to an open-phase fault analysis:
  - Acceptability
  - Detectability
- Acceptability involves the ability continue functioning during the open-phase condition without damage and/or spurious operations.
- Detectability involves the ability of protection systems to detect the open-phase condition.
OPF Study Objective

- Outcome of OPF analysis is to identify levels of unbalance (voltage and current) throughout the plant auxiliary power system
- Determine if existing protective systems will sense the OPF condition
- For any cases where the open-phase condition cannot be detected with existing protection systems, this should be identified as a potential vulnerability

OPF Study

- Overall analytical method is a steady-state load flow technique
- Cannot determine the immediate transient response of the power system to an open-phase fault
- Usually not necessary as the steady-state (~30 cycle) voltages and currents (phase and sequence quantities) throughout the plant power system (including at load terminals) can typically be used to properly characterize the potential vulnerabilities to an OPF condition
**OPF Study Requirements**

- The OPF analysis should consider
  - operating scenarios (events/loading)
  - alignments (configurations)
  - Amount of potential voltage unbalance in the incoming plant power supplies (grid unbalance)

- Enter additional transformer data
  - Zero-Sequence Impedances (%Z and X/R), obtained from zero-sequence short-circuit tests, but for transformer with “buried delta” regulating winding, also need zero-sequence open-circuit tests (e.g. Pri-regulating, Sec-regulating, Pri-Sec)
  - Zero Sequence No Load Losses (%FLA and kW)

**OPF Study Requirements**

- Ensure induction motors have all required data to support the OPF analysis, especially negative-sequence reactance (X2)
- The amount of impedance between open phase and ground (transformer side of the open) can be simulated in ETAP by adding a “phase adapter” and a single phase “infinite load” referenced to ground (see inset). The impedance can be varied to simulate any situation from true open to solid ground
Computer Simulation Software Requirements

- Graphical Placement of the Open-Phase on the One Line Diagram
- Induction motor modeling.
- Transformer type.
- Transformer Embedded winding
- Report current flow inside Transformer Embedded winding
- Ground Impedance

OPF Analysis Steps

- Determine the voltage unbalance at each critical bus
- Determine the motor on each bus with the worst-case current unbalance
- Consider both balanced and unbalanced grid conditions
- Ensure sufficient study cases are run to bound all combinations of OSP transformers, amount of transformer loading, and amount of open-phase ground impedance
OPF Scenarios

- Two offsite power sources
  - Startup/Shutdown Transformer
  - Main Transformer with connected Unit Auxiliary Transformer (consider with and without main generator connected)
- Three transformer loading scenarios
  - Heaviest (e.g. LOCA loading with any extra plant buses connected)
  - Normal Operation (normal alignment)
  - Lightest (e.g. Refuel loading)
- Two types of open-phase faults
  - Open
  - Open w/ solid ground

OPF Detectability

- Compare the OPF results to existing plant protective device schemes/settings to determine if the open-phase condition is adequately detected
- Transformer differential (87T), transformer neutral overcurrent (51N), transmission line negative-sequence, and in-plant bus undervoltage relays
- Consider application of margins when determining acceptability. Suggested values are:
  - undervoltage detection: 10%
  - overcurrent detection: 10%
  - differential detection: 5%
OPF Results

OPFA Results for Shutdown Transformer XYZ

<table>
<thead>
<tr>
<th>OPF Type</th>
<th>Transformer Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Light (Refuel)</td>
</tr>
<tr>
<td>Grounded</td>
<td>Detectable</td>
</tr>
<tr>
<td>Ungrounded</td>
<td>Not Detectable(2)</td>
</tr>
</tbody>
</table>

2D view of limited case studies does not fully characterize outcome of an OPF on a given transformer.

Complete characterization (i.e. all eventualities for both detectability and acceptability) can be thought of as five “dimensions”, which are:

- Transformer loading (analysis variable)
- Open-phase grounding (analysis variable)
- Worst-case bus voltage unbalance (analysis result)
- Protective device detectability (analysis result)
- Acceptability of worst-case current unbalance on motor loads (analysis result)
Why ETAP?

ETAP is the most commonly used analysis software in US nuclear plants and has established itself as the de facto standard: **60 out of 64 operating plants (94%) have standardized on ETAP.**

ETAP Nuclear is used throughout the world by nuclear plants, research laboratories, consulting firms, government agencies, and other organizations.

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ETAP NUUG

- ETAP NUUG began review of ETAP’s ability to perform OPFA shortly after the Byron open-phase event in early 2012
- **May 2012**: ETAP developer (OTI) issued Informative Report INFR-12-003 to identify limitations and future enhancements related to OPFA
- **February 2013**: Revised version of ETAP issued to better simulate open-phase faults
- **March 2013**: ETAP NUUG formed OPFA Task Force
OPFA Task Force Goals

- Assess the ability of ETAP 12 to perform detailed quantitative analysis for the effects of open-phase faults on a typical nuclear power plant
- Develop a basic approach for using ETAP 12 to perform OPFA

OPFA Task Force and Peer Review Team*

Exelon
Duke
Southern Nuclear
TVA
Enercon
MPR Associates, Inc.
Sargent & Lundy

* Recognized industry experts
OPFA Task Force Effort

- 3 month effort (March thru May 2013)
- Performed “mock” OPFA using existing ETAP models
  - Reviewed additional data entry needed
  - Considered broad spectrum of plant types, offsite power configurations, transformer types, and operating conditions
  - Developed basic approach for modeling open-phase faults (open, open w/ gnd, open w/ hi-Z gnd)
- Reviewed available results related to OPFA
  - Voltage and current results: “L-L”, “L-N”, and “sequences”
  - Xfmr neutral and buried delta results
- Format developed to evaluate the “mock” results

ETAP Simulation

- ETAP allows quick and efficient simulation of the analysis variables and relatively easy evaluation of the results
- Multiple OPF simulations can be performed for the analysis variables (transformer loading and open-phase grounding) to allow plotting these five dimensions in sufficient detail to fully characterize the OPF analysis
ETAP Simulation

Voltage Unbalance vs Resistance to Ground and Transformer Loading

- Light Green – Detectable
- Red – Possible Motor Damage
- Yellow – Possible Motor Tripping
- Dark Green – Adequate Voltage

ETAP Utilization

- Detailed modeling required for open phase fault simulation is possible in EMTP however it is impractical and not required:
  - Protective relaying settings will be based on steady state values in order to avoid nuisance tripping
  - EMTP requires considerable amount of time to model a complete power electrical system
  - Most of the electrical systems from HV to LV have already been modeled in ETAP and minimal data entry is need in order to expand the model to perform open phase fault simulation
ETAP Interface

Updated model

- Circuit parameters, update ETAP motor model
- Enter correct Z2 and initial powers
ETAP Validation

- Mtr1 (100% loading) terminal line-neutral voltages:

ETAP Validation

- Mtr2 (100% loading) terminal line-neutral voltages:
ETAP Validation

- Mtr1 (100% loading) Currents:

- Mtr2 (100% loading) Currents:
ETAP Validation

- Motor (100% loading) Powers:

ETAP Validation

- Mtr1 (50% loading) terminal line-line voltages:
ETAP Validation

- Mtr2 (50% loading) terminal line-line voltages:

OPFA Task Force Results

- ETAP 12 is validated to perform OPFA (steady-state)
- Minimal additional data entry needed for OPFA (beyond a typical ETAP plant model)
- ETAP 12 can simulate open-phase faults with specific values of ground Z
- ETAP 12 was shown to accurately simulate Xfmr factory impedance tests (positive and zero-sequence short-circuit tests) as well as actual open-phase “events”
- Issues / Limitations
  - Unavailable/incorrect/incomplete Xfmr data
  - Not intended for dynamic/transient analysis
Summary of Findings

• Under low loading, certain transformer configurations, and depending on the amount of impedance between the open transformer phase and ground, detection of an open-phase condition on the primary side of a transformer can be difficult on the secondary side.

• In some cases, detection of the fault is not possible by monitoring the phase currents and voltages. Under voltage relay schemes are not always able to detect a single open phase.

Summary of Findings

• Depending on the location of the relays/monitoring devices, the effects of motor back-emf and voltage drop across cables can be significant for detection.

• Better accuracy of simulation results is obtained with an actual detailed system model rather than a simplified model.
Summary of Findings

- Motor and transformer modeling changes are essential. These expanded models are currently unavailable in other software tools and are essential for obtaining accurate results.
- The user of the tool must understand that the accuracy of the open phase fault simulation is directly affected by the unavailable, incorrect or incomplete transformer data.

Conclusion

- ETAP 12 is a validated analysis software package that is now available to allow current nuclear users to quickly move toward performing a qualitative analysis of their plant’s response to an open-phase fault
- ETAP 12.6 includes double phase open fault simulation capability
- ETAP 14 includes simulation of simultaneous complex faults
Questions

Thank you