Alternative Approaches and Dynamic Analysis Considerations for Detecting Open Phase Conductors in Three Phase Power Systems

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***Abstract*-- Open phase conductors in three-phase power systems can be difficult to detect with conventional protection relay schemes. Such events can have adverse consequences to power system equipment and cause excessive heating in transformer core and coil assemblies and tanks. The resultant voltage unbalance associated with open phase events can reduce the available starting and running torque of motors, increase motor acceleration time, cause inadvertent tripping of critical loads, and thermally damage plant equipment.**

Power system response to an open phase condition is highly dependent on a number of factors, including the type of open phase condition (events involving one or two phase conductors, coupled with or without a ground), the location of the open phase, the topology of the power system, transformer core design and winding connections, and type and magnitude of system loading.

This paper briefly describes industry operating experience with open phase events. It summarizes the various alternative approaches for detecting open phase conductors on large station service transformers. Dynamic modeling considerations and techniques are described and a summary of analytical results which convey the challenges, advantages, and disadvantages associated with different detection strategies are presented. The role symmetrical components and sequence components can play in understanding the impact of open phase conditions on power system equipment also is discussed.

***Keywords*: Open phase, transmission faults, transformers, power system modelling, power system transient analysis, unbalanced voltages, power plants, industrial power systems**

I. INTRODUCTION

In January 2012, a mechanical failure of an underhung isolator caused an open circuit in a single phase conductor of a three-phase, 345 kV overhead power line feeding the two system auxiliary transformers (SATs) at the Byron Nuclear Station, Unit 2. The open phase caused unbalanced voltages on the plant buses, the automatic trip of certain plant equipment, and a significant plant transient. The event revealed a previously unanalyzed design vulnerability in the station's offsite to onsite power system. Subsequent reviews of industry operating experience indicate that open phase events occur in industrial power systems more frequently than desired.[1] For example, IAEA Safety Report No. 91 [2] summarizes fourteen open phase events at nuclear power plants in various countries worldwide. These events involved systems operating at 115 kV to 400 kV and were due to a variety of causes including broken or fatigued conductors, misoperated circuit breaker poles, failed insulators, and loose connections.

Open Phase Conditions (OPCs) can be difficult to detect, cause inadvertent trips of critical plant loads, and damage equipment. When a motor is supplied from a wye-delta or delta-wye transformer, an open phase on the primary (or line) side of the transformer results in increased current that may go undetected by the motor's overload protection because the positive sequence current is not excessive. However, the voltage unbalance at the terminals of the machine may cause excessive heating due to negative sequence currents. Significant voltage unbalance can cause running motors to stall and trip off. Negative sequence voltages produce torques during motor starting conditions which retard motor acceleration causing longer acceleration times and create the potential for mission critical loads already running to stall or trip on overload.

II. APPROACH FOR DETECTING OPEN PHASE CONDITION

The primary function of an Open Phase Detection (OPD) system is to reliably protect against unbalance conditions that can adversely impact critical safety functions, damage major capital assets, or interrupt plant production. An OPD system must also provide adequate security against false tripping for both routine, non-harmful unbalance conditions and momentary or short lived transient unbalance conditions. OPCs on the primary side of transformers under light loading conditions are very difficult to detect with conventional protection relay schemes. Differential relays are designed to trip only if there is a substantial current imbalance within the differential zone of protection. Consequently, differential relays generally do not provide open phase detection. Secondary side undervoltage protection is typically incapable of detecting low levels of unbalance which occur during no load or light loading conditions.

There are several commercially available OPD systems. Each employs different schemes for detection of OPCs. These schemes can be classified based on the location monitored. For example, several schemes use transformer primary side phase current for detection of open phase conditions. Alternatively, primary side neutral current and zero sequence impedance detection schemes have been installed on wye-wound transformers with grounded neutrals. And traditionally, secondary side voltage unbalance or negative sequence voltage relays have been employed.

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Primary side phase current detection schemes typically use a combination of phase current magnitude and phase as well as the corresponding sequence currents. They can employ either a single set of current transformers (CTs) for sensing or a dual set of CTs. In the latter case, one set of CTs is used to detect low levels of current, e.g., transformer magnetizing current, and the second set is used to detect higher levels of load current. Special wire wound or optical air core CTs, and various digital filtering techniques also can be used to enhance the sensitivity of the CT measurements.

The transformer neutral overcurrent and zero sequence impedance detection schemes use a combination of neutral overcurrent and modified subharmonic injection current. Subharmonic injection systems (ANSI device 64S) have traditionally been applied in generator protection schemes for detection of stator ground faults. These schemes actively inject zero sequence current into the transformer neutral at a frequency other than the fundamental frequency and its corresponding harmonics. Such systems take advantage of the overall change in zero sequence impedance of the power system which occurs during open phase events and is expressed as a corresponding change in the measured subharmonic injection current.

Transformer secondary side negative sequence voltage schemes use various voltage sensing relays applied at buses powering critical plant loads. This includes three phase undervoltage relays (ANSI device 27), voltage balance relays (device 60), and phase voltage unbalance or negative sequence relays (device 47). These relays typically are not designed specifically for OPD but can provide critical asset protection during unbalanced conditions present during open phase. Attention to the potential transformer (PT) connections is necessary to ensure the effectiveness of these devices.

III. System Conditions Affecting Open Phase Detection

The functional objective for OPD systems is to reliably discern OPCs from system unbalance conditions that occur normally. Such power system unbalances may be present due to unbalanced line loading or compensation and un-transposed transmission lines. Switching events and system faults also impose transient unbalances on the system. The ability of an OPD scheme to detect an open phase condition depends on variety of factors including the following:

A. Switchyard Impedance and Voltage

Typical system analyses for power plants and industrial power systems consider the transmission system and interconnecting substation or switchyard as an ideal voltage source. However, for the purposes of analyzing OPCs and establishing the appropriate setpoints for an OPD system, applicable substation or switchyard impedance and expected range of 'normal' system voltage unbalance need to be considered. Switchyard positive, negative, and zero sequence impedance can be determined from the single-line-to-ground, line-line-to-ground, and three phase bolted fault current studies. Furthermore, a range of impedance (representing a weak grid / strong grid) may need to be calculated based on the number of transmission lines and generation sources connected to the plant switchyard and the switchyard arrangement.

Analyses of OPCs require the modeling and evaluation of parallel paths. The impact of switchyard impedance can be evaluated based on the zero sequence network shown in Figure 1. In Figure 1, $V_{G,1}$ and Z_{COMB} represent the Thevenin equivalent of the positive and negative sequence networks and are typically readily available. The connected impedances represent a single OPC on transformer T2. The zero sequence network shows a connection of two parallel transformers to the plant's switchyard. A higher transmission system zero sequence impedance ($Z_{G,0}$) will result in higher current in the unfaulted transformer neutral. Consequently, an open phase on one transformer could be falsely detected as an open phase on the other unit if the setpoints for the OPD systems are not properly coordinated.

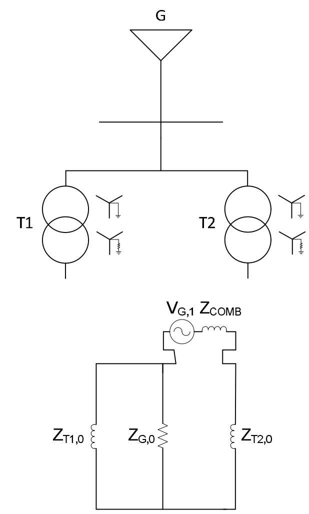

Figure 1. Coupling of Zero Sequence Impedance of Parallel Transformers

Power system analyses of plant distribution networks often assume a balanced three phase source. However, substation or switchyard voltages can be unbalanced during normal operating conditions. There is limited published guidance on EHV and UHV transmission system voltage unbalance. Annex C to ANSI Standard C84.1 [3] states that "Field surveys tend to indicate that the voltage unbalances range from 0–2.5 percent to 0–4.0 percent with the average at approximately 0–3.0 percent", but these data are rather dated and actual conditions are site specific. An estimate of system voltage unbalance can be established by reviewing historical synchro-phasor or digital fault recorder (DFR) data. The estimate should make use of statistical techniques to fully understand the maximum expected range of system unbalance. Another challenge that arises with establishing the inputs for modeling and simulation arises from the various definitions of voltage unbalance. In comparing data from different sources, it should be noted that voltage unbalance is often defined in different ways. If the normal expected range of source voltage unbalance is not properly considered, inadvertent or false tripping of OPD systems can occur.

B. Transformer Core Design and Winding Configuration

Transformer core design and winding configuration have a major influence on how the effects of OPCs propagate through the plant AC distribution system. Consequently, the type, accuracy, and fidelity of the transformer models used for modeling and simulating have a huge impact on the validity of the results obtained.

The positive and negative sequence impedance of a transformer are equal. Considerable time should be devoted to determining the appropriate transformer zero sequence impedance and selection the type of transformer model to use as these elements are crucial. Unfortunately, the transformer zero sequence impedance often is not included with nameplate and factory acceptance test data for older units. References [4] and [5] describe the zero sequence characteristics for common transformer types.

Two common and effective transformer models used in electromagnetic transient programs (EMTP) analyses are the BCTRAN model and the unified magnetic equivalent circuit (UMEC) model, see References [6] and [7]. Each has its advantages and disadvantages. As an example Figure 2 illustrates the resultant open phase zero sequence current for different transformer core designs and winding configurations as a function of load.

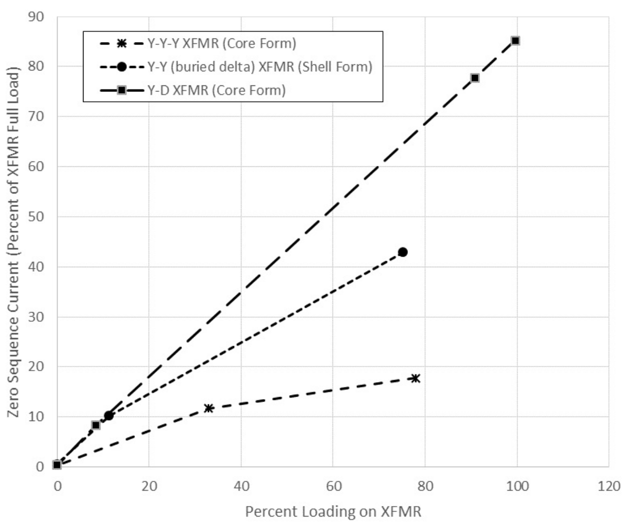

Figure 2. Single Open Phase on Different Types of Transformers

C. Plant Loading Conditions

Additional plant load impacts the degree of system unbalance experienced during an OPC by reducing the overall positive and negative sequence impedance of the plant system. For an unloaded transformer, the positive sequence impedance is dominated by the transformer magnetizing branch. The transformer magnetizing branch impedance is very high and thus the transformer draws current on the order of less than one percent of its nameplate rated current under no load conditions. A loaded transformer draws more current because the positive sequence impedance of the system is lower. During an open phase condition, a lower positive sequence impedance drives more current in negative and zero sequence paths. Therefore, a range of loading conditions would have to be considered to understand the impact of an open phase condition.

D. Type of Plant Loads

An understanding of the applicable sequence network connections for a given OPC offers the analyst significant insight on the expected response of an OPD system. Typically, positive sequence networks are well understood as these networks are used routinely for balanced conditions. Often plant loads are ungrounded. Consequently, plant loads impact the positive and negative sequence networks.

Typical plant AC loads consist of motors, heaters, lighting panels, battery chargers, etc. Most of the dynamic load in a power plant or an industrial power system consists of motor loads that drive various rotating equipment such as pumps, fans, and conveyors. Dynamic loads have a time varying response during an OPC. The changing impedance of the dynamic load results in a change in system current as a function of time, which means there is an inherent feedback mechanism whereby unbalance at the terminals of the machines impact the operating condition of the load, which in turn affects the power demand on the system and thus the amount of system unbalance. Consequently, certain OPD systems may exhibit increased sensitivity to the time varying change in system impedance and may not detect some OPCs until the system reaches steady state.

IV. Dynamic Modeling Considerations

Open phase conditions result in unbalanced system voltages and system loading. An effective OPD scheme must not only detect open phase conditions but it must also be sophisticated enough to discern open phase events from normal system unbalances and other plant transients such as short circuits and motor starting events. Consequently, analyses to select an appropriate OPD scheme and setpoints must consider various plant loading scenarios, system switching events, bus transfers, motor starting transients, and system faults.

Prior to developing a detailed model and running various simulation cases it is important to establish acceptance criteria to ensure the reliability and security of the OPD systems under consideration. For example, as discussed in Section III.A the maximum expected range for ‘normal’ voltage unbalance requires consideration to prevent false tripping. The minimum time delay for the OPD system should be based on the maximum fault clearing time upstream and downstream of the system. The various plant operating modes, bus and breaker alignments, and system loading conditions must be considered. The maximum allowable voltage unbalance for various plant equipment, especially motors, should be established. Acceptance criteria must consider the effects of additional system and load currents due to voltage unbalance and the limits necessary to prevent motor overheating or thermal damage.

Existing industry standards and peer-reviewed publications provide only limited guidance for the allowable time motors can operate with unbalanced voltages greater than five percent. Additionally, the available guidance does not distinguish between motor types and sizes. Existing guidance on the impact of voltage unbalance on poly-phase motor operation is applicable to relatively low magnitude voltage unbalances (i.e., < 5 percentage) under continuous operation. NEMA Standard MG-1 [8] and IEC Standard 60034-26 [9] recommend limiting the operation of induction motors and synchronous machines to 5 percent or less voltage unbalance.

Limited and sometimes inconsistent guidance exists on the use of the magnitude of I_2^2t for protecting motors against voltage unbalances. The existing limits suggested for the magnitude of I_2^2t are based on correlations with limits for large synchronous machines. Gleason, et al. [10] recommended a maximum permissible I_2^2t magnitude of 40 in 1958, although the authors acknowledge that "No comparable standard has been established for short time operation of motors on unbalance." Less conservatively, Cummings, et al. [11] suggested in 1985, a value of $I_2^2t \leq 120$ "as a guide for short durations." However, these limits are not based on extensive tests of asynchronous induction motors, and there is very little distinguishing guidance for different types and sizes of motors in the literature.

Yet another type of criteria for verifying the efficacy of OPD systems, is to ensure that the protective devices such as overcurrent relays and thermal overloads for critical plant equipment will not actuated inadvertently before the OPC is detected and isolated.

Steady-state or quasi-steady state modeling analyses provide limited information and may be adequate for an initial study of the plant's vulnerability to open phase events. For example, compliance with the NEMA MG 1 percent voltage unbalance criteria can be confirmed from three-phase line voltage magnitudes obtained from a steady-state analysis. Additionally, the number of true positives and false alarms asserted by protective devices can be determined at steady-state conditions. However, accurate trip times which are not overly conservative will most likely require a time-domain dynamic analysis.

Dynamic models typically require more data and more time and effort to construct than steady-state models. They also require more computation time. However, there are many important benefits of dynamic models which justify the additional effort. For example, as described in Section III.D, certain OPD systems are sensitive to time-varying changes in the system's impedance due to dynamic loads, which may negatively impact the OPD system's ability to actuate a timely trip and increase risks of equipment damage if not properly accounted for. On the same note, to provide reasonable assurance that the timer settings for an OPD system have been set to avoid motor damage due to excessive unbalanced currents, the time-varying motor I_2^2t should be accurately determined through dynamic modeling.

Dynamic modeling also provides means of analyzing the power system's response to routine plant operations such as motor starting and fast bus transfers they may occur in conjunction with an OPC. Fast bus transfer schemes are commonly used in industrial and power generating plants to improve system reliability. These schemes provide a means of transferring voltage to a new source when the primary source is removed. Such a transfer could happen when an open phase detection scheme would detect and trip the voltage source. A fast transfer is not an intended consequence of an open phase analysis but would require evaluation. The initial conditions of a typical fast bus transfer analysis include separation from a balanced source and transfer to an alternate balanced source. However, the initial condition for a fast transfer following an open phase trip could include separation from a severely unbalanced source. The analysis result for a fast bus transfer from an unbalanced source can be very different than those obtained for same conditions with a balanced source. Therefore, an updated analysis is recommended to determine whether the existing transfer scheme is safe or if must be blocked immediately following an OPC trip.

The ability to generate time-domain simulation data (e.g., COMTRADE files) for testing is also a benefit of a dynamic modeling approach.

Dynamic time-domain modeling involves construction of three-phase representations of static loads and dynamic loads, transformers, switches and breakers, offsite and onsite power sources, and protective devices. Motor models should be able to simulate both positive and negative sequence currents, which vary with three-phase terminal voltage and motor slip. Motor slip should account for the interaction between the motor's torque-speed characteristic, the motor inertia, and torque-speed curve of the driven load. Transformer models should be able to simulate magnetic coupling between multiple windings and different types of winding connections (wye, delta), as well as the positive/negative and zero sequence characteristics of transformers. In special cases, capacitance and the asymmetrical nature of the magnetic coupling between phases and may need to be considered. Models for switches and breakers should be able to simulate the timed opening or closing of individual phases so as to cover all types of single and double open phase conditions. Offsite and onsite source models should be able to simulate voltage on each of the three phases independently in order to evaluate both balanced and unbalanced voltages. Incorporating representations of protective devices in the model, including OPD schemes under consideration, simplifies the amount of post processing and evaluation of setpoints and time delays.

Determining which set of initial conditions will provide bounding results is a challenge for open phase analysis. For example, with the maximum source voltage set as a boundary condition, fewer motors are likely to stall during a postulated open phase event. However, if they do, the system will draw significant amounts of unbalanced currents due to high source voltage. Conversely, with minimum source voltage available, it is likely that more motors will stall under an open phase condition which also will cause the system to also draw significant unbalanced currents despite the low source voltage. Hence, the boundary condition that results in higher unbalanced currents could be due to either the maximum or minimum source voltage depending on the type of load running. In general, it is challenging to reliably predict the electrical system's behavior with respect to certain system conditions, which inevitably result in running more simulation cases to account for these uncertainties and bound the system's behavior.

Developing an understanding of how symmetrical component sequence networks for the power system under consideration are coupled together during postulated OPCs allows for the construction of simpler dynamic models that do not compromise simulation quality or fidelity of results. This is discussed in greater detail in Section V.

V. Role of Symmetrical Components in Understanding Open Phase Conditions

Symmetrical components simplify the analysis of unbalanced three-phase electrical systems by decomposing the system into positive, negative, and zero sequence components. They also provide an intuitive framework for planning and designing simulation cases, as well as interpreting and presenting open phase results.

Identifying the locations where OPCs should be considered and understanding how the sequence networks for those postulated conditions are interconnected before developing the simulation model can potentially reduce the amount of zero sequence model parameters required. Figure 3 and Figure 4 provide illustrative examples for this. Figure 3 depicts a single open phase between Grid G and Bus B1, and Figure 4 depicts a single phase-to-ground fault on Bus B2. The impedances circled in dashed lines on the sequence network connections in both figures indicate the zero sequence impedances that are not required for each analysis. If both the single open phase condition and the single phase-to-ground condition are to be analyzed using the same system model, then the zero sequence impedances not required is the intersection of the unnecessary zero sequence impedances indicated in both figures.

When planning simulation cases to evaluate the effectiveness of OPD systems, it is important to understand under which system conditions the protection system is most sensitive and design simulation cases to test it at the credible limits. Often this is more easily done in terms of sequence components versus phase quantities.

When interpreting analysis results, certain phenomena become more apparent when expressed as sequence components. For example, motors stall when the motor

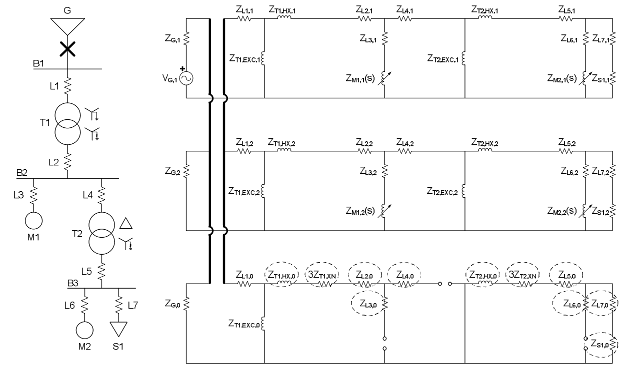

Figure 3. Single Open Phase between Grid G and Bus B1

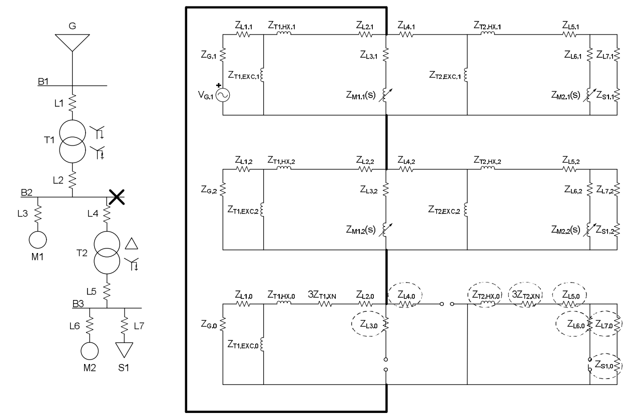

Figure 4. Single Phase-to-Ground Fault on Bus B2

torque is less than the load torque. When the terminal voltage is unbalanced, the negative sequence voltages produced a decelerating torque on the motor. Table 1 shows two sets EMTP-RV simulation results for a 4,000 V motor. By simply looking at the phase voltages (V_{LN}), it is not clear why the motor would stall on one set of voltages but not on another. However, by examining the associated sequence voltages, it becomes clearer why the motor stalled.

Table 1. Motor Unbalanced Voltages

Motor Stalled?	**Van**	**Vbn**	**Vcn**	**V1**	**V2**
No	2670 V ∠ 0°	2376 V ∠ -124°	2376 V ∠ 124°	**2470 V** ∠ 0°	**200 V** ∠ 0°
Yes	3470 V ∠ 0°	2152 V ∠ -144°	2152 V ∠ 144°	**2470 V** ∠ 0°	**1000 V** ∠ 0°

Simplified sequence networks can also be used to independently validate computer models. For example, comparing the results obtained from test model and those derived separately from hand calculations based on its equivalent sequence network diagrams is especially valuable when using software component libraries that have not been previously validated.

Table 2 summarizes simulation results for an 11 MVA, 345 kV - 4160V station service transformer under different postulated open phase conditions, including single and double open phase. Table 2 illustrates the resultant unbalance due to single open phase is significantly less than that obtained from a double open phase, especially under light load.

Table 2. Voltage under different Open Phase Conditions

Condition	% Load	V1	V2	V0	NEMA V Unbal.
No Open Phase	No Load	2463 V	0	0	0%
Open Phase	No Load	2448 V	16 V	16 V	1%
Open Phase	20%	2357 V	82 V	92 V	3%
Open Phase	50%	2243 V	218 V	247 V	10%
Open Phase with Ground	No Load	1642 V	822 V	820 V	39%
Double Open Phase	No Load	1228 V	1228 V	8V	100%

VI. OPD SYSTEM TOLERANCES

Installation of an OPD system requires consideration of the applicable tolerances with detection sensors and signal processing equipment. For primary side phase current based detection schemes, the sensors provide reasonable accuracy in phase current magnitude measurements. However, these measurements are used by multi-function digital relays which calculate root mean square (RMS) phase current and corresponding sequence current magnitudes. The accuracy of the phase current sensors can be directly translated to the calculated phase currents but to determine the accuracy of the calculated sequence currents is not straight forward and Monte Carlo simulations may be required. Some phase current based detection schemes use the ratio of sequence currents. With measurement of small values of current, large variations in ratios can result after signal error is accounted for. This makes setpoint analysis for these schemes complicated.

Neutral overcurrent and subharmonic current injection schemes can be susceptible to noise when power system transient responses last for a few seconds. During OPCs, transformer neutral currents includes current at the fundamental frequency. The true magnitude of the subharmonic injection current can be masked by the fundamental frequency current due to spectral leakage in the signal processing.

Transformer secondary side bus voltage detection schemes provide a simpler methodology to detect unbalance at plant buses. The tolerance of such relays and associated potential transformers (PTs) generally is coarse. The application of these relays is typically for larger unbalances at motor terminals due to motor single phasing or to detect loss of phase in control circuits. The unbalances present at plant buses during open phase conditions can range from very low to very high levels of imbalance, depending on plant loading and the type of open phase condition. Thus, for certain conditions, it may not be possible to establish an appropriate setpoint for these schemes.

VII. CONCLUSION

Open phase conductors in three phase power systems occur more frequently than desired. Such events can cause inadvertent trips or damage to critical plant equipment, or result in undesired plant transients or lost availability. Although open phase conditions can be difficult to detect, there are several different type of systems available for open phase protection. Dynamic simulation is an effective way to evaluate and select a protection system and establish setpoints for it that provide reliable detection and adequate security against false tripping. Early consideration of: (a) the applicable functional requirements for the system (e.g., under what scenarios does it need to protect) and (b) the acceptance criteria for the analysis, is very important. A comprehensive model, properly validated, and a thorough analysis are necessary for verifying the effectiveness of an open phase detection system and establishing appropriate setpoints for it. An effective OPD scheme must not only detect open phase conditions but it must also be sophisticated enough to discern open phase events from normal system unbalances and other plant transients such as short circuits and motor starting events. Because of the challenges involved with fully analyzing the complex set of system interactions involved and fully validating power system models, an on-line, alarm only, monitoring period is warranted before enabling trip functions.

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