Electric Power Systems Research 163 (2018) 59–65

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Alternative approaches and dynamic analysis considerations for detecting open phase conductors in three phase power systems

Robert M. Carritte*, Kawa Cheung, Mohit Malik

MPR Associates, Inc., VA 22314, USA

ARTICLE INFO

Keywords:
Open phase
Transmission faults
Transformers
Power system transient modeling
Unbalanced voltages
Industrial power systems

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 reliability and performance. The resultant voltage unbalance associated with open phase events can cause excessive heating in transformer core and coil assemblies and tanks, 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.

1. 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–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 due to abnormal starting currents.

2. 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

Abbreviations: SAT, System auxiliary transformer; OPC, Open phase condition; OPD, Open phase detection; CT, Current transformer; PT, Potential transformer; DFR, Digital fault recorder; EMTP, Electromagnetic transient programs; UMEC, Unified magnetic equivalent circuit; VLN, Phase voltages; RMS, Root mean square

* Corresponding author at: MPR Associates, Inc., 320 King Street, Alexandria, VA 22314, USA.
E-mail addresses: rcarritte@mpr.com (R.M. Carritte), kcheung@mpr.com (K. Cheung), mmalik@mpr.com (M. Malik).

https://doi.org/10.1016/j.epsr.2018.05.012
Received 12 December 2017; Received in revised form 29 March 2018; Accepted 8 May 2018

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 and may not even provide detection during open phase with ground conditions on unloaded transformers. This is because zero sequence current is the major contributor to phase current during open phase with ground currents. The current transformers (CTs) on Wye-wound transformers usually are connected in a delta connection and thus do not pass on the zero sequence component to the relay. Further, during no load or light loading conditions, the differential current for an ungrounded open phase (and in some cases an open phase with ground) might not exceed the zero through-current restraint setting. Additionally, 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.

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 are not designed specifically for OPD but can provide critical asset protection for moderate to high unbalanced conditions present during certain types of open phase conditions. Attention to the potential transformer (PT) connections is necessary to ensure the effectiveness of these devices. However, unbalances present due to light load conditions on single open phase conditions may not be detected by unbalance voltage relays and could results in equipment damage or reduced insulation life during prolonged operation.

3. 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 and trip in adequate time to protect equipment depends on variety of factors including the following:

3.1. 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 any parallel paths or feeds. The impact of switchyard impedance can be evaluated based on the zero sequence network shown in Fig. 1, where $V_{G,1}$ 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, and vice versa. 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 and

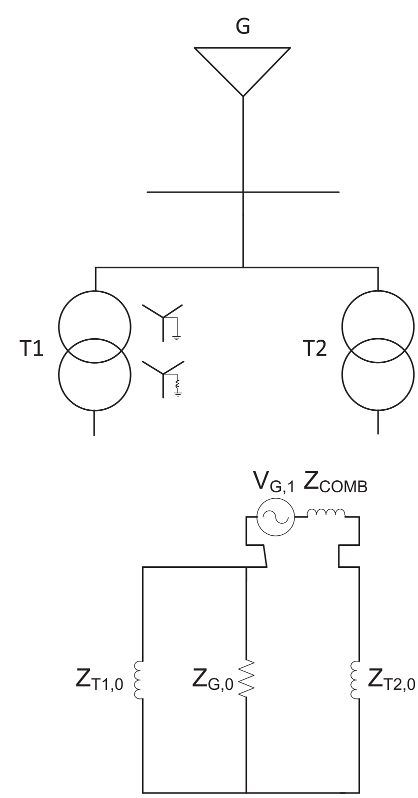

Fig. 1. Coupling of zero sequence impedance of parallel transformers.