OPEN PHASE DETECTION FOR POWER TRANSFORMERS USING VT TRIGGERED OPTICAL CTS AND IEC 61850-9.2LE COMPLIANT RELAYS

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Abstract

We demonstrate the use of IEC 61850 process bus transformer relays together with optical CTs for the detection of open phase conditions on the high side of a range of step-down power transformers. A set of optical CTs generates 12 waveforms which are slotted into six IEC 61850-9.2LE data streams which are in turn input into the relay programmable stream logic for the detection of open phase conditions.

I. INTRODUCTION

Due to the fact that optical current transformers (OCT's, here of fiber construction [1] – [12]) have properties that differ significantly from conventional iron core CTs, differently optimized architectures for distributing their data to the secondary devices are being developed. OCTs have measurement advantages over conventional iron core CTs which include orders of magnitude wider dynamic range, no saturation, and much larger frequency response including DC. Additionally, OCTs do not tap into the power of the energized line and require no oil insulation, thus making them inherently safer devices. On the negative side, OCTs come at a higher cost than their conventional CT counterparts at lower voltage applications (at least at the present time) and they exhibit a small additive zero-mean white noise component (typically 0.1 to 1 A rms) to the measurement that is absent from iron core CTs.

In this paper we consider specifically the adaptation of fiber optic OCTs to the problem of open phase detection (OPD), a situation currently of considerable interest to the power industry. Since detection of an open phase condition in an unloaded transformer is generally more difficult than in a loaded transformer, we largely restrict our discussion here to the description of OPD in unloaded power transformers. Several key points are made. After the OPD problem and solution architecture is described, we show the concept and advantages of using multi-stream signal processing within the OCT itself. Because of the wide dynamic range of the OCT, the same sensor can be used to detect both the magnetizing currents flowing into an unloaded power transformer as well as the currents flowing into it when it is loaded, including fault currents. Further developing the concept of multi-stream digital signal processing, we demonstrate that complex mathematical calculations can be made within the OCT electronics, the results of which can be simply communicated to an over/under current relay element for the detection of an open phase condition. This allows for programming the "fingerprint" of the magnetizing currents flowing into the high side of an unloaded power transformer into the OCT electronics. Detection of deviations from this transformer specific pre-programmed fingerprint is used to determine the presence or absence of an open phase condition for the case of an unloaded transformer. Finally, we present a few examples of the results obtained from live tests of varying types of unloaded transformers in various open phase conditions.

II. OPEN-PHASE DETECTION SYSTEM

A typical illustrative situation of an open phase scenario is described as follows. A power generation plant has certain safety equipment (e.g., cooling pumps) that must operate continuously. Normally, the safety equipment is powered by the plant itself, but in certain situations (whether in maintenance or fault situations) the plant power may not be available for this purpose. In this case, power is tapped from the grid to run the safety equipment. This power from the grid runs through a step-down transformer to the safety equipment. In the case that the power connection from the grid to the step-down transformer is unavailable, backup diesel generators are employed to power the safety equipment.

But, what happens if an open phase condition exists on the high side of the aforementioned step-down transformer? While the transformer is unconnected to any load (e.g., the safety equipment), the installed protection devices may not be able to detect a broken line feeding its high side due to the tendency of the transformer to rebalance itself through induction, and also that in many scenarios (though not all) the resulting current flows remain quite small. It may be only after the load is connected that the power is discovered to be "bad" (e.g., the transformer is powered by only two phases on the high side). Such conditions can quickly degrade the safety equipment motors. A critical purpose of the OPD system is thus to detect that the step-down transformer is not properly energized on its high side before any attempt is made to use it as a power source.

Our approach to detecting such an open phase condition is to measure the excitation currents flowing into the high side of the unloaded transformer and to compare these measurements to what magnetizing currents are "expected", that is to see if there is a fingerprint match. The OPD system must be able to detect any combination of open phases, grounded phases, and high impedance grounded phases. In order to detect an open phase condition on an unloaded transformer, the high side current sensors must be able to measure the excitation currents within an uncertainty of a few milliamps, given that the differences between the measured currents and the expected fingerprint can be as low as a few tens of milliamps (depending on the size and configuration of the transformer, as well as the nature of the open phase fault).

Figure 1 shows a block diagram of the OPD system. OCT sensing rings are placed over the bushing on each phase of the high side of the power transformer. The optical signals from each of the sensors is detected in the OCT electronics and converted to digital signals representing the individual phase currents. These currents are then processed and sent to a process bus relay via an optical Ethernet link. The relay makes the determination of the open phase condition. When an open phase condition is detected, the relay then triggers an annunciation alarm for plant operations, as well as a process bus compliant digital fault recorder, which also receives its data via Ethernet link from the OCT electronics.

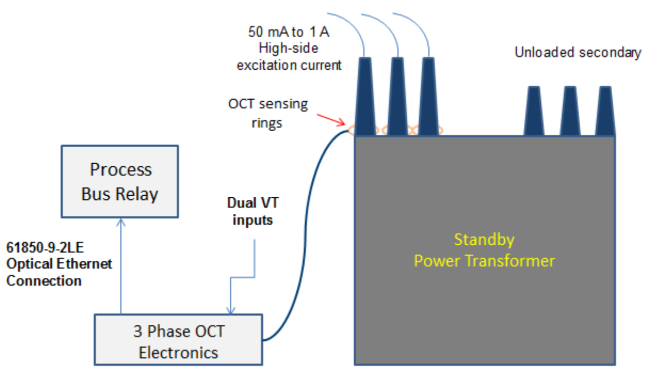

Figure 1 – Open Phase Detection System using OCTs and IEC 61850 Process Bus Relay

III. Multi-Stream Digital Signal Processing

The OCT electronics receives the raw optical signals from the sensing rings, calculates the individual phase currents and then performs a number of filtering operations as well as mathematical analyses of the relationships between the magnitudes and phase angles of the three phase currents. In the end, 12 separate real-time quantities are calculated and fed to the IEC 61850-9.2LE process bus compliant relay. These 12 quantities contain a mix of phase currents, sequence currents, and proprietary calculations. Six of these quantities are used by the programmable scheme logic (PSL) within the relay to detect an open phase condition when the transformer is loaded and the other six are used to detect the existence of an open phase condition when the transformer is unloaded.

In order to bring these 12 waveforms into the relay, we chose a process bus compliant transformer protection relay. The process bus compliant transformer protection relay allows for three independent sets of three phase currents, as well as three individual and independent neutral currents, netting 12 independent signals in total. The OCT electronics outputs these 12 waveforms within six digital streams as shown in Table 1. The three phase slots for streams 1-3 are used as well as the neutral slot for each of streams 4-6.

TABLE 1

Six IEC 61850-9.2LE Data Streams used for Open Phase Detection

Stream #	Slot 1 Data	Slot 2 Data	Slot 3 Data	Slot 4 Data
1	IA comb filtered	IB comb filtered	IC comb filtered	0
2	IA lightly filtered	IB lightly filtered	IC lightly filtered	0
3	Sequence current calculation	Sequence current calculation	Sequence current calculation	0
4	0	0	0	Proprietary calculation
5	0	0	0	Proprietary calculation
6	0	0	0	Proprietary calculation

As an aside, we mention here the good synergy that exists between the process bus communications protocol of IEC 61850 and the OCT technology. Due to the fact that the OCT has such wide dynamic range and bandwidth, a single OCT is capable of performing multiple measurement functions. However, the secondary devices, which tend to be for single functions, do not each need all the dynamic range and bandwidth of the OCT. The OCT we are using provides 29 bits of amplitude information at a rate of 333 kHz. However, the transformer relay only makes use of 18 bits of CT information arriving at a rate of 4.8 kHz (80 samples per cycle). There must therefore be a down selection of the OCT bits as well as filtering to reduce the sample rate in order to prepare the OCT data for the transformer relay. But, in general, different applications require different bit sets, as well as data rates. Metering and protection are two obvious applications requiring different current ranges and frequency responses. The OCT signal processing can be used to select both the range and frequency band of currents to be communicated to different secondary devices. This is done by separating the raw digital data within the OCT electronics into different streams for different bit selections and filtering. The OCT being used for this work has the capability of division into six separate streams, each of which can be individually scaled and filtered. For the OPD application, all six streams were found to be necessary. Thus, the OPD system presented here illustrates the full use of the OCT stream division capability.

Since the raw OCT signal contains white noise on the order of 100mA-150mA within the IEC 61850-9.2LE data rate (the OCT contains 60 fiber turns), and a noise floor of a few mA is required for OPD security on the unloaded transformer, the raw data must be significantly filtered for the case of the unloaded transformer. We also mention that it must be at least lightly filtered for the loaded transformer case.

For the unloaded case, we pass the raw data through a digital comb filter having a four second time constant. This reduces the noise by about a factor of 100, leaving a noise floor of approximately 1.5 mA. However, it is important to note that with such a narrow comb filter (± 1/8 Hz), the comb filter center frequency must be synchronized to the line frequency. This is accomplished by providing for a VT input into the OCT electronics. Though only one line frequency comb sync signal is required, the OCT electronics provides for dual VT inputs for redundancy.

IV. Test Results

The full suite of open phase conditions have been both simulated and tested on all relevant types of power transformers including core form and shell form transformers having both wye and delta high sides. It is beyond the scope of this paper to present the complete data set. However, to illustrate the function of the OPD system and the analysis of the data, we present test results here obtained from three particular cases, each for an unloaded transformer. The first is a wye-wye transformer with a single open phase, the second is a wye-delta transformer with one phase open and a second phase grounded, and the third is a delta-wye transformer with a single phase grounded.

A. Wye-Wye Core Form Transformer with Single Open Phase

Figure 2 shows a photograph of the transformer under test with the open phase located 120 meters from the transformer. The yellow arrow in Figure 2 shows the OCT ring.

Figure 2 – Open Phase Field Testing on a 238 kV Wye-Wye Transformer

Figure 3 shows the unloaded transformer "fingerprint". As can be seen, the phase B magnetization current magnitude is less than that of phases A and C, and the phase angles of A and C have been pulled towards that of B. All of these conditions are fully expected from the core form construction of the transformer. In addition, Figure 3 shows that I_B has lower magnitude than I_A and I_C and that I_A and I_C phase angles have been pulled toward I_B from the 120 degree separation of the excitation voltage. Figure 4 shows the magnetization currents flowing into the transformer with phase C open. As can be seen, the fingerprint of the phasor diagram with an open phase condition is quite different from that of a properly energized transformer. Figure 4 also shows that I_C is very small, while the phase angle difference between I_A and I_B has been reduced to 43 degrees.

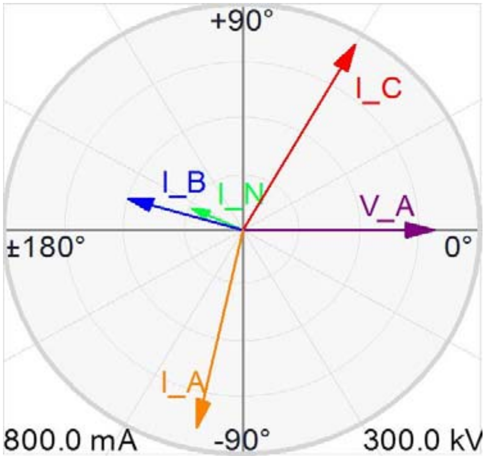

Figure 3 – The Phase Current "Fingerprint" in a Normally Excited, Unloaded Wye-Wye Transformer

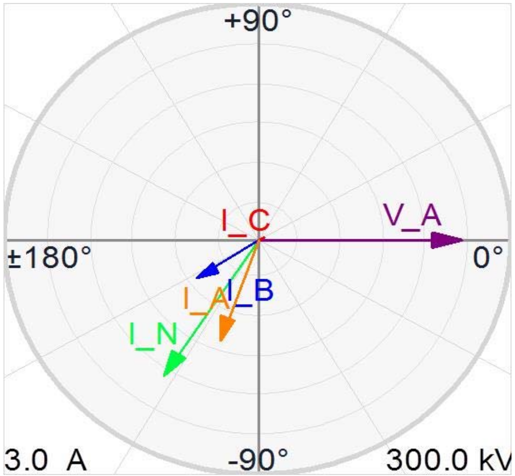

Figure 4 – Phase Currents Flowing in an Unloaded Wye-Wye Transformer with Phase C Open

It is interesting to note here that the C phase current, though very much reduced in amplitude, did not go precisely to zero when it was opened. This is explained by the fact that there is capacitive coupling between the phases over the 120 meters of line between the transformer and the opened phase. It is important here to note that for open phase conditions occurring far from the transformer, it is not sufficient to simply look for a reduced phase current to detect an open phase. A fuller treatment of the fingerprint analysis is required.

B. Wye-Delta Transformer with One Phase Open and a Second Phase Grounded

Figure 5 shows a fault recording for an unloaded wye-delta transformer when phase B was grounded and phase A was opened. The records are of the comb filtered rms phase currents, along with the three OPD evaluation signatures used to determine an open phase condition. The sequence of events for the fault is: first phase B was opened, second phase B was grounded, and third phase A was opened. The OPD annunciation occurred at time T=0 on the fault recording about 1.5 seconds after the OPD detection threshold was crossed, the delay being set by timers within the relay programmable logic.

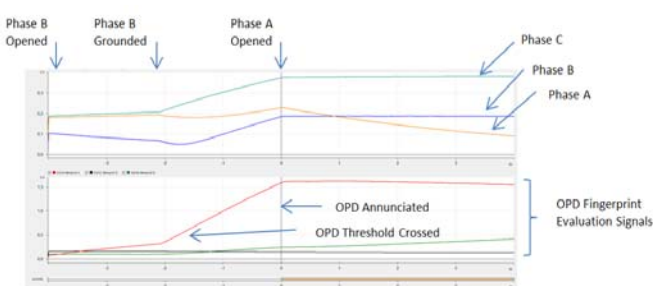

Figure 5 – Wye-Delta Unloaded Transformer Fault Record with Phase B grounded and Phase A Opened

C. Delta-Wye Transformer with Single Phase Grounded

Figure 6 shows a fault recording for an unloaded delta-wye transformer with phase C grounded. The records are of the comb filtered rms phase currents, along with the OPD evaluation signatures used to determine an open phase condition. First phase C was opened and then it was grounded. The OPD annunciation occurred at time T=0 on the fault recording about 1.5 seconds after the OPD detection threshold was crossed, the delay being set by timers within the relay programmable logic.

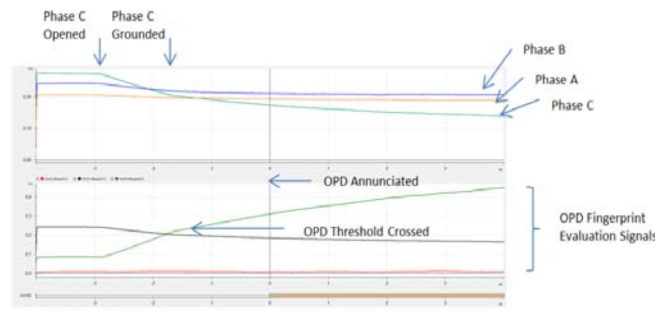

Figure 6 – Delta-Wye Unloaded Transformer Fault Record with Phase C Grounded

V. Conclusions

We have demonstrated the use of IEC 61850 process bus transformer relays together with optical CTs for the evaluation and detection of open phase conditions on the high side of a range of step-down power transformer types including wye-wye, wye-delta, and delta-wye. A set of three OCTs generates 12 waveforms which are slotted into six IEC 61850-9.2LE data streams which are in turn input into the relay programmable stream logic for the detection of open phase conditions. Representative data reproduced here shows the correct operation of the open phase detection system.

VI. Biographies

Dr. Jim Blake is the R&D Director of the Digital Instrument Transformers Group at GE Grid Solutions in Phoenix, AZ. Jim received his BSEE from UC Berkeley in 1981 and a Ph.D. in Electrical Engineering from Stanford University in 1988. After three years at Honeywell Aerospace working on the fiber optic gyroscope, Jim joined the faculty at Texas A&M University where he was an Associate Professor of Electrical Engineering. In 1999, Jim left academia to help found NxtPhase developing digital and optical current and voltage transformers. He has since stayed with the group following its transfer of ownership to Areva T&D, Alstom Grid, and GE Grid Solutions.

Eric Hadley is a Lead Electronics Engineer for the Digital Instruments Transformers group at GE Grid Solutions, LLC.
Eric has been with the DIT group in Phoenix, AZ since its founding as NxtPhase in 1999. From 1989-1999, Eric was a

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Dylan Stewart is a Senior Product Manager for the Digital Instruments Transformer group at GE Grid Solutions, LLC. Dylan received a Bachelor of Science in Computer Engineering with Distinction from the University of Alberta in 1998 and has worked for several companies in the utility and telecommunication industries. He has been with the Digital Instrument Transformers group since 2003. In 2012, Dylan was appointed as a member of the Alstom Technical Expert Community. Dylan is an active participant in developing guidelines and standards related to next generation substation equipment through his membership in the following committees: IEEE PSRC I11, IEC TC38 WG37, IEC TC57 WG10, and CIGRE A3.31.

Allen Rose is Senior Operations Manager for GE Grid Solutions, LLC. He holds a Ph.D. (1986) and M.S. (1983) in physics from the University of Arkansas, Fayetteville, and a B.S. (1981) in physics from Abilene Christian University, Abilene, TX. From 1986-87 he completed an NRC Postdoctoral Fellow with the U.S. Army's Ballistic Research Laboratory, Aberdeen Proving Ground, MD. Dr. Rose has published over 90 articles, received an R&D 100 award for the development of the optical fiber current sensor in 1991, and the NIST Bronze Medal for the development of a standard optical retarder in 1998. He was an associate editor for *Photonics Technology Letters* from 2000-2008. He is a senior member of the Optical Society of America, and a member of the IEEE Lasers & Electro-Optics Society.

Calvin Vo is a Lead Customer Application Engineer at GE Grid Solutions, LLC supporting the Protection and Control portfolio. Previously, Calvin was employed as a protection and control engineer at ComEd in Chicago as well as other test equipment and relay vendors. He has a BSEE from Illinois Institute of Technology.

Joseph Schaefer is a Principal Engineer at Florida Power & Light Company. Joe is responsible for developing and testing protective relay systems related to transmission, distribution, and distributed generation applications. Previously, Joe was employed as a protection field engineer responsible for substation and plant relay equipment from 480V to 500kV applications. Joe received his BSEE from University of Florida and joined Florida Power & Light in 1987. He is a member of IEEE.

Alan D. Baker is a Principal Engineer at Florida Power & Light Company. Alan works in Technical Services and is primarily responsible for Generation Protection and DME equipment. Previous experience includes Settings and Standards Engineering, Protection and Control Project Engineering, Nuclear Electrical Engineering, and Protection and Control Field Engineer. Alan received his BSEE from University of Florida and joined Florida Power & Light in 1981. He is a member of IEEE and holds a PE License in the state of Florida.

Michael Putt is the General Manager for Power Delivery Design and Standards group for Florida Power & Light Company. Mike's team is responsible to developing innovative Protection and Control standards for Transmission and Distribution Systems. Mike has worked been working in the field of Protection and Control for 29 years; 13 years in consulting throughout North America and 16 years for FPL. Mike has a BSEE from Pennsylvania State University, PE in Florida and Six Sigma Black belt.

Dr. Ayodele Ishola-Salawu is a Principal Engineer at Florida Power & Light Company. Prior to that, he served as an Adjunct Professor of Electrical & Electronics Engineering at Laurel College, Maryland and a research associate at Howard University Center for Energy Systems & Control. He has a PhD in Electrical Engineering from Howard University in 2006. He has over 20 years of industrial and research working experience, nine of which are in the Nuclear Power Industry. He is a Working Group member for IEEE/PES/Nuclear Power Engineering Committee (NPEC)/Sub-Committee 4 (SC-4) "Auxiliary Power." Dr. Ishola-Salawu is a founding member of the open phase analysis focus group jointly organized by the US Nuclear Power Industry and the Nuclear Energy Institute (NEI) with full support of the Institute for Nuclear Power Operations (INPO).

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