Power Hardware-in-the-Loop Testing of Zero-Sequence Current Transformers for Fire Prevention Applications

Hasan Bayat[1], Yujie Yin[1], Terrence Smith[1], Nathan Dunn[1]
Matthew Webster[2], Jesse Rorabaugh[2], and Arturo Torres[2]
[1]GE Grid Solutions
[2]Southern California Edison

Abstract— **The use of Arc Suppression Coils (ASCs) has been proposed as a means to reduce the possibility of a fire ignition by ground faults. The ASC compensates for the capacitive component of the fault current, hence resulting in a very small ground fault current, which reduces the probability of ignition from a ground fault. The reduced fault current, however, leads to a new challenge of ground fault detection and direction (reverse or forward); in other words, traditional directional elements are rendered inadequate to reliably identify faulted feeders when fault currents are small. Transient Ground Fault Detection (TGFD) is a patented algorithm that can reliably detect ground faults and identify its direction in compensated-grounded systems. Because of the small magnitude of the fault current in a compensated-grounded system, more accurate Zero-Sequence Current Transformer (ZSCT) is required for the operation of the TGFD. This study evaluates the impact of phase angle error of the ZSCT on TGFD performance in fire mitigation applications. The results of a comprehensive set of tests show satisfactory performance of the TGFD function for fire mitigation applications, i.e., very low fault currents even with an inverse impact from CT phase angle error.**

Keywords — ***Arc Suppression Coil, fire mitigation, ground fault, Petersen coil, Rapid Earth Fault Current Limiter, Transient Ground Fault Detection.***

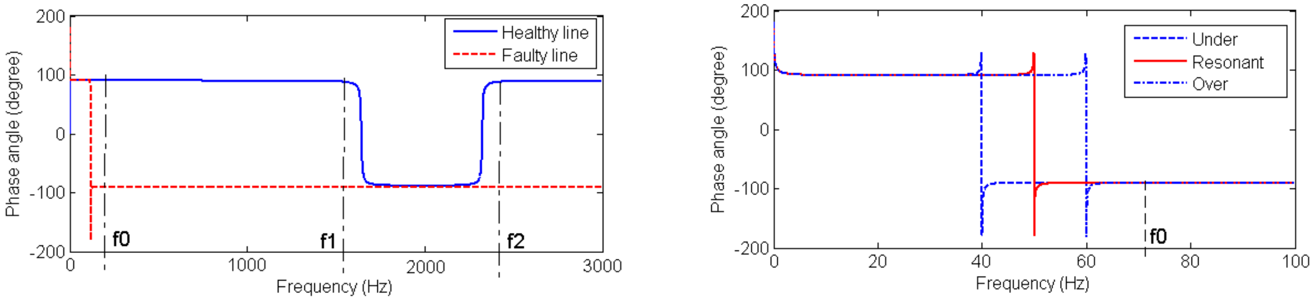
I. INTRODUCTION

Ground faults have been identified as one of the catalysts in starting a fire ignition. In ungrounded systems, the level of fault current is greatly reduced; however, the fault arc due to the charging capacitance of the system can still be large enough to start ignition. This has led to a renewed interest towards compensated-grounded systems using inductive coils. The inductive coil is referred to as either Petersen coil or Arc Suppression Coil (ASC) in the literature, which are used interchangeably in this paper. Depending on the compensation level, the ASC compensates for the capacitive component of the fault current, thereby resulting in a very small resistive fault current. In some cases, a Residual Current Compensation (RCC) module is also utilized to compensate for the resistive component of the fault current, hence further reducing the ground fault current/energy; this, in turn, reduces the probability of ignition from a ground fault in the feeder by about 90 percent [1]. The reduced fault current, however, leads to a new challenge of detecting the fault current direction (i.e., reverse or forward). Due to the small value of ground fault currents, the traditional directional elements including Wattmetric function (32N) are rendered inadequate to reliably identify the faulted feeder.

Transient Ground Fault Detection (TGFD) is a patented algorithm which identifies the direction of the fault in ungrounded, resistive-grounded, and resonant-grounded systems (with or without RCC). The TGFD operation does not require any special equipment, and it can be added to relays as a firmware upgrade. Moreover, it uses regular sampling frequency that is utilized for other protection functions/elements.

The TGFD function uses a different frequency than the power system frequency to determine the fault direction in a faulted feeder. Consequently, its dependency on the ground fault current magnitude is low and can operate for faults with very small current magnitudes. This means that the function can be applied in ungrounded, resistance grounded, and compensated-grounded systems (with arc suppression coils). The TGFD function has mainly been used for grid reliability purposes as it can prevent unnecessary interruptions caused by temporary faults. This study, however, examines the performance of the TGFD function for fire mitigation applications in compensated-grounded systems considering the phase angel and magnitude errors introduced by sensing devices, i.e. zero-sequence current transformers. The paper provides the methodology, results, and findings of testing and evaluation of GE's TGFD algorithm for application in Southern California Edison's (SCE) compensated-grounded distribution systems.

The rest of this paper is organized as follows. It will first provide an overview of the operating fundamentals of the TGFD function; some of the design considerations including Current Transformer (CT) selection criteria are also described in this section. Next, the challenges caused by the phase angle error of the ZSCT is investigated. Finally, the results of the Power Hardware-In-the-Loop (PHIL) testing for a realistic distribution substation (with two feeders) are presented to demonstrate the effectiveness of the TGFD function considering the phase angle error of the CT. A detailed model of a utility distribution system that is grounded using the ASC is created in the Real-Time Digital Simulator (RTDS) and the RTDS is interfaced with two relays where their TFGD functions are properly set. A comprehensive set of tests is conducted under various conditions (different fault resistances, fault locations, compensation level, etc.) to evaluate the impact of CT phase angle error on effectiveness of the TGFD element implemented in the relays.



(a) (b)

Figure 1- Phase-frequency response of line admittances (healthy feeder vs faulted feeder)

II. TRANSIENT GROUND FAULT DETECTION (TGFD)

The TGFD function identifies the direction of the fault in ungrounded, resistive grounded, and resonant-grounded systems [2]. The operating quantity for the TGFD function is zero-sequence current and zero-sequence voltage of the feeder at a frequency different than the power system frequencies. The frequencies of interest are 264 Hz and 220 Hz for 60 Hz and 50 Hz power systems, respectively. These frequency components are extracted and utilized to calculate transient active and reactive powers. The TGFD operation does not require any special equipment, and it is added to the relay as a firmware update. Furthermore, the sampling frequency does not need to be high and the regular sampling frequency used for other protection functions does suffice.

II.A. *TGFD Background*

The frequency that can be used to differentiate between a healthy and faulted line is not an absolute value. As shown in Figure 1, the differentiation frequency band stretches from $f_0 \approx$ 75Hz to $f_1 \approx$ 1500Hz [2]. The distinctive feature between the faulted and healthy lines is the phase angle of the zero-sequence admittance seen by the relay for the frequencies between f_0 and f_1 [3]. Figure 1(a) shows the phase-frequency response of the admittance seen by the relay in a healthy line versus that of a faulted line, while Figure 1(b) shows an enlarged portion of Figure 1(a) around phase angle inflection point of the faulted line admittance. The inflection point at which the phase angle of the faulted line admittance changes from 90˚ to -90˚ is affected by the compensation level of the Arc Suppression Coil (ASC).

Any frequency residing between f_0 and f_1 could be used to determine the fault direction. However, the following are the three main reasons behind the selection of 264Hz (for a 60-Hz system):

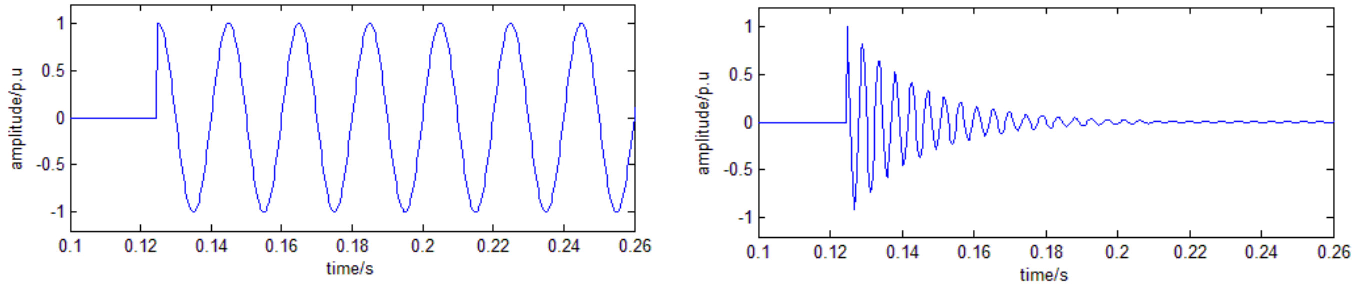
1- Accurate measurement of 264 Hz does not require extra hardware and the existing relay hardware is capable of measuring this frequency accurately.

2- Measuring 264 Hz does not require higher sampling frequency and the existing sampling rate in the relays is enough for measuring this frequency accurately.

3- This frequency is an inter-harmonic and does not exist in the power system. By using this frequency, the multiples of fundamental frequency are avoided.

The zero-sequence current and zero-sequence voltage values measured by the relay prior to Single-Line-Ground (SLG) faults are zero (for a balanced system) and small (in an unbalanced system). However, when a fault occurs, the zero-sequence current and zero-sequence voltage rise to higher values immediately or gradually depending on the fault impedance and Point On Wave (POW) at which the fault happens. The amount of increase in zero-sequence current caused by the fault affects the transient reactive power measured by the relay. Figure 2(a) shows the zero-sequence current seen by the relay before and after a SLG fault in a balanced system, where the fault happens at the peak of the phase voltage (POW = 90°), causing a sharp jump in the zero-sequence current. Figure 2(b) shows the filtered zero-sequence current at the output of 264 Hz filter. It is noted that the 264 Hz current component is transient in nature and gradually decays to zero.

The transient reactive power is calculated using the 264 Hz component of the zero-sequence current and zero-sequence voltage. If the calculated reactive power is negative and lower



(a) (b)

Figure 2- Zero-sequence current and its 220 Hz component consequent to a SLG fault

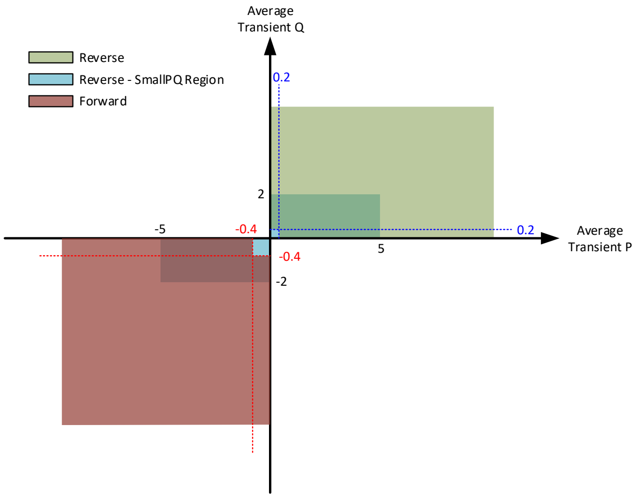


Figure 3 - Operating region of the TGFD

than the dynamically calculated threshold, then the fault is declared as Forward (feeder is faulted). Since, the magnitude of the 264 Hz current component is affected by the instance at which the fault happens as well as the fault impedance, there is a possibility that the transient reactive power (Q) measured by the relay will not be enough to cause the operation of the TGFD element, e.g., when the fault happens exactly at zero crossing of the phase voltage. In such a case, the transient active power (P) is expected to operate, leading to higher reliability of the overall function [4]. As such, when the transient Q is small, the TGFD function automatically switches to transient P. The transient P is obtained from unfiltered zero-sequence current and voltage which includes fundamental component. The operation logic based on transient P is similar to that of the transient Q. The calculated transient P is compared against dynamically calculated negative and positive thresholds. If it is lower than the negative threshold, the fault will be declared as forward while if the measured transit P is greater than the positive threshold, the fault will be classified as reverse.

II.B. *TGFD Operating Region*

TGFD operates based on two quantities calculated using the time domain zero-sequence voltage and current. The operating region of the TGFD is shown on a transient P-Q plane in Figure 3. The calculated transient P and Q need to have the right sign and value to be used for determining the fault direction. The transient P-Q is divided to three regions showing the forward fault characteristic (red), reverse fault characteristic (green), and SmallPQ (blue) region. The SmallPQ region will lead to assertion of reverse fault flag after 500 ms. Beside falling in the right region, the absolute value of transient P and Q must be higher than a dynamically calculated threshold to guarantee the security of the algorithm. As a result, the function has negative and positive pickup setpoints for transient P and Q.

II.C. *Current Transformer (CT) Selection*

The objective of this study is to investigate the effectiveness of TGFD in wildfire prevention due to power line failures while considering the measurement errors due to the CT phase angle and magnitude errors. ASC is used to limit the fault current in case of a ground fault and decrease the likelihood of an ignition.

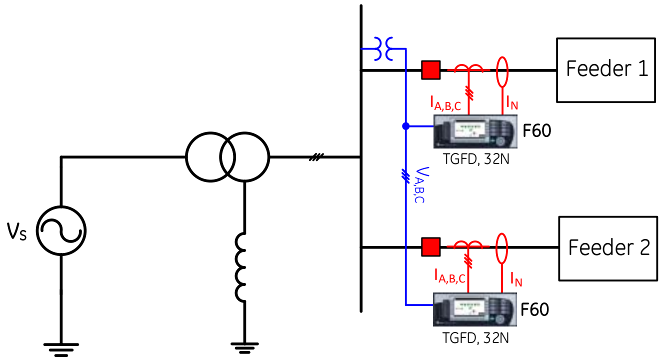


Figure 4 - Simplified SLD of the study system

In this study, the fault current of interest is 0.5A. As a result, the Current Transformer (CT) of interest must have high accuracy and be able to measure a 0.5 A resistive fault current superimposed on top of system's charging current accurately. The 0.5A fault current detection comes from SCE's requirement for fault detection in Petersen-coil-grounded systems. The testing was performed using two physical 50:5 ZSCTs.

Two CT types were considered to be used in conjunction with the TGFD in this study: Holmgren CTs and Core-Balanced CTs. Since the required CT ratio is small, the Holmgren CT will have a high circulating current at its secondary due to the load current. Secondly, there are concerns about the exact match between the CTs of Holmgren connection which may cause some spill of load current into zero-sequence current. Therefore, core-balanced zero-sequence CTs were selected for the TGFD application since it does have a small secondary current in normal operating mode of the system and is available in lower CT ratios.

III. TEST RESULTS

In this section, the results of the Power Hardware-in-the-Loop (PHIL) testing using the Real-Time Digital simulator (RTDS) are presented and discussed. Comprehensive sets of tests were executed to evaluate the impact of the ZSCT at the performance of the Transient Ground Fault Detection (TFGD) function in a compensated-grounded distribution system (using Petersen coil) under various fault scenarios. The results of a selected number of test cases are described in more detail to provide additional information on the CT impact.

III.A. *Test Setup*

A simplified Single-Line Diagram (SLD) of the system under study is shown in Figure 4 ("*study system*"). As can be seen in this figure, the study system has two feeders, namely, FEEDER1 and FEEDER2. A detailed model of the study system has been created in the RTDS. The location of the main P&C hardware devices on the feeder and the substation are indicated in Figure 4; these devices are part of the PHIL testing.

The power hardware-in-the-loop testbed was developed in the GE Digital Integration Lab (DIL); Figure 5 shows a picture of the lab test setup. In relay rack at the middle of the figure encloses the two relays. The amplifiers are located at the bottom of the figure.

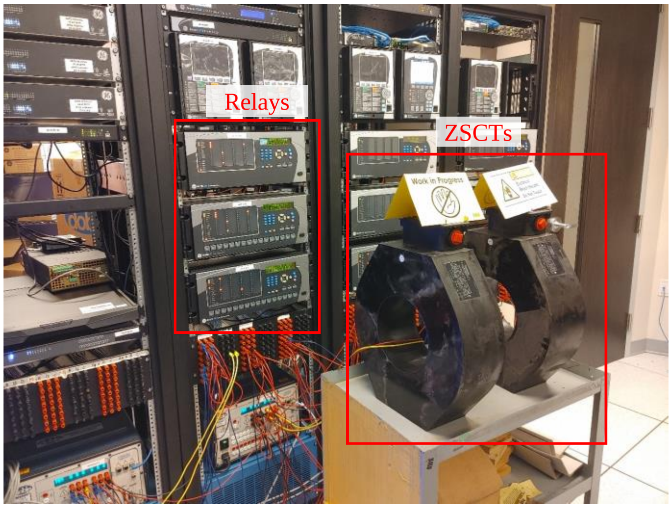


Figure 5 – CT testing setup at the GE

III.B. *Test Cases*

The test cases used for CT testing is the same test cases used for the first phase of this project to be able to compare the results directly. This section outlines the cases that have been tested to analyze the performance of the TGFD function under various transient incidents and fault scenarios. In the preparation of the test cases, various factors that can potentially impact the TGFD performance are considered; the main factors include:

- Fault location
- Fault resistance
- Point of Wave (POW)
- Grounding compensation level
- Feeder loading
- Fault type (affected phase)
- Load trip (transient)

It should be noted that the test cases are chosen in a manner that worst-case scenarios are covered, such that the total number of cases is managed. Table 1 summarizes the list of test cases that were executed for one compensation level (100%). These tests were repeated for at least two more compensation levels (Under-compensation: 92% and Over-compensation: 120%).

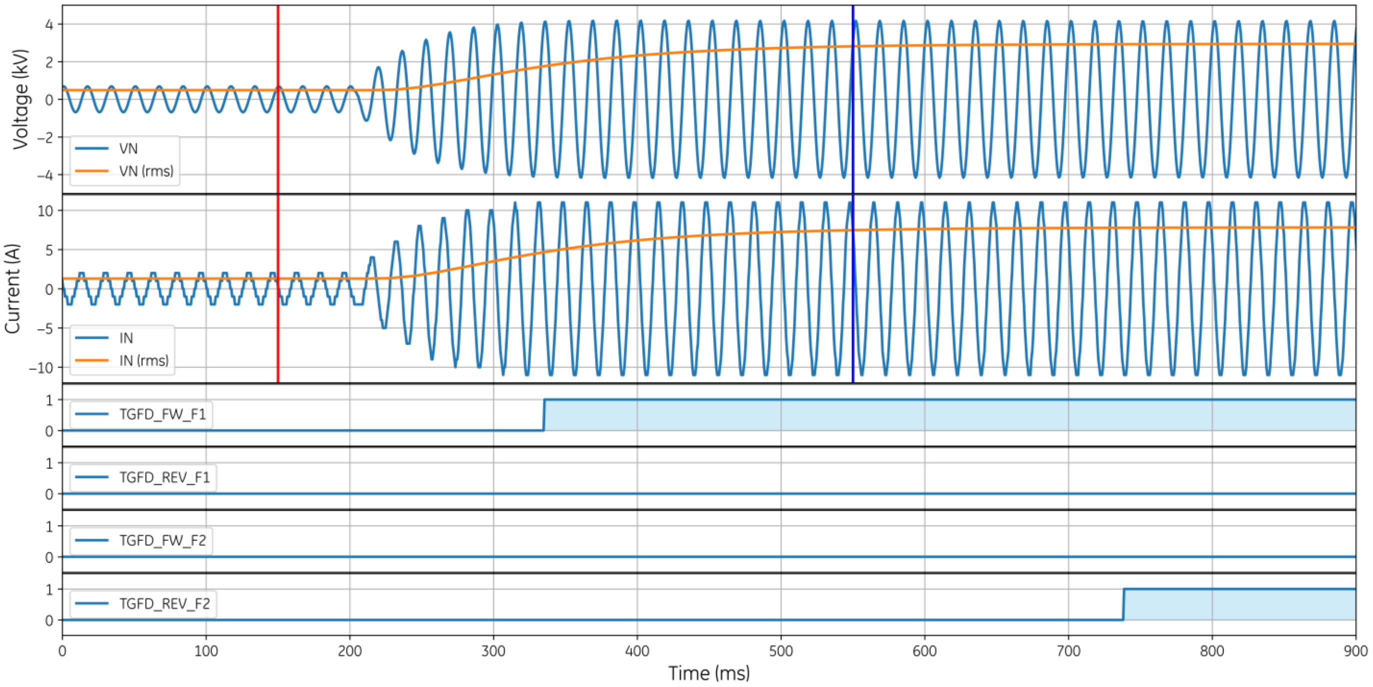
III.C. *Challenges*

The main challenge associated with using the ZSCT is the phase angle error introduced to the measured current. The datasheet of the ZSCT presents the maximum phase angle error of the CTs to be below 1°. However, the test results do not match the data provided in the manufacturer datasheet and the test results show phase angle error of almost 3°. This phase angle error is a potential mis-operation source for the TGFD algorithm for fire prevention applications since the operating quantity of the algorithm depends on the phase angle between zero-sequence current and zero-sequence voltage to determine the direction of a SLG fault. The ZSCT's phase angle error is particularly more important for high-impedance faults where the TGFD makes decision based on very small amount of transient active power.

Table 1 - List of test cases for full compensation level (100%)

Case ID	Faulted Feeder	R_f (Ohm)	Faulted Phase	POW (deg)	Feeder Loading
1001	FEEDER1	0.01	A	0	Loaded
1002	FEEDER1	0.01	A	45	Loaded
1003	FEEDER1	0.01	A	90	Loaded
1004	FEEDER1	0.01	A	135	Loaded
1005	FEEDER1	0.01	A	0	Unloaded
1006	FEEDER1	10000	A	0	Loaded
1007	FEEDER1	10000	A	45	Loaded
1008	FEEDER1	10000	A	90	Loaded
1009	FEEDER1	10000	A	135	Loaded
1010	FEEDER1	10000	A	0	Unloaded
2001	FEEDER2	0.01	A	0	Loaded
2002	FEEDER2	0.01	A	45	Loaded
2003	FEEDER2	0.01	A	90	Loaded
2004	FEEDER2	0.01	A	135	Loaded
2005	FEEDER2	0.01	A	0	Unloaded
2006	FEEDER2	10000	A	0	Loaded
2007	FEEDER2	10000	A	45	Loaded
2008	FEEDER2	10000	A	90	Loaded
2009	FEEDER2	10000	A	135	Loaded
2010	FEEDER2	10000	A	0	Unloaded
3001	SUB	0.01	A	0	Loaded
3002	SUB	0.01	A	45	Loaded
3003	SUB	0.01	A	90	Loaded
3004	SUB	0.01	A	135	Loaded
3005	SUB	0.01	A	0	Unloaded
3006	SUB	10000	A	0	Loaded
3007	SUB	10000	A	45	Loaded
3008	SUB	10000	A	90	Loaded
3009	SUB	10000	A	135	Loaded
3010	SUB	10000	A	0	Unloaded
5001	FEEDER1	0.01	B	0	Loaded
5002	FEEDER1	0.01	C	0	Loaded
5003	FEEDER1	8000	B	0	Loaded
5004	FEEDER1	7000	C	0	Loaded
5005	FEEDER2	0.01	B	0	Loaded
5006	FEEDER2	0.01	C	0	Loaded
5007	FEEDER2	8000	B	0	Loaded
5008	FEEDER2	7000	C	0	Loaded
5009	SUB	0.01	B	0	Loaded
5010	SUB	0.01	C	0	Loaded
5011	SUB	8000	B	0	Loaded
5012	SUB	7000	C	0	Loaded
5013	FEEDER1	8000	B	0	Unloaded
5014	FEEDER1	7000	C	0	Unloaded
5015	SUB	8000	B	0	Unloaded
5016	SUB	7000	C	0	Unloaded

Two mis-operations were observed for high-impedance faults at the substation during the testing. After reviewing waveforms and internal variable recordings from the feeders' relays and the RTDS, it was observed that the feeders' relays had measured negative transient P which is associated with a faulted feeder. However, examining the transient P measured at the RTDS for the same feeder revealed that the actual transient P is positive which indicates a healthy feeder. The relay has seen a different waveform compared to the waveforms generated by the RTDS and consequently it has measured different sign and magnitude for transient P. The source of the transient power mismatch between the RTDS and the relay is the phase angle error introduced by the ZSCTs. The impedance of the fault at the substation is 4000Ω on phase A and FEEDER1 relay has mis-operated while the FEEDER2 relay has operated correctly despite measuring a negative P.



(a) VN, IN, and feeder relays TGFD indications recorded by the RTDS

(b) VN and IN phase angle at red line and CT primary (P < 0)

(c) VN and IN phase angle at blue line and CT primary (P > 0)

(d) VN and IN phase angle at red line and CT secondary (P < 0)

(e) VN and IN phase angle at blue line and CT secondary (P < 0)

Figure 6 - Operating quantities of the TGFD recorded by Feeder 1 and Feeder 2 relays and zero sequence current and voltage phases measured before and after the fault

Figure 6 shows the RTDS recordings of the phase angle between the zero-sequence voltage and zero-sequence current of FEEDER1 before the inception of the fault (left side phasor diagrams) and during a high-impedance substation fault (right side phasor diagrams). Figure 6(c) and Figure 6(e) are the important parameters to look at since Figure 6(c) shows the phase angle between V_N and I_N at the primary side of the ZSCT while Figure 6(e) shows the same quantity at the secondary side of the ZSCT. According to Figure 6(c) the $\angle(VN - IN) = 88.73^o$ at ZSCT primary which means that the transient P is positive and the feeder is healthy, however the same phase angle is measured 91.56^o at ZSCT secondary in Figure 6 (e) which yields a negative transient P and indicates a faulted feeder. This discrepancy and mis-operation is introduced by the phase angle error of the ZSCT. In this example, the phase angle error is $91.56^o - 88.73^o = 2.83^o$.

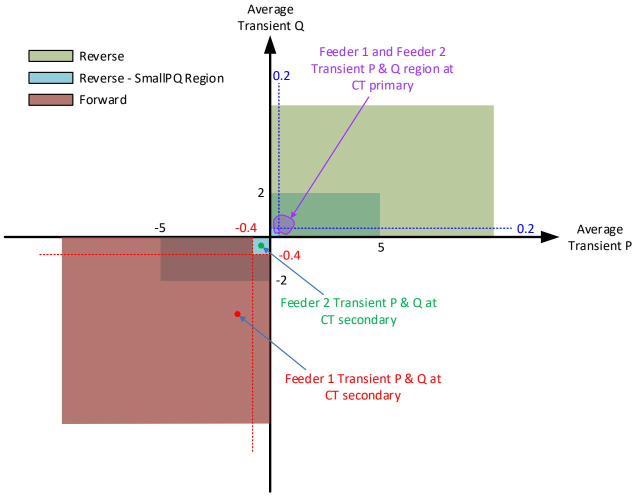


Figure 7 – Transient P and Q at the primary and secondary side of the ZSCT

Figure 7 shows the transient P and Q region for a HIF at the substation shown in Figure 4. Since the fault is in reverse direction for both feeder relay, the expectation is that both relays measure a positive transient P and Q. However, as shown in the figure, both relays have measured a negative transient P and Q. The negative P and Q measured at the secondary of the ZSCT is caused by the phase angle error of the CT. The measured transient quantities for Feeder 2 are insignificant and are corrected by the SmallPQ feature which results in correct operation of the function. However, the transit P and Q measured at Feeder 1 are larger than the absolute value of the dynamic threshold and cause a mis-operation.

Figure 8 shows the phase angle error of the ZSCT as per the datasheet. The datasheet specifies that the phase angle error of the ZSCT is limited to below 1^o, however, the testing results show 2.83^o phase angle error for this specific case. The discrepancy could be associated with test conditions or other sources of phase angle error may exist in the setup prepared for this project. Regardless of the source of the phase angle error, this error has impacts on the operation of the TGFD since this error may change the sign of the transient P leading to mis-operation of the algorithm.

III.D. *Result Analysis*

In this section, the results of a sub-set of test cases (from each compensation level) are selected to be discussed in more details. This sub-set of cases has been selected in a manner that important observations and findings are highlighted. Figure 9 is used to illustrate the transient P at the CT primary and secondary for all compensation levels since the impact of the CT error is the same in all compensation levels. The CT phase angle error shifts the measured P from first quadrant towards the third quadrant. This means that for high-impedance fault cases, the reverse faults that normally would result in positive transient P can wrongly be classified as forward fault since the measured transient P becomes negative due to the CT phase angle error.

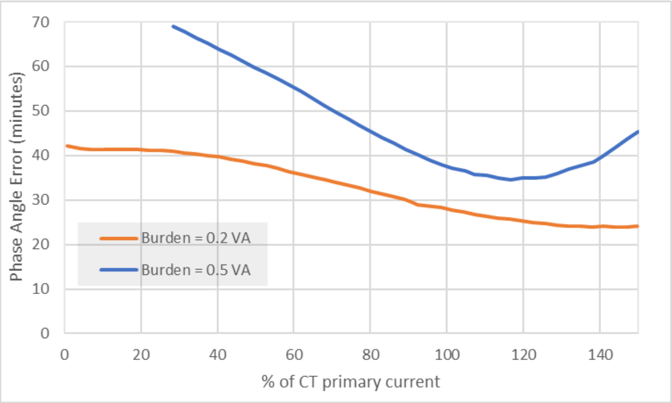


Figure 8 – Phase angle error of the ZSCT

III.D.1.*Full Compensation*

Let us consider an AG High-Impedance Fault (HIF) on Feeder 1 (Case 1007 in Table 1). Figure 9 provides the transient P and Q measured by the relays on both feeders at CT primary and secondary. The TGFD function of the relays have operated correctly for both feeders in this case. The transient active power is the basis of operation for HIF since the amount of transient reactive power is too small. As shown in Figure 9, Feeder 1 relay has measured a negative power and hence has declared a forward fault. However, the Feeder 2 relay has also measured a negative power which indicates a faulted feeder. However, this relay has measured wrong transient P in terms of the sign and magnitude but has not mis-operated because the magnitude of the transient P is not significant to reach the dynamic threshold and relay has declared a reverse fault using its SmallPQ function as elaborated in Section II.B. Phase angle error introduced by the ZSCT is the reason that Feeder 2 relay has measured a negative transient active power while it was expected to measure a positive value.

III.D.2.*Over-Compensation*

The results of a HIF on Feeder 1 with 120% compensation level are shown in Figure 9. This test case is equivalent of Case 1007 in Table 1 while the system is over-compensated. The TGFD function on both feeder relays have operated correctly.

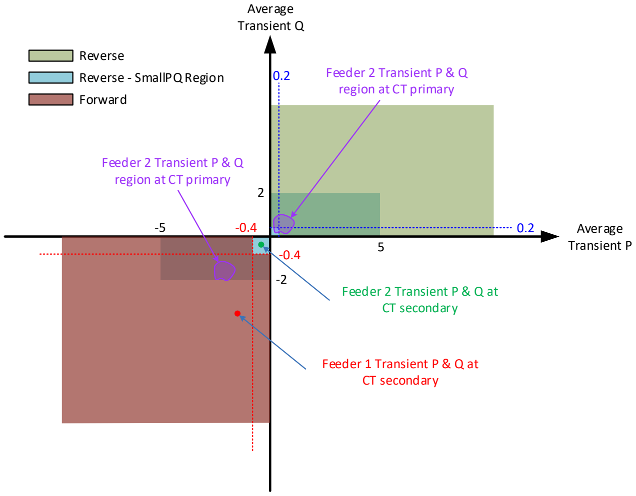


Figure 9 – Transient P and Q at the primary and secondary side of the ZSCT

Since this case is a high-impedance fault, the TGFD operates based on active power and as seen in Figure 9, the measured transient P is negative which indicates Feeder 1 is the faulted feeder. However, Figure 9 also shows that the transient power measured by Feeder 2 relay is negative while it is supposed to be positive since the Feeder 2 is a healthy feeder. As discussed earlier, this is caused by the phase angle error of the ZSCT. The magnitude of the negative P is not large enough for this case and does not cause a mis-operation but regardless, the amount and sign of the measured P is wrong.

III.D.3.*Under-Compensation*

Figure 9 also represents the results of a HIF on Feeder 1 with 92% compensation level. This test case is equivalent to Case 1007 in Table 1 while the system is under-compensated. The TGFD function on both feeder relays have operated correctly. However, Feeder 2 relay has operated correctly despite measuring wrong transient power sign. The correct operation of this relay is due to the SmallPQ feature embedded in the TGFD algorithm. The negative transient P measured by Feeder 2 relay, although wrong sign, is not significant enough to cause a mis-operation.

IV. CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the findings and observations of this study that was conducted to evaluate the impact of the phase angle error of the zero-sequence current transformers on the operation of Transient Ground Fault Detection (TGFD) function for a SCE Petersen-Coil-grounded distribution substation. Recommendations and mitigation solutions to some of the identified challenges are also discussed in this section.

The following are major findings of this study:

- The minimum fault current that the relay can detect is a function of the system characteristics (i.e., line charging current and its resistive component). The resistive component of the fault current helps with the detection of high-impedance faults (or cases with less transients, e.g., when POW = 0). In case the fault causes high transient reactive power, the resistive portion of the fault current is not used by the relay (the relay uses transient Q to define the fault direction).
- The ZSCTs introduce magnitude and phase angle errors to the measured current. The magnitude error of the ZSCT is low and does not interfere with operation of the TGFD. However, the phase angle error of the ZSCT causes some challenges.
- The phase angle error of the ZSCT causes the relays to measure wrong transient P during a reverse high-impedance fault since it reduces the phase angle between the zero-sequence voltage and zero sequence current below 90˚ during reverse high-impedance single phase to ground fault.
- Out of 138 test cases, there was two mis-operations of FEEDER1 relay’s TGFD function during high-impedance faults on the substation. This fault’s direction is reverse to feeder relays and the transient active power seen by the relay during this fault must be positive. However, due to the phase angle error of the ZSCT, the transient P was measured negative and was large enough to cause a mis-operation.

Based on the analysis of test results, the following recommendations are made for successful application of the TGFD function on SCE distribution circuits:

- The tested ZSCTs have adequate magnitude accuracy for successful deployment of the TGFD. However, their phase angle error is not suitable for high-impedance reverse faults.
- To mitigate the mis-operations for high-impedance reverse faults caused by the phase angle error of the ZSCT, one solution is to de-sensitize the setting of the TGFD.
- The new pickup setting recommended for TGFD is 0.4W instead of 0.2W. With the new setting, the relay would not mis-operate for reverse faults even if it sees a wrong sign of the P during a high-impedance reverse fault.
- The recommended setting for the TGFD was tested for the mis-operation cases which resulted in successful operation of the TGFD for the cases that mis-operated with the previous setting.

V. ACKNOWLEDGEMENT

This project was funded by Southern California Edison (SCE) through Electric Program Investment Charge (EPIC) program of the California Public Utilities Commission (CPUC).

VI. REFERENCE

[1] T. Marxsen, "Analysis of resonant earthed networks," Marxsen Consulting Pty Ltd, 2015.

[2] H. Hengxu and C. Liu, "Ground fault direction determination for medium or high voltage distribution networks". Patent EP 2 741 389 B1, 12 10 2012.

[3] K. Venkataraman, B. Kirby, H. Ha and P. Newman, "Transient Earth Fault Detection on Compensated Earthed System," 2013.

[4] "F60 Feeder Protection Sysstem Instuction Manual, Product version: 8.0x, GE publication code: 1601-0093-AJ2 (GEK-134143A)," GE Grid Solutions.

[5] *T60 Transformer Protection Sysstem Instuction Manual, Product version: 8.0x, GE publication code: 1601-0090-AJ2 (GEK-134152A),* GE Grid Solutions.

[6] T. Marxsen, "Powerline Bushfire Safety Program, REFCL Technologies Test Program – Final Report," Victoria State Governmentpp, Victoria, Australia, 2015.