CIGRE-311 **2020 CIGRE Canada Conference**
Toronto, Ontario, October 19-22, 2020

Hardware-In-the-Loop Testing of Transient Ground Fault Detection Function for Wildfire Mitigation Applications

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SUMMARY

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 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 Peterson coil or Arc Suppression Coil (ASC) in the literature, which are used interchangeably in this paper. Depending on the compensation level, the Petersen coil 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 significantly [1]. The reduced fault current, however, leads to a new challenge of detection of the fault direction (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 faulty feeder.

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

The TGFD function has mainly been used for grid reliability purposes as it can avoid unnecessary interruption caused by temporary faults. This study, however, examined the application of the TGFD function for fire mitigation applications in compensated-grounded systems. The paper first provides an overview of the power system grounding schemes followed by TGFD fundamentals. A detailed model of a realistic distribution system that is grounded using the ASC is created in the Real-Time Digital Simulator (RTDS), and the RTDS is interfaced with relays whose TFGD functions is properly set. A comparative set of tests is conducted under various conditions (different fault resistances, fault locations, compensation level, etc.) to evaluate the effectiveness of the TGFD element implemented in GE UR relays. The results show satisfactory performance of the TGFD function for fire mitigation applications, i.e., very low fault currents.

KEYWORDS

Ground fault direction, Petersen coil, Residual Current Compensator, Arc Suppression Coil, Rapid Earth Fault Current Limiter, TGFD, Wildfire mitigation

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1. INTRODUCTION

This paper provides the methodology, results, and findings of testing and evaluation of GE's Transient Ground Fault Detection (TGFD) algorithm for application in Southern California Edison's (SCE) compensated-grounded distribution systems. Compensated-grounded distribution systems using ASC have the potential to reduce the possibility of fire ignition caused by power system faults. This feature arises from the fact that the ground fault current in resonant-grounded systems will be limited to small values, which do not normally cause an ignition. However, having a small ground fault current poses another challenge to the protection system and renders conventional directional protection elements/functions ineffective.

The TGFD function uses a different frequency than the power system frequency to determine the fault direction in a feeder. Consequently, its dependency on the ground fault current magnitude is lower and can operate for faults with small current magnitudes. The TGFD function can also be applied in ungrounded, resistance grounded, and compensated-grounded systems (with ASC or Petersen coil).

In this study, a realistic two-feeder 12.47kV substation is studied to examine the performance of the TGFD function. The system under study is supplied by a Delta/Wye-G transformer bank (the Wye-G is on the low-voltage side, i.e., the 12.47kV side). In addition, the system is only grounded at the substation transformer bank via an ASC. The main goal is to evaluate the performance of the TGFD function for fire mitigation applications (i.e., fast detection and isolation of very low fault currents). Hardware-in-the Loop (HIL) testing were conducted, and the results were analyzed categorically to draw a conclusion regarding the effectiveness of the TGFD function for this application.

2. POWER SYSTEM GROUNDING

There are different types of grounding methods used in power systems. The main four grounding schemes are briefly discussed in this section.

- Solidly grounded systems are widely used in North America because of the high fault current, which makes fault detection and coordination of protective devices a straightforward task. Moreover, the overvoltage(s) caused by single-line-to-ground (SLG) faults are smaller in solidly grounded systems. Figure 1(a) shows a solidly grounded system.
- Ungrounded systems have relatively limited use since the phase-to-ground loads are not permitted in this scheme. This system also has high overvoltage in case of SLG faults. An ungrounded system is shown in Figure 1(b).
- Resistance grounded systems are divided into two groups: low-resistance grounding and high-resistance grounding. The low-resistance grounding is closer to solidly grounded systems in terms of fault current and overvoltage while the high-resistance grounded systems are closer to ungrounded systems. A resistance grounded system is shown in Figure 1(c).
- Resonant-grounded systems are common in European countries and China. However, their merits have recently drawn attention to this grounding system in other parts of the world. One feature of this grounding scheme is that it allows continuous operation of power system in the presence of a SLG fault and ensures continuity of service (i.e., enhanced reliability). It also limits the ground fault current to low values such that the possibility of fire ignition is reduced by about 90% [2], which is the main objective of this study. A resonant-grounded system is shown in Figure 1(d).

A comparison of different grounding systems based on three main criteria is provided in Table 1.

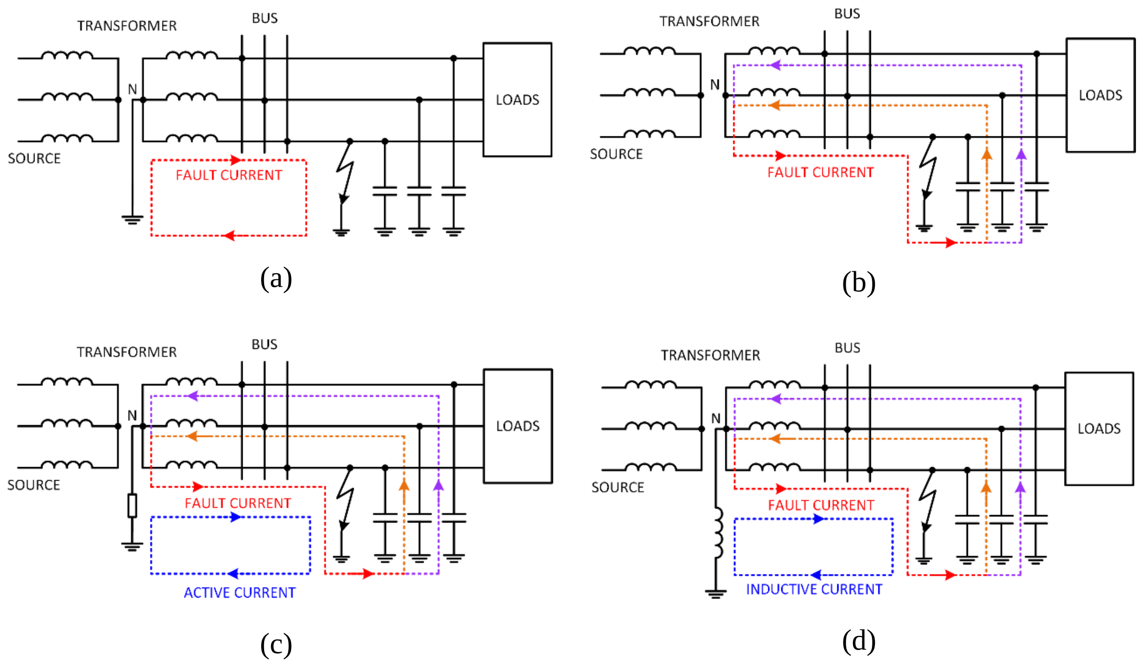


Figure 1 System Grounding Scheme: (a) Solidly grounded, (b) Ungrounded, (c) Resistance grounded, and (d) compensated (Petersen-Coil) grounded

Table 1 Grounding systems comparison

	Grounding System				
	Solidly Grounded	**Ungrounded**	**Resistance**		**Resonant Grounded**
			High	**Low**	
Transient Overvoltage	Low	High	Low	Low	Medium
Continuous operation with a SLG fault	No	Yes	Yes	No	Yes
Self-Extinguishing Ground Fault	No	Yes	Yes	No	Yes

3. PROTECTION OF COMPENSATED GROUNDED SYSTEMS

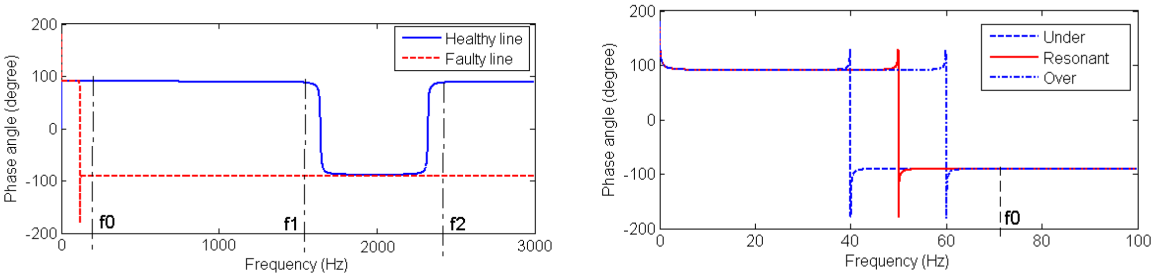
3.1. Transient Ground Fault Detection (TGFD) Function

As stated earlier, TGFD is a patented algorithm which identifies the direction of the fault in ungrounded, resistive grounded, and resonant-grounded systems [3]. The operating quantity for 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 264Hz and 220Hz for 60-Hz and 50-Hz power systems, respectively. The TGFD operation does not require any special equipment, and it is added to the relay as a firmware update. Further, the sampling frequency does not need to be high, and the regular sampling frequency used for other protection functions does suffice.

3.2. TGFD Background

The frequency that can be used to differentiate between a healthy and faulty line is not an absolute value. It is a frequency band which stretches from $f0 \approx 75$Hz to $f1 \approx 1500$Hz (see Figure 2). The distinctive feature between the faulty and healthy lines is the phase angle of the zero-sequence admittance seen by the relay for the frequencies between f0 and f1 [4]. Figure 2(a) shows the phase-frequency response of the admittance seen by the relay in a healthy line versus a faulty line, while Figure 2 (b) shows the shift in phase-frequency response for frequencies below f0.
Any frequency residing between f0 and f1 could be used to determine fault direction. However, the following are three main reasons behind the selection of 264Hz (for a 60-Hz system):

1- Accurate measurement of 264Hz does not require extra hardware and the existing GE URs hardware is capable of measuring this frequency accurately.
2- Measuring 264Hz does not require higher sampling frequency and the existing sampling rate in GE URs 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.

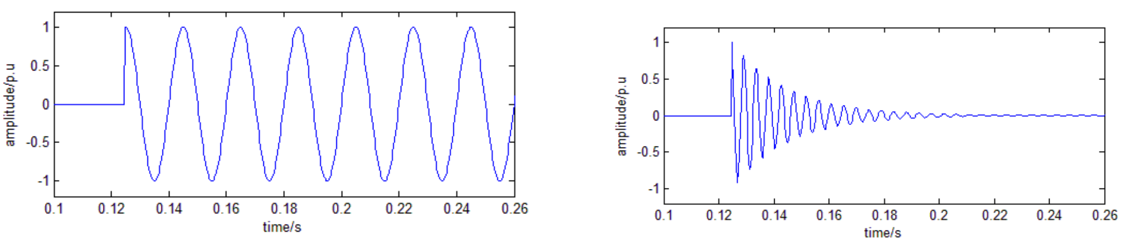


(a) (b)

Figure 2 Phase-frequency response of line admittances (healthy feeder vs fault feeder)

The zero-sequence current and zero-sequence voltage values measured by the relay prior to single-phase-to-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). The amount of increase in current caused by the fault affects the transient reactive power measured by the relay. Figure 3(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 3(b) shows the filtered zero-sequence current at the output of 264Hz filter. It is noted that the transient nature of the 264-Hz current component gradually decays to zero.

The transient reactive power is calculated from the 264Hz components of the zero-sequence current and zero-sequence voltage. If the calculated reactive power is negative and lower than the dynamically calculated threshold, then the fault is declared as Forward (feeder is faulty). 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 [5]. 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 and all other transients. The operation logic based on transient P is similar to that of the transient Q. The calculated transient P is compared against 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.



(a) (b)

Figure 3 (a) Zero-sequence current seen by the relay (fault at t~0.12s), and (b) Transient 264-Hz current caused by a SLG fault

4. TEST SETUP AND PROCEDURES

In this section, the results of the Hardware-in-the-Loop (HIL) testing using the Real-Time Digital simulator (RTDS) are presented and discussed. Comprehensive sets of tests were executed to evaluate the performance of the 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 details to provide additional information on the TGFD function capability and sensitivity.

4.1. Test Setup

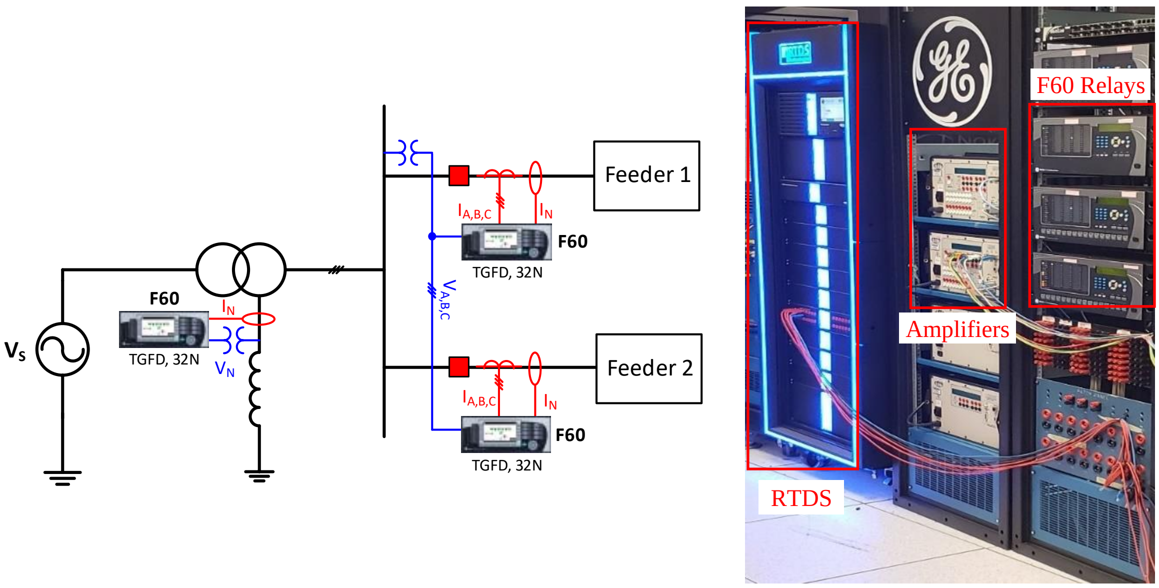
A simplified Single-Line Diagram (SLD) of the system under study is shown in Figure 4(a) ("*study system*"). As can be seen in this figure, the study system has two feeders, namely, Feeder 1 and Feeder 2. A detailed model of the study system has been created in the RTDS. The location of the physical/hardware devices (relays) on the feeder and the substation are indicated in Figure 4(a); these devices are part of the HIL testing.

The control hardware-in-the-loop testbed was developed in the GE Digital Integration Lab; Figure 4(b) shows a picture of the lab test setup. The rack on the right side of the picture encloses all three relays (F60 UR). The middle rack embeds amplifiers, while the left-side rack is the RTDS.

4.2. Test Cases

This section outlines the cases that have been tested to analyze the performance of the TGFD function under various fault scenarios and transient incidents. 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;
- Faulted phase; and
- Load trip (transient)



(a) (b)

Figure 4 (a) Simplified SLD of the study system, and (b) HIL test setup at the GE Digital Integration Lab

It should be noted that the test cases are chosen in a manner that worst-case scenarios are covered while the total number of cases is managed. Tests were carried out for full/resonant grounding, 80% compensated system (under-compensation) and 120% compensated system (over-compensation). The number of tests performed in this study is more than 140 tests.

4.3. HIL Test Results

In this section, a sub-set of test cases from the resonant-grounded scenario is selected to be discussed in more details. This sub-set of results has been selected in a manner that important observations and findings are highlighted. Table 2 provides selected test results for the full-compensation scenario (resonant grounding); similar tests were also carried out for under- and over-compensation scenarios, but dues the limited space, the results are not presented in this paper. However, an overview of all findings is presented in Section 5.

Neutral voltage is not usually zero in a typical distribution substation due to normal system imbalance. The TGFD function starts when the neutral voltage rises above a threshold. Neutral voltage in normal operating condition should be considered when setting the neutral voltage trigger of the TGFD. The threshold should be higher than the normal neutral voltage of the system and lower than the voltage expected in case of high-impedance fault.

4.3.1. Solid Fault on Feeder 1 - R_f=0.01Ω (Case ID 1001)

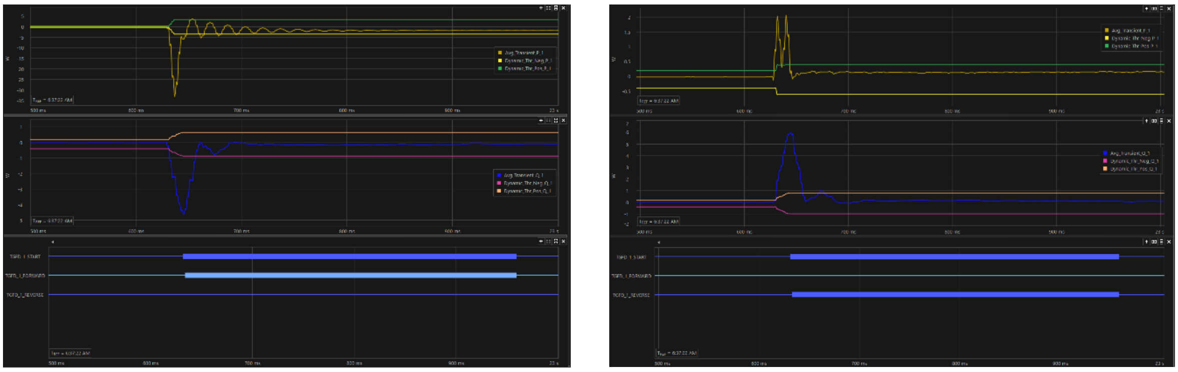
In this case, a solid single-phase-to-ground (AG) fault is simulated on Feeder 1 (POW is set at 0 to represent the result of a worst-case scenario). Upon the occurrence of the fault, the system neutral voltage increases significantly which works as the trigger for the TGFD function.

Table 2 A summary of test results for fully compensated scenario

Rapid Earth Fault Current Limiter (REFCL) - SCE - Full Compensated							
Case ID	**Faulty Feeder**	**Rf (Ohm)**	**Faulty Phase**	**POW (deg)**	**Flt Current (A_{RMS})**	**Feeder 1 TGFD (ms)**	**Feeder 2 TGFD (ms)**
1001	FEEDER 1	0	A	0	1.55	FW/11ms	RE/11ms
1002	FEEDER 1	0	A	45	1.55	FW/9ms	RE/11ms
1003	FEEDER 1	0	A	90	1.525	FW/9ms	RE/11ms
1004	FEEDER 1	0	A	135	1.54	FW/9ms	RE/10ms
1006	FEEDER 1	10,000	A	0	0.522	FW/8ms	RE/542ms
1007	FEEDER 1	10,000	A	45	0.519	FW/8ms	RE/540ms
1008	FEEDER 1	10,000	A	90	0.521	FW/76ms	RE/540ms
1009	FEEDER 1	10,000	A	135	0.519	FW/73ms	RE/54ms
2001	FEEDER 2	0	A	0	1.59	RE/10ms	FW/9ms
2002	FEEDER 2	0	A	45	1.59	RE/11ms	FW/9ms
2003	FEEDER 2	0	A	90	1.55	RE/11ms	FW/9ms
2004	FEEDER 2	0	A	135	1.58	RE/13ms	FW/11ms
2006	FEEDER 2	10,000	A	0	0.488	RE/545ms	FW/55ms
2007	FEEDER 2	10,000	A	45	0.488	RE/543ms	FW/53ms
2008	FEEDER 2	10,000	A	90	0.493	RE/545ms	FW/54ms
2009	FEEDER 2	10,000	A	135	0.492	RE/547ms	FW/57ms
5001	FEEDER 1	0	B	0	1.61	FW/11ms	RE/11ms
5002	FEEDER 1	0	C	0	1.75	FW/10ms	RE/12ms
5003	FEEDER 1	8,000	B	0	0.585	FW/55ms	RE/540ms
5004	FEEDER 1	7,000	C	0	0.69	FW/79ms	RE/55ms
5005	FEEDER 2	0	B	0	1.71	RE/11ms	FW/9ms
5006	FEEDER 2	0	C	0	1.84	RE/12ms	FW/10ms
5007	FEEDER 2	8,000	B	0	0.592	RE/542ms	FW/51ms
5008	FEEDER 2	7,000	C	0	0.701	RE/66ms	FW/62ms

FW: Forward; RE: Reverse

Figure 5(a) shows the transient real and reactive powers measured by the relay on Feeder 1 (faulty feeder). This figure also indicates different pickup and operation signals of the relay including TGFD trigger (‘TGFD_1_START’), TGFD forward operation (‘TGFD_1_FORWARD’), and TGFD reverse operation (‘TGFD_1_REVERSE’). As can be observed in this figure, subsequent to the fault, the TGFD function is triggered; further, since the fault is solid (R_f=0.01Ω), a negative reactive power is measured by the relay which causes the relay to detect a forward fault [5] correctly (in about 11ms). It is noted that, in this case, the TGFD function makes decision based on transient reactive power (transient Q) and does not switch to transient active power (transient P) mode; this is because transient Q is large enough (in magnitude) to exceed its negative threshold.



(a) (b)

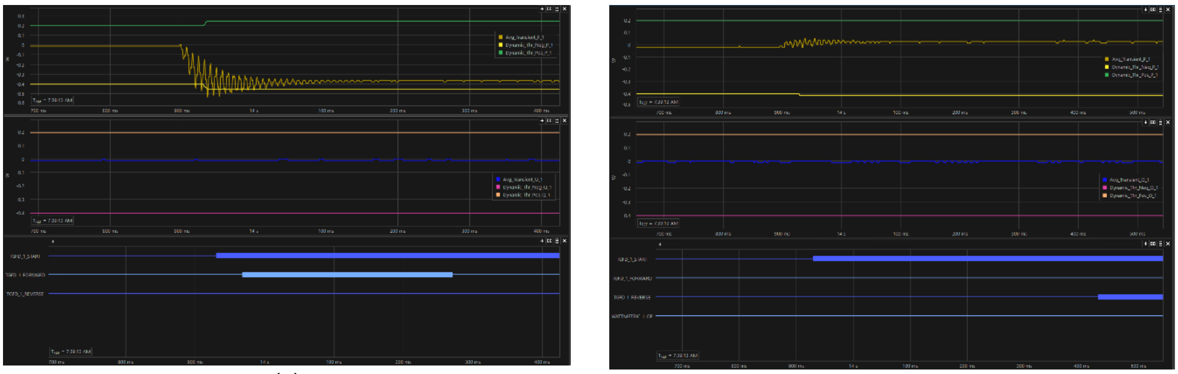
Figure 5 Low-impedance fault on Feeder 1: (a) faulty feeder and (b) healthy feeder

Figure 5(b) shows the transient P and Q measured by the relay of the healthy feeder (Feeder 2). The transient P and Q measured by this relay are positive and above their respective thresholds, indicating a healthy feeder. The decision in this test case is made base on the transient Q since its value is large and assertive.

4.3.2. High-Impedance Fault on Feeder 1 – Rf=10kΩ (Case ID 1006)

Let us consider an AG High-Impedance Fault (HIF) on Feeder 1. Figure 6(a) shows the transient P and transient Q measured by Feeder 1 relay (Faulty feeder). As can be observed in this figure, the TGFD function have operated based on transient P since the amount of transient Q is insignificant. In case of a HIF, the transient reactive power measured at 264Hz is normally small and does not reach its threshold to determine the fault direction. Therefore, the TGFD function switches to transient P and operates based on this quantity.

Figure 6(b) shows the transient P and Q recorded by the relay on Feeder 2 (Healthy feeder) while a HIF happens at the Feeder 1. As shown in the figure, both the transient active and reactive power are too small to define the fault direction. In this test case, the healthy feeder's relay uses "smallPQ" function and announces a reverse fault after 500ms. "SmallPQ" function is incorporated in the TGFD algorithm to make a decision when both transient P and Q are too small and do not reach their thresholds.



(a) (b)

Figure 6 High Impedance Fault on Feeder 1, (a) Faulty Feeder (b) Healthy Feeder

As stated before, more than 140 cases were tested in this study. A summary of results/finding is provided in Table 3. As shown in this table, the TGFD function is capable of detecting fault currents as low as $0.85A_{RMS}$ in a typical utility distribution substation. The minimum fault current detected by the TGFD function was as low as $0.485A_{RMS}$ in some test cases, depending on the compensation level, system imbalance, and point on wave.

Table 3 A summary of minimum fault current (maximum fault impedance) detected by TGFD

Affected Phase	Resonant- Grounded		92% Compensated		120% Compensated		Worst Cases	
	Z_f (kΩ)	I_f (A_{RMS})	Z_f (kΩ)	I_f (A_{RMS})	Z_f (kΩ)	I_f (A_{RMS})	Z_f (kΩ)	I_f (A_{RMS})
A	10	0.485	7.5	0.78	7.0	0.85	7.0	0.85
B	8	0.61	7.5	0.82	7.0	0.77	7.0	0.77
C	7	0.73	7.5	0.83	7.0	0.79	7.0	0.79

5. CONCLUSIONS AND RECOMMENDATIONS

This paper presented the operating principles of the Transient Ground Fault Detection (TGFD) function in compensated-grounded systems. The effectiveness of this function was verified using HIL testing on a pilot utility project. The results demonstrated satisfactory performance of the TGFD function for very low fault currents in a resonant-grounded system. The following is a list of conclusions and recommendations based on the results of this study:

- To detect low fault currents, it is important to intelligently select the CT ratio, type, and accuracy. For fire mitigation applications, lower CT ratios with the accuracy of 0.3% or better is recommended.
- 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).
- As the compensation level drifts from the full-resonance level, the neutral voltage rise will be affected. It is important to ensure the system works close to the full compensation level.
- The minimum fault current detected by the relay (maximum fault resistance) depends on the compensation level. To reach lower fault current detection, the system should be as close as possible to full-resonance compensation.
- Depending on the affected phase (A, B, or C), the TGFD may detect lower fault current. This is due to the system voltage imbalance under normal condition.
- The guaranteed minimum fault current that could be detected by the TGFD in this study system (worst-case scenario including incomplete compensation and system imbalance) is about 0.85A.

ACKNOWLEDGEMENT

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

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