A Proposed Scheme to Protect Transformer Bank and Arc Suppression Coil in Compensated-Grounded Distribution Systems

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***Abstract*— Transformer banks are usually protected by differential relay as the main protection in conjunction with timed and instantaneous overcurrent elements. Such a protection design is adequate in solidly grounded systems, which are widely utilized in North America. However, due to their advantages, some utilities have embarked on programs to utilize compensated grounding schemes in part of their distribution grid using Arc Suppression Coils (ASC), also referred to as Petersen coils. The main motivation for changing the grounding system is to (i) mitigate the possibility of fire ignition by power line failures and (ii) reduce power interruptions caused by temporary faults.**

Tuning the ASC to create resonant grounding results in reduced fault current in a distribution system which, in turn, poses challenges to operation of the transformer bank protection including differential element. Moreover, the continuity of the grounding path needs to be monitored to ensure that the grounding scheme is intact. This paper proposes a strategy for the protection of transformer banks and ASC in a compensated-grounded distribution substation

Index Terms— 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, 2].

The reduced fault current, on the other hand, leads to new challenges for transformer protection scheme. Due to the small value of ground fault current in the compensated-grounded side of the transformer bank, the differential protection (87T) cannot identify a Single Line to Ground (SLG) fault. Restricted Ground Fault (RGF) is a differential scheme with zone of protection between the phase CTs and the neutral CT. RGF is utilized to widen the coverage of the differential scheme on the compensated-grounded side of the transformer. The pickup setting of the RGF needs to be lower than the pickup of 87T so it extends the differential coverage zone. Neutral overvoltage element (59G) is also used as the back up protection which operates according to a definite time curve and takes an action if the neutral voltage remains above the pickup for a predefined time.

Another challenge in compensated-grounded systems is to ensure the continuity of the grounding path. If the neutral of the transformer in a compensated-grounded system is shorted, e.g., due to a ground fault, there will not be enough electrical signature for traditional overcurrent or differential protection to operate. If this type of fault remains undetected, the second fault will cause a very large ground fault current since the system grounding has practically become solidly grounded. An open/broken neutral conductor also falls into this non-coverage zone since it will not generate an electrical signature that can be detected by overcurrent or differential schemes. If the neutral conductor is broken and remains undetected, the sensitive grounding schemes become inactive as it can not allow the predefined ground fault current to flow. The predefined ground fault current is intended to enable the overcurrent elements to selectively identify and isolate the fault. An impedance-based algorithm is proposed in this paper to monitor continuity of the intended grounding path and detect the internal faults of the ASC.

The rest of this paper is organized as follows. Section II will first provide an overview of the study system. The protection of compensated-grounded transformer bank will also be discussed in this section, including RGF and impedance-based ASC protection logic. Section III discusses the procedure and setup for Hardware-in-the-Loop (HIL) testing of a realistic distribution substation (with two feeders); finally, the test results are presented in Section IV to evaluate the transformer bank protection scheme and the impedance-based ASC protection. The results show effective performance of the proposed scheme for various fault scenarios.

II. THE STUDY SYSTEM

This section presents the single-line diagram of the study system, the placement of the protective devices, and the protection philosophy to protect the transformer bank and the coil.

II.A. *Single Line Diagram (SLD)*

Figure 1 shows a single-line diagram of the study system which is a 12.47kV distribution substation. The substation of the study has two feeders: Feeder1 and Feeder2. The substation is supplied through a 5MVA transformer bank with 34.5kV delta-connected primary. The secondary winding of the transformer bank is Y connected and grounded through a Petersen coil in normal operating mode. The inductance of the Petersen coil is calculated according to the maximum phase charging current measured at the substation and is dynamically adjusted by the ASC controller to keep the impedance of the coil in resonance value. The X/R ratio of the Petersen coil is 33.3 and its rated current is 0.5A to 50A depending on its impedance value for the 12.47kV system.

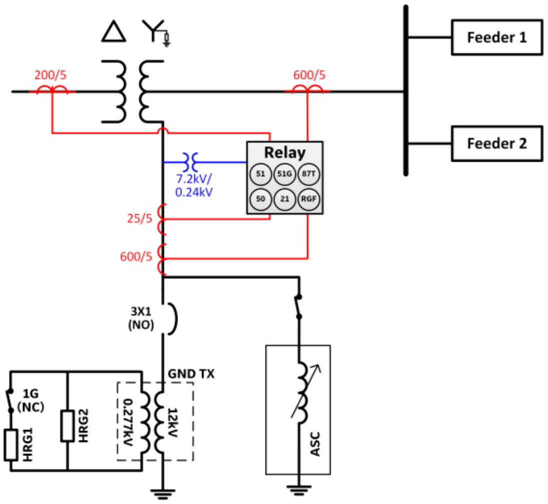


Figure 1 - SLD of the study system

Following are the parameters of the system in normal operating condition:

1- Grounding transformer: Single phase 12 kV/0.277 kV
2- HRG1 resistor: 0.0588Ω at the LV side of the grounding transformer
3- HRG2 resistor: 19.2 Ω at the LV side of the grounding transformer
4- ASC impedance: $376.2 \angle 88.3^\circ$ Ω at resonance condition and at the HV side of the grounding transformer

II.B. *Protection Philosophy*

The protection scheme for the transformer and ASC consists of differential (87T) and Restricted-Ground Fault (87RGF) protections, Impedance-based ASC protection, ground and phase timed and instantaneous overcurrent protections (50P, 51P, 50G, 51G), and neutral over-voltage protection (59G). Differential protection (87T) is intended to operate for the faults happening within the protection zone of the transformer differential with relatively large fault currents (e.g., HV-side faults). However, the fault current would be very small for SLG faults within the protection zone of the 87T at the LV side of the transformer. The RGF is mainly intended to operate for these types of faults that are within the differential protection zone and have small fault current magnitudes (i.e., LV-side faults). It should be noted that the RGF function operates only when Breaker 3X1 in Figure 1 is closed; prior to closing 3X1, the fault current is very small and does not cause the RGF to pick up.

The 51G function is intended to provide protection against the second fault in the system where the first fault have been missed by the protection system ('N-1' contingency). For example, if the neutral of the system is grounded because of a fault which is not detected by the primary protection, a second SLG fault happening in the system will cause very large fault current since the system is practically grounded with a low impedance.

The 59G function acts as backup to all the protections if the fault causes the neutral voltage to rise. This function is delayed by 5sec, i.e., if the neutral voltage remains high for more than 5sec, the 59G function would operate.

II.B.1. *Restricted Ground Fault (RGF)*

RGF is a differential protection element with protection zone between the LV phase CTs (600:5) and the neutral CT (600:5). This function is used to protect the transformer bank against the faults happening on the LV side that are within differential protection zone. For these types of faults, or those on the transformer neutral, the fault current is small (not large enough to cause the operation of the 87T function). The differential current pickup for this function is set to 0.02pu (12 A_{pri}) with the slope of 40%.

II.B.2. *Impedance-based ASC Protection*

The transformer protection relay used in this study has the built-in distance function (21) that can calculate the impedance seen by the relay for each phase of the system [3]. In order to enable the relay to calculate the grounding system impedance, the neutral current and voltage are fed to appropriate CT/VT inputs of the relay. As a result, the impedance calculation algorithm of the relay will calculate the impedance of the neutral scheme (ASC impedance). However, protection zone curves associated with the distance function (such as Mho and Quadrilateral) will not be enabled since they require a minimum of 0.8 pu of positive-sequence voltage and/or 0.025pu of positive-sequence current to operate reliably.

To address the abovementioned challenge, logic processing capability of the relay is used to implement a zone for the impedance-based protection of the ASC as described below:

- Logic Element 1 (LE1) is used to implement an impedance protection zone of 0.12pu which corresponds to a circle with 0.12*240/5 = 5.76 Ohm on the secondary of the neutral CT and VT.
- Logic Element 2 (LE2) is used to monitor the rate of change of the neutral impedance when it equals 0.3pu impedance change (corresponding to 0.3*240/5 = 14.4 ohm on the secondary of the neutral CT and VT) within 4 cycles.

The output of LE2 is used to identify the abnormal condition at the neutral of the system, while the output of LE1 in conjunction with abnormal condition flag (N_Abnormal) has been used to differentiate between a fault or an open conductor at the neural (see Figure 2). It should be noted that the discrimination between these two conditions is not possible for all scenarios, and both flags (Possible-N-Fault and Possible-N-Open) may be asserted for the same abnormal neutral condition; this is mainly caused by large CT/VT ratio. Figure 2 shows the logic used for identifying abnormal condition at the transformer neutral, which will be explained in the following paragraphs.

Since the logic for detection of abnormal conditions in the transformer neutral depends on the change of the impedance measured at the neutral, it will not provide protection for the whole grounding scheme. As elaborated in Operating Mode Section, the grounding scheme is changed during a SLG fault, which causes changes in the impedance measured by the relay. The changes on the grounding system can also change the value of the neutral current and voltage in such a way that those parameters cannot be measured by the sensing devices (CT and VT modules). As a result, the status of the Breaker 3X1 is monitored by the relay to disable the abnormal neutral logic when the breaker is ON/Closed.

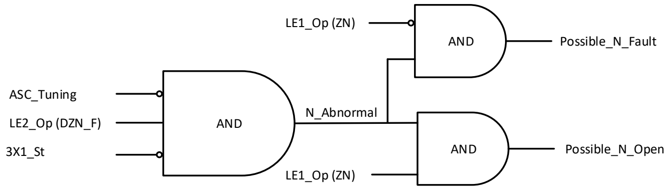


Figure 2 - Logic for detection of abnormal condition on the transformer neutral

As mentioned earlier, the impedance of the ASC is dynamically adjusted to adapt to the operating condition of the system. ASC tuning signal is the active tuning signal of the ASC. This signal is commanded by the coil controller and remain ON (asserted) when the coil controller is actively changing the impedance of the coil. This signal (ASC Tuning) is used to block the operation of the impedance-based ASC protection while the impedance of the coil is being tuned by its controller rather than an internal fault.

II.C. *Neutral Impedance Operating Range*

Table 1 shows the operating range of the neutral impedance in different switching conditions. The neutral impedance in normal operation mode corresponds to the impedance of the ASC which is tuned to resonance compensation. Since the current of the ASC can vary between 0.5A and 40A, its impedance would vary between 173.25Ω and 13.86kΩ.

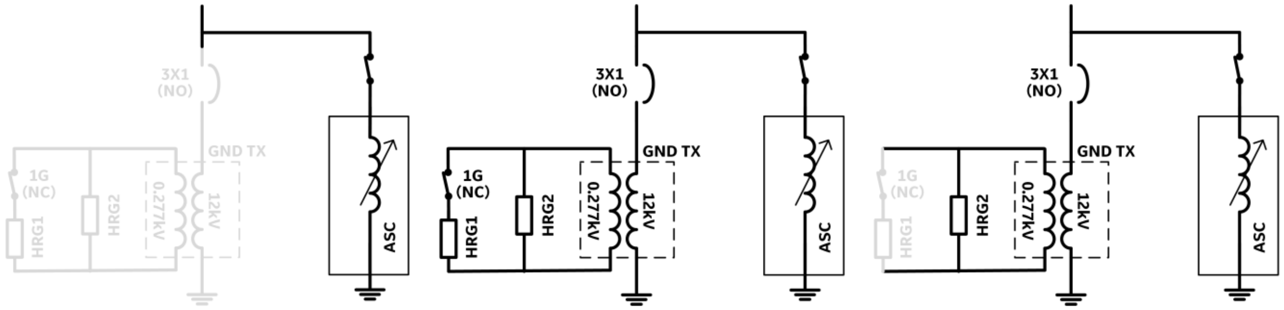
II.D. *Operating Modes*

The grounding scheme of the substation is a combination of Petersen-Coil grounding (ASC) and two High-Resistance Grounding (HRG. The system is designed in such a way that 0.5 second after the inception of a SLG fault (which causes the neutral voltage rise), Breaker 3X1 (see Figure 1) is closed changing the grounding scheme from the ASC to ASC in parallel with HRG1 and HRG2. If the fault is persistent for longer than 2 seconds, Breaker 1G is opened which changes the system grounding scheme to Petersen-Coil grounding in parallel with HRG2.

Figure 3(a) shows the grounding scheme in normal operation where the system is healthy, and the standing neutral voltage is below the pickup. In this mode of operation, the grounding is through the ASC which is tuned to resonance operation. Figure 3(b) shows the grounding scheme within 0.5s after the detection of a ground fault through 59G element. In this mode, the grounding of the system is ASC in parallel with HRG1 and HRG2. However, since the impedance of the HRG1 is much smaller than the impedance of the ASC and HRG2, the grounding system impedance is practically HRG1. The let-through current to the grounding scheme in this mode is 56A for a SLG fault which enables selectivity between the 51G of the feeder relays and the sensitive ground protection scheme. Figure 3(c) shows the grounding scheme 2 seconds after the detection of the ground fault. At this point in time, the main and backup ground fault protection has failed to identify the fault location and isolate it, consequently, the grounding of the system is switched to HRG2 in parallel with the ASC by opening Breaker 1G to limit the fault current and allow the continuity of the service. This mode is practically is ASC grounded system tuned at resonance which has higher damping compared to the normal resonance grounding. In particular, Figure 3(d) and Figure 3 (e) are not considered normal operation of the system. However, they may happen due to ground scheme switching problems and/or operator mistake and, thus, they are included in miscellaneous test cases.

Table 1 - Operating range of the neutral impedance

Mode	**Condition description**	**Normal Impedance**			**Minimum Impedance**			**Maximum Impedance**		
		Pri (Ω)	**Sec (Ω)**	**Angle (°)**	**Pri (Ω)**	**Sec (Ω)**	**Angle (°)**	**Pri (Ω)**	**Sec (Ω)**	**Angle (°)**
1	ASC only 3X1: Open	376.2	62.7	88.3	173.25	28.9	88.3	13860	2310	88.3
2	ASC || HRG1 || HRG2 376 ∠ 88.3° || 36033 || 110 3X1: Closed 1G: Closed	104.4	17.4	16.1	91.7	15.3	31.9	110.0	18.3	0.5
3	ASC || HRG2 376 ∠ 88.3° || 36033 3X1: Closed 1G: Open	376.1	62.7	87.7	173.2	28.9	88.0	12809.3	2134.9	67.5
4	HRG1 || HRG2 1G: Closed	110.0	18.3	0.0	110.0	18.3	0.0	110.0	18.3	0.0
5	HRG2 only 1G: Open	36033.0	6005.5	0.0	36033.0	6005.5	0.0	36033.0	6005.5	0.0



Mode 1: Pre-fault
$Z_{min} = 173 \angle 88°$
$Z_{max} = 13860 \angle 88°$
$Z_{Normal} = 376 \angle 88°$

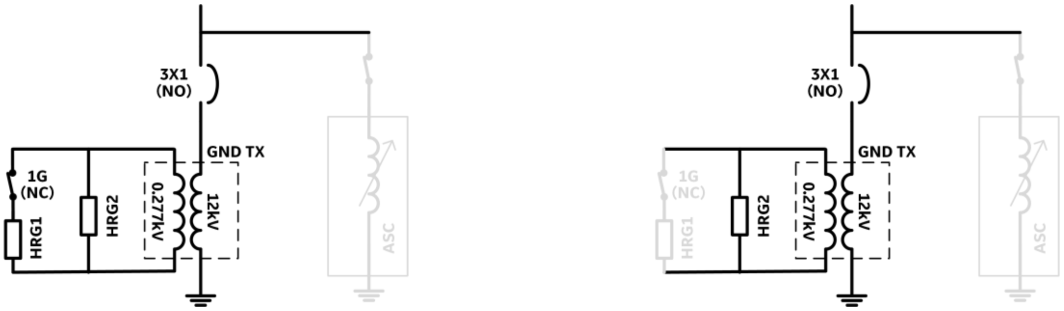
(a)

Mode 2: 0.5sec into fault
$Z_{min} = 92 \angle 32°$
$Z_{max} = 110 \angle 0.5°$
$Z_{Normal} = 104 \angle 16°$

(b)

Mode 3: 2 second into fault
$Z_{min} = 173 \angle 88°$
$Z_{max} = 12809 \angle 67°$
$Z_{Normal} = 376 \angle 88°$

(c)



Mode 4: ASC Out
$Z_{min} = 110 \angle 0°$
$Z_{max} = 110 \angle 0°$
$Z_{Normal} = 110 \angle 0°$

(d)

Mode 5: ASC Out
$Z_{min} = 36033 \angle 0°$
$Z_{max} = 36033 \angle 0°$
$Z_{Normal} = 36033 \angle 0°$

(e)

Figure 3 - Operating modes of the grounding scheme

III. HARDWARE-IN-THE-LOOP TESTING

In this section, the procedure and results of the Hardware-in-the-Loop (HIL) testing using the Real-Time Digital Simulator (RTDS) are presented and discussed. A detailed model of a utility distribution system that is grounded using a combination of ASC and two High Resistance Grounding (HRG) paths is created in the RTDS. The RTDS is then interfaced with a transformer protection relay using amplifiers. Moreover, the trip signal and internal variables of the relays are communicated to the RTDS using GOOSE messages for monitoring and capturing purpose. A comprehensive set of tests is conducted under various conditions (different fault types and locations, neutral open conductor, compensation level, etc.) to evaluate the performance of the transformer bank protection and impedance-based ASC protection. The results of a selected number of test cases are described in more details to provide additional information on the protection scheme and its effectiveness.

III.A. *Challenges*

Initially, a 25:5 neutral CT in conjunction with a 600:5 phase CT was used for the RGF. However, with this configuration, it was observed that the RGF will mis-operate for high-current single-phase-to-ground faults that occur outside the protection zone on distribution feeders. The high-current ground fault will happen if a transformer neutral is shorted (e.g., due to the first ground fault) and remains undetected. The investigations following the mis-operation revealed that the 25:5 neutral CT was saturated for the high fault current while the 600:5 phase CTs were not saturated. As a result, the neutral current measured by the 25:5 CT was very different from that measured by the 600:5 phase CT. The difference in the measured current would cause a large RGF differential current leading to a mis-operation. As a result, the 600:5 neutral CT was also used for the neutral to match the phase CTs.

III.B. *Test Setup*

A simplified Single-Line Diagram (SLD) of the system under study is shown in Figure 1 (“*study system*”). As can be seen in this figure, the study system has two grounding schemes in parallel, namely, Peterson coil scheme and sensitive ground scheme. A detailed model of the study system has been created in the RTDS.

The HIL control testbed was developed in the GE Digital Integration Lab; Figure 4 shows a picture of the lab test setup. In this figure, the rack on the right side of the picture includes the transformer differential relay. The middle rack embeds amplifiers, while the left-side rack is the RTDS.

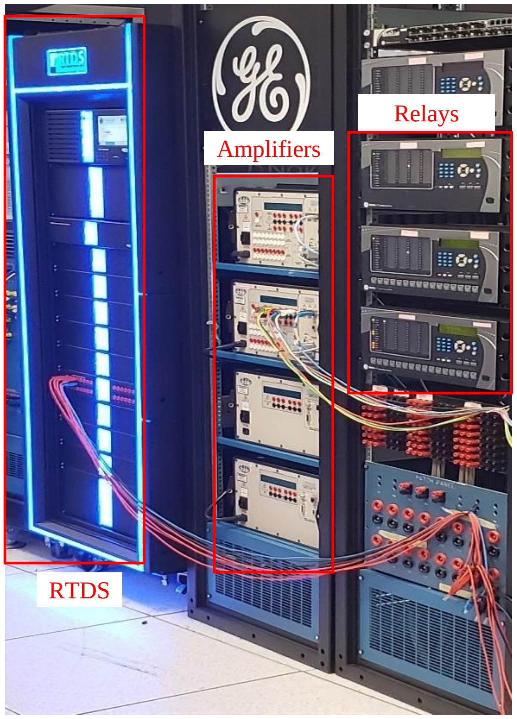


Figure 4 - Test setup

III.C. *Test Cases*

To evaluate the performance of the protection system under various operating conditions, 79 different test cases were considered for testing. The test cases were selected based on fault location, fault type, compensation level, and the operating mode of the grounding system (see Figure 3 for operating modes). Three compensation levels are considered for the tests which include under-compensation (92%), full compensation (100%), and over-compensation (120%). Two more compensation levels are also considered which correspond to the maximum and minimum reactive current that the ASC can provide during a SLG fault (the ASC is assumed to cover a current range from 0.5A to 40A).

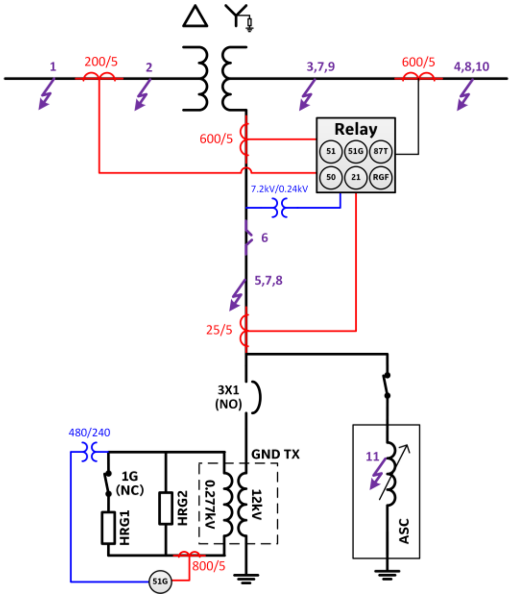


Figure 5 - Fault locations for test cases

Figure 5 shows the fault locations used to create the test cases. The numbers appearing in two locations (such as 7 and 8) represent scenarios that involve two consecutive faults at two locations. For fault number 7 and 8, the first fault happens at the neutral of the system which is assumed to be missed by the protection system. Then the second fault occurs on the secondary side inside and outside the protection zone of the 87T and RGF functions. For fault number 9 and 10, the assumption is that a single-phase-to-ground happens first and evolves to a phase-to-phase-to-ground fault.

Table 2 shows list of the test cases used for full compensation level. The same tests are also performed for under-compensated (92%) and over-compensated (120%) systems. Table 3 shows miscellaneous test cases which do not belong to specific compensation level, but the minimum and maximum current of the ASC. In Table 2 and Table 3, TGxx represents a turn to ground fault inside the ASC which shorts xx% of the coil to the ground.

Table 2 - Test cases for full compensation (100%)

Case ID	Fault Location ID	R_f (Ohm)	Fault Type
1001	1	0	AG
1002	1	0	ABG
1003	1	0	ABCG
1004	2	30	AG
1005	2	30	ABG
1006	2	30	ABCG
1007	3	3	AG
1008	3	3	ABG
1009	3	3	ABCG
1010	4	3	AG
1011	4	3	ABG
1012	4	3	ABCG
1013	5	0	NG
1014	6	0	OpenN
1015	7	3	NG->AG
1016	8	3	NG->AG
1017	9	3	AG->ABG
1018	10	0	AG->ABG
1019	11	0	TG90
1020	11	0	TG75
1021	11	0	TG50
1022	11	0	TG25
1023	11	0	TG10

Table 3 - Miscellaneous test cases

Case ID	Fault Location ID	R_f (Ohm)	Fault Type	ASC
1301	11	0	TG90	MAX
1302	11	0	TG75	MAX
1303	11	0	TG50	MAX
1304	11	0	TG25	MAX
1305	11	0	TG90	MIN
1306	11	0	TG75	MIN
1307	11	0	TG50	MIN
1308	11	0	TG25	MIN
1309	11	0	TG10	MIN
1310	11	0	TG10	MAX

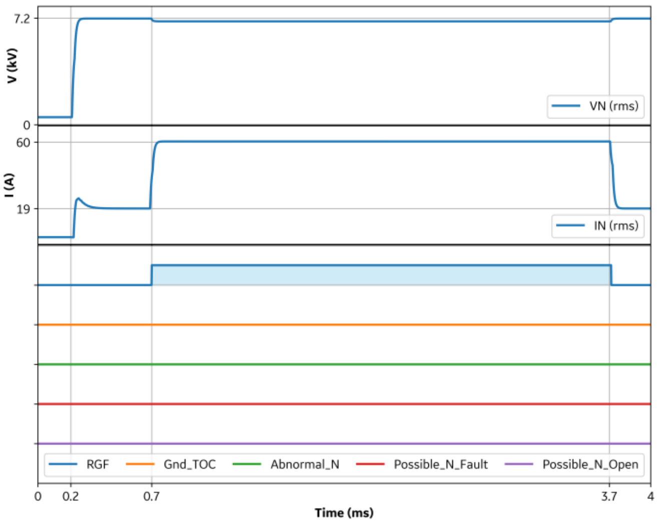


Figure 6 - RTDS data recorded for Case 1

IV. 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. Four different test results are discussed in this section, each one highlighting the performance of one of the functions tested in this project.

IV.A. *Full Compensation*

IV.A.1.*SLG Fault on LV Side Within RGF Protection Zone- R_f=3Ω (Case ID 1)*

In this case, a single-phase-to-ground (AG) fault is applied on the LV side of the transformer which falls within the 87T and RGF protection zones. The fault current is very small due to presence of the ASC in the system. As a result, neither RGF nor 87T will pick up for this fault. However, after 0.5s, when the grounding scheme switches to sensitive grounding (due to closing of Breaker 3X1); this causes the RGF function to operate. Figure 6 shows the recorded operating signals from the relay for this case.

IV.A.2.*AS Turn-to-Ground (TG) Fault (Case ID 2)*

In this case, an internal turn-to-ground (TG) fault is simulated at the ASC winding. The fault bypasses 25% of the ASC winding which causes a 25% change in the impedance measured by the relay. The impedance change causes the impedance-based logic to assert the Abnormal_N variable/trip. Then, in conjunction with FxE1, it declares this abnormal condition as a fault at the neutral. This case is an example of the condition where the impedance-based protection logic can differentiate between a fault and a broken conductor. Figure 7 shows the test results for this scenario from RTDS recordings.

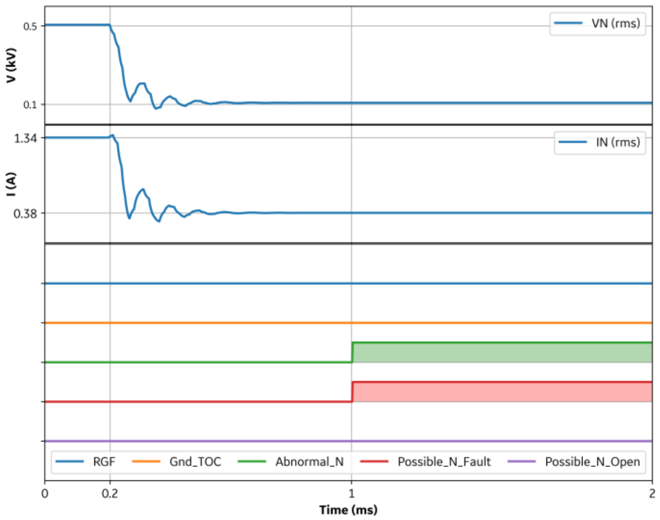


Figure 7 - RTDS data recorded for Case 2

IV.B. *Over-Compensation*

This section focuses on scenarios where the reactive current of the Petersen Coil during the fault is larger than the line charging/capacitive current (i.e., the Petersen Coil is larger than its resonant value[1]). For the purpose of this study, it is assumed that the Petersen Coil is 20% larger than its resonant value, which is a conservative assumption to test worst-case scenarios.

IV.B.1.*Open Conductor on System Neutral (Case ID 3)*

For this test case, an open phase/conductor is simulated at the neutral of the system. As a result of the open conductor, the neutral voltage and current drop to zero, and the relay loses the measurement points to make any decision. However, the impedance-based ASC protection logic is expected to operate when it detects a change in the neutral impedance. Figure 8 shows the test results for this scenario from RTDS recordings. It can be observed that the impedance-based logic asserts the Abnormal_N variable/trip; however, it cannot distinguish a broken conductor condition from a neutral fault condition.

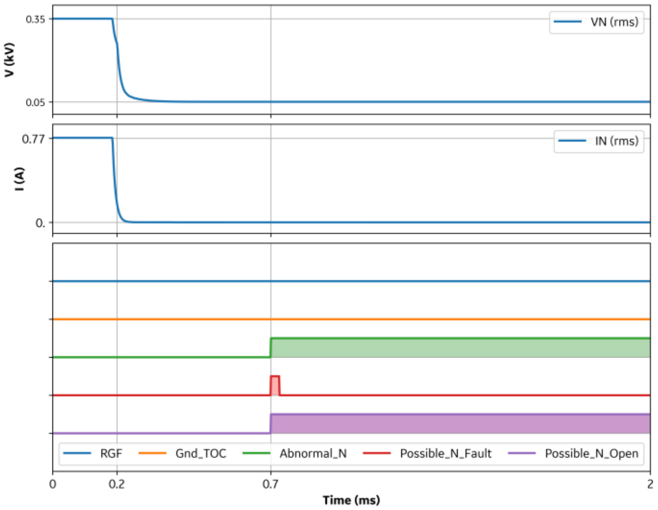


Figure 8 - RTDS data recorded for Case 3

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[1] 'Resonant Value' of the Petersen coil refers to it value under full compensation scenario, i.e., when the reactive current of the Petersen coil is almost equal (in magnitude) to the charging current of the substation.

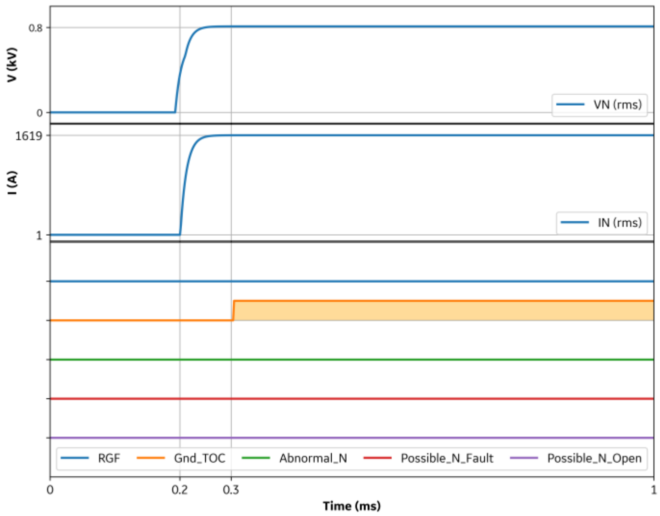

Figure 9 - RTDS data recorded for Case 4

IV.B.2. *Second Fault on the LV Side Outside of 87T and RGF Protection Zones (Case ID 4)*

In this case, a short-circuit fault is simulated at the neutral of the system, and the assumption is that the protection system fails to detect/isolate this incident. As a result, the system becomes solidly grounded after the first fault, and the second fault would cause a large fault current. It is expected that 51G function operates for this condition since the main protection has failed to detect the first fault (51G would operate as a backup for the main protection). Figure 9 shows the test results for this scenario from RTDS recordings.

IV.C. *Under-Compensation*

This section focuses on scenarios where the reactive current of the Petersen Coil during the fault is smaller than substation charging/capacitive current (i.e., the Petersen Coil is smaller than its resonant value). The Petersen coil will have an automatic tuning device which will ensure the system is under resonant compensation at all times. However, to account for the cases where the speed of coil adjustment is slower than the change happing in the charging current of the system, we have tested under-compensated case. For the purpose of this study, it is assumed that the Petersen Coil is 8% smaller than its resonant value.

IV.C.1. *Solid Fault on System Neutral - $R_f=0.01\Omega$ (Case ID 5)*

This case includes a solid short-circuit fault on the neutral of the transformer bank. The impedance-based method is expected to operate for this case. As shown in the Figure 10, the protection logic declares abnormal neutral condition. However, it does not distinguish the fault from a broken conductor.

V. CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the findings and observations of this study that was conducted to evaluate the performance of a proposed scheme for the protection of the transformer bank and the ASC in a distribution substation with hybrid grounding scheme. Recommendations and mitigation solutions to some of the identified challenges are also discussed.

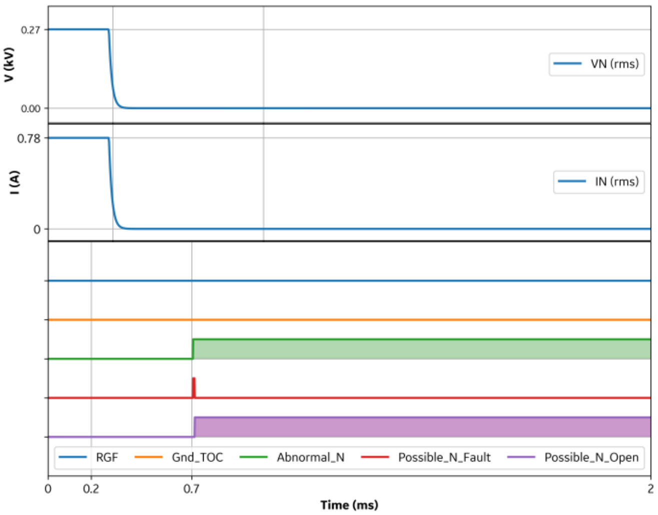

Figure 10 - RTDS data recorded for Case 5

The following are major findings of the study:

- The protection scheme operated properly for all test cases.
- It is important that the CTs that are used for the RGF protection function have similar characteristics (same ratio and saturation curves). If the CTs do not match properly, the RGF may mis-operate for faults happening outside its protection zone.
- The 87T function is not able to protect the transformer against the SLG faults on the LV side of the transformer. This is mainly because the SLG fault currents are too small in the presence of the ASC.
- For internal SLG faults on the LV side of the transformer, the RGF function detects the faults after switching the grounding scheme to sensitive grounding which causes 56A neutral current. Before switching to sensitive grounding, the fault current is too small to cause the RGF operation.
- The impedance-based ASC logic operates satisfactorily in declaring abnormal neutral conditions. However, it does not always reliably distinguish a broken conductor from a fault at the neutral of the transformer bank. One of the main reasons is that the low neutral voltage/current cannot be accurately sensed by sensing devices such as CT and VT. Based on the test results, the turn-to-ground faults that short less than 25% of the ASC winding cannot be detected.

Based on the analysis of test results, the following recommendations are made for successful application of the protection scheme for Petersen-coil grounded systems in SCE distribution circuits:

- The CTs used for RGF need to have the same ratio
- The sensitive grounding scheme should allow enough fault current for RGF pickup
- A lower neutral VT ratio can enhance the protection coverage for various ASC short-circuit faults.

VI. 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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