Case Study: How CT Saturation Due to Incorrect Point-on-Wave Switching Affects Shunt Reactor Differential Protection

Fabio Bassi and Gianluca Ramundo
Terna Rete Italia S.p.A.

Andrea Di Tomasso, Yusuf Zafer Korkmaz, and Marcos Donolo
Schweitzer Engineering Laboratories, Inc.

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***Abstract*—In this paper, we examine undesired operations (UOs) of differential elements that protect shunt reactors installed on high-voltage and extra-high-voltage transmission lines. In particular, we study UOs that occur because of a mismatch between the current transformers (CTs) and CT burden, a consequence of energizing shunt reactors away from the voltage peak.**

Our goal is to help the industry and system operators to quickly identify the problem and to list techniques to minimize or avoid the problem. We present field events and point to several identifiable characteristics of these UOs. We also present data captured during field tests that show the behavior of the system from energization to steady state.

To verify that all the relevant mechanisms were accounted for, we model the power system and CTs and confirm that the model matches the field data. We use this model to show the sensitivity of the system to CT mismatch.

Finally, we review the trade-offs of different techniques that can be used to avoid this type of UO.

I. Introduction

Lightly loaded high-voltage (HV) and extra-high-voltage (EHV) transmission lines generate reactive power that must be absorbed by the transmission system to keep the system voltage within safe operational limits. To compensate for this capacitive reactive power, the industry employs several methods, including running generators with synchronous condensers, applying static volt-ampere reactive (VAR) compensators, and using shunt reactors. With inverter-based generation accounting for an increasing share of the generation mix, there are fewer rotating generators that can regulate system voltage by absorbing reactive power when necessary. Therefore, shunt reactors with switching schemes are often connected to busbars at EHV substations or to transmission line ends.

The shunt reactor circuit breaker switching is often managed by a point-on-wave (POW) switching device, with the purpose of reducing inrush current during the switching operation to preserve the shunt reactor and to reduce circuit breaker stresses. Because of equipment aging and ambient condition changes, breaker operating times can drift from the values initially measured during the commissioning of the POW switching device. Also, without periodic tests, any adaptive function in a POW switching device might deviate unnoticed, resulting in breaker poles switching at suboptimal voltage angles. In such cases, the resulting unipolar characteristic of inrush current causes an increase of flux inside the current transformers (CTs) used for protection. Depending on conditions such as switching angle and initial remanence, the flux in the core can reach a high value and cause asymmetric saturation of the CTs used for reactor differential protection. If the CTs have different magnetic characteristics or different secondary winding and wiring impedances, the level of saturation can differ between the two CTs. Because of the unpredictable nature of the drift of the POW switching scheme, the consequence of its incorrect operation might not be observed immediately after most switching operations.

In this case study, our practice- and experience-based solution, pending a detailed technical response, was to insert the shunt reactors with the tap changer positioned for the minimum reactive power compensation. This solution reduced the likelihood of the event occurring, and the event has not occurred again since the solution implementation. As always, an experience-based solution such as this should be later replaced by rules based on field investigations and checks.

II. Protection and Control System Description

The system discussed in this case study is composed of three single-phase reactors connected to a 380 kV busbar. The circuit breaker has a POW device that governs the circuit breaker switching operations for each pole independently. The protection scheme in Fig. 1 uses two different relays in a main-and-backup configuration. The main protective relay uses a percentage current differential scheme that can detect both phase-to-phase and phase-to-ground faults. The backup protective relay employs two maximum phase overcurrent functions to detect phase-to-phase faults: one that uses the bus-side CTs, and another that uses the ground-side CTs.

This relay also uses two residual ground overcurrent functions to detect ground faults, again with one using the bus-side CTs and the other using the ground-side CTs. The residual ground overcurrent element that uses the ground-side CTs can detect ground faults in the portions of the reactor windings close to the star point, because a fault in this area creates a large amount of circulating current in those portions of the windings, resembling the operation of an autotransformer with its secondary short-circuited.

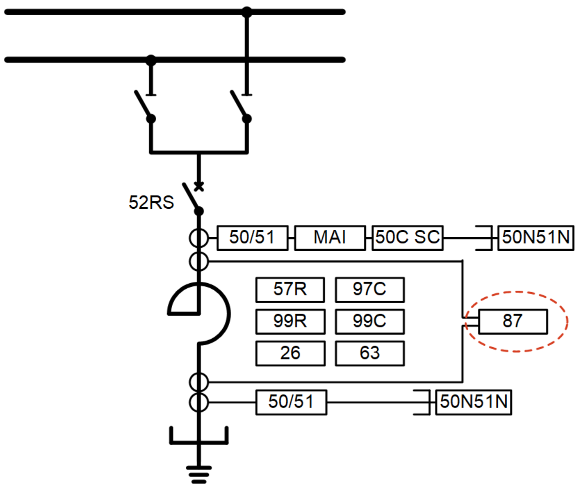

Fig. 1. Shunt reactor protection scheme.

The protection devices are located out in the switchyard in a control house in front of the bay. Fig. 2 shows the ground-side and bus-side CTs. Ideally, a differential protection zone should be composed of similar CTs.

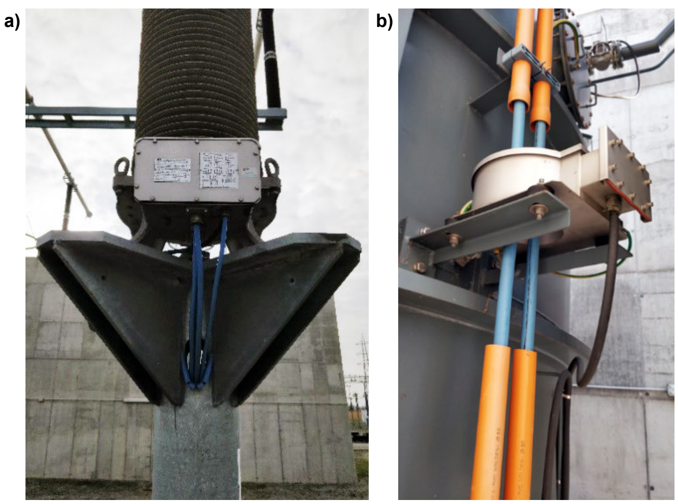

Fig. 2. a) Bus-side and b) ground-side CTs.

III. Percentage Differential Element

Differential protection operates on the sum of currents entering the protected zone. This sum, called *differential current* or *operating current*, is proportional to the fault current for internal faults and approaches zero for any other operating condition.

This study includes protective relays that have three independent phase differential elements. Each differential element operates based on the phase currents of the bus and ground sides of the shunt reactor. Fig. 3 shows the current connections of one of these protective relays. The red dashed line shows the protected zones of each differential element.

While an internal fault is the only condition that leads to valid operating currents in the primary system, spurious operating currents in the secondary circuit can result when the bus-side and ground-side CTs respond differently for the same through current.

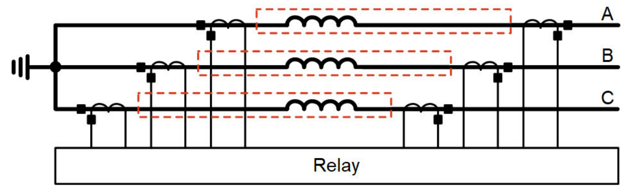

Fig. 3. Current measurements used by the differential element.

CT and relay measurement errors are the source of these spurious operating currents. To address the issue, the solution uses percentage differential elements that define a restraining current proportional to the through current and assert if the operating current is greater than a minimum pickup threshold and also greater than a percentage of the restraining current, as shown in (1).

$$\left(I_{OP} > O87PU\right) \text{ AND } \left(I_{OP} > SLP \bullet I_{RT}\right) \qquad (1)$$

where:

I_{OP} is the operating current.

I_{RT} is the restraining current.

O87PU is the minimum pickup threshold.

SLP is a scaling factor.

These two conditions determine the operating characteristic shown in Fig. 4.

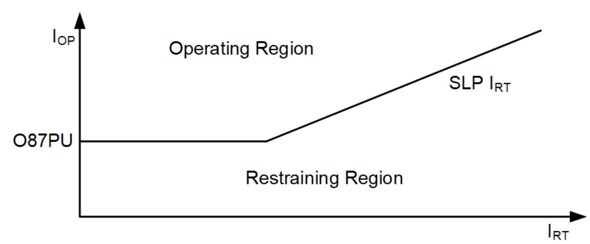

Fig. 4. Differential element operating characteristic.

For further details, see [1] and [2].

IV. Detailed Event Analysis

This section focuses on a specific UO, and the field events and simulations that we performed to explain the UO. The nominal data of the shunt reactor are as follows:

- Nominal power = 258 MVAR.
- Nominal voltage (Vn) = 400 kV.
- Nominal current (In) = 372.4 A.

CTs installed on the ground side and bus side are very different: usually the ground-side installation is a toroidal CT that the manufacturer supplies along with the reactor, while the bus-side installation is a typical CT used for a transmission line or a power transformer (see Fig. 2). They can have very different features, such as different magnetizing curves or internal resistance.

For this study, we computed the CT burden and the burden mismatch percentage for CTs in the same phase based on the estimated distances to each of the CTs. These data are summarized in Table I.

A. *Analysis of the UO*

Fig. 5 shows the unfiltered currents corresponding to a B-phase differential trip. The vertical dashed line in the figure represents the pickup time and phase.

A hallmark characteristic of this type of UO is a large, slowly decaying dc component in the unfiltered currents. Such a slowly decaying dc component is consistent with the large X/R ratio expected on a shunt reactor. We observed that the dc component most often appeared in all three phases, but sometimes it appeared in only two of them, depending on the switching angles. This observation pointed to a bias affecting all phases in the POW closing device. Aside from the dc offset present in the currents, we found that no other distortion was visible in the unfiltered current signals, meaning that there was no harmonic distortion. For this to happen, the primary current must be harmonic-free and the CT must introduce no harmonics. The primary current was harmonic-free because most shunt reactors for HV and EHV systems are constructed with an air core or include an air gap [3], as was the case in this instance.

CTs are known for introducing harmonic distortion while under saturation. However, in protection-class CTs with no intentional air gap, harmonic distortion still appears for currents well above the nominal rating and is not as much a consequence of dc offset for currents below nominal—this can be verified experimentally [4] or by using standard CT models [2] [5].

Although the differential element in the B-phase operated in this event, the dc currents in the C-phase are marginally greater, making conditions for C-phase CTs less favorable than conditions for B-phase CTs. Even without the complete event information, we can explain the B-phase tripping instead of the C-phase as a combination of the following:

- Favorable initial residual flux in C-phase CTs.
- A later C-phase close time (as many as several cycles later than the B-phase).
- Better-matched C-phase CTs and CT burdens.

Fig. 6 shows the time evolution of the operate and restraint currents. In this event, the differential element operated at 0.106 seconds, immediately after the CT on the ground side of the reactor stopped reproducing the primary current dc component.

Fig. 7 shows the B-phase operate versus restraint current diagram, including the percentage differential characteristic with a slope of 15 percent. A more secure slope of 30 percent would have prevented this UO with a good security margin.

TABLE I
ESTIMATED CT BURDEN MISMATCH FOR EACH PHASE

CT	Lead Loop Length (meters)	Approximate Loop Resistance (ohms)	CT Resistance (ohms)	Approximate Total Secondary Resistance (ohms)	Burden Mismatch
B-phase ground side	120	0.2412	0.2	0.4412	57%
B-phase bus side	40	0.0804	0.1	0.1804	
C-phase ground side	100	0.2010	0.2	0.4010	54%
C-phase bus side	30	0.0603	0.1	0.1603	
A-phase ground side	80	0.1608	0.2	0.3608	44%
A-phase bus side	25	0.0503	0.1	0.1503	

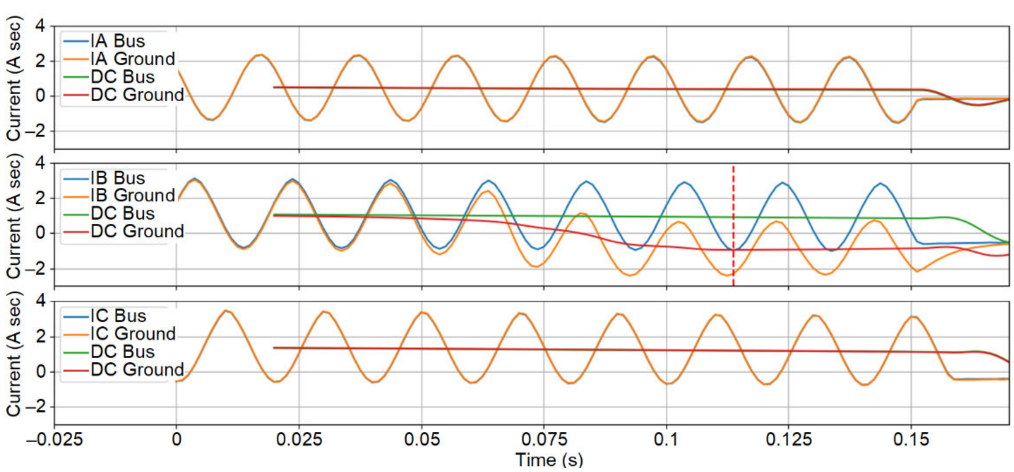

Fig. 5. UO caused by B-phase differential currents.

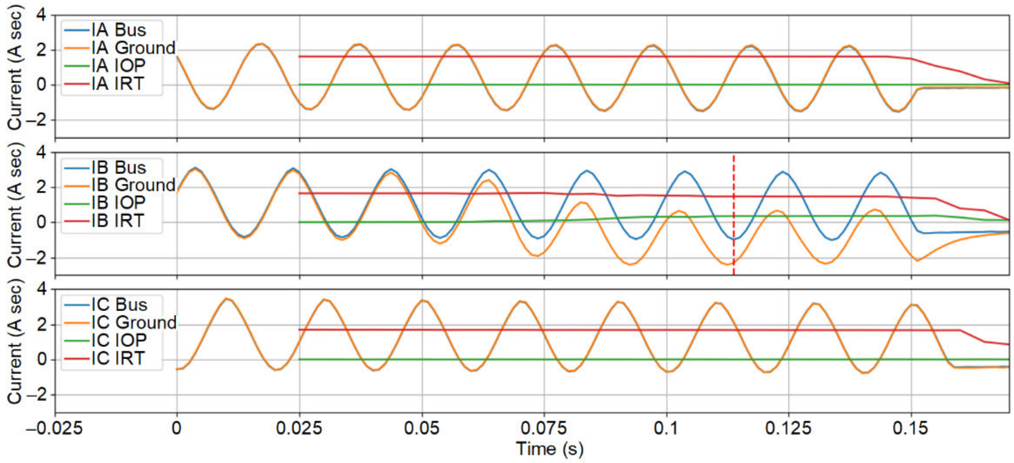

Fig. 6. Operate and restraint currents associated with the event.

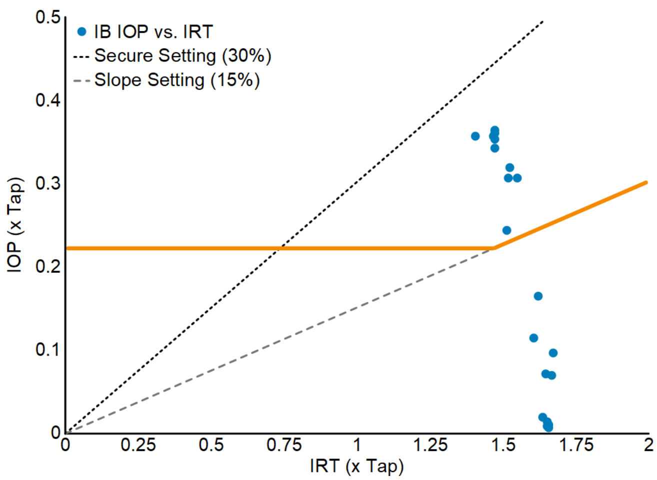

Fig. 7. The operate current goes above the slope setting of 15 percent but remains below a more secure slope setting of 30 percent.

B. Field Tests

Oscillography event reports associated with the UO in the previous section do not include the instant in which the reactor was energized. This is because the time between energization and trip can be seconds long, and most event reports are configured to capture only a few cycles of pre-event data. Consequently, in this installation, it was not possible to determine the shunt reactor energization phase angle or the total time between the energization of a particular phase and when saturation was detected in it.

We conducted field tests to observe the behavior of the system from energization to trip. Fig. 8 and Fig. 9 present data from one such field test where the B-phase behavior closely matches the behavior observed in the UO from Subsection A.

In this field test, the B-phase differential element would have tripped the reactor at 0.835 seconds, but the trip coil was disconnected to capture the data after the trip time. As shown in Fig. 10, the operate current reaches 0.3, which is slightly lower than what was measured during the UO but enough to operate the differential element at a restraint current of 1.5.

C. Model Performance

The field tests provided a more complete picture of the energization-trip events, but they did not fully expose the behavior of the actual primary current. This is because we always measure behind CTs, and these CTs contain variables hidden to us, including the actual magnetization curve, remnant flux, and actual CT burden.

To obtain the actual primary currents, we modeled the transmission line shunt reactor and energized it at a zero-crossing of the voltage signal. We then used these primary currents and the best estimates we had for the CTs and CT burdens to obtain the secondary currents that would be measured by the protective relays.

Fig. 11 shows the ratio, bus-side, and ground-side currents that we calculated. The bus-side current matches the all the way to 1.1 seconds into the event, while the ground-side current gets noticeably attenuated 0.7 seconds into the event. These currents are consistent with values obtained in the field tests.

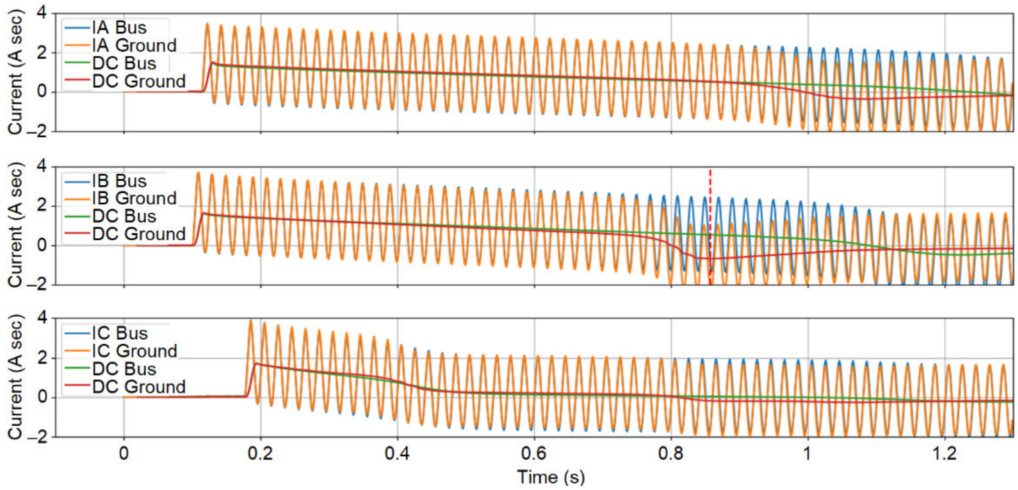

Fig. 8. Field test B-phase current measurements that resemble those observed in the UO.

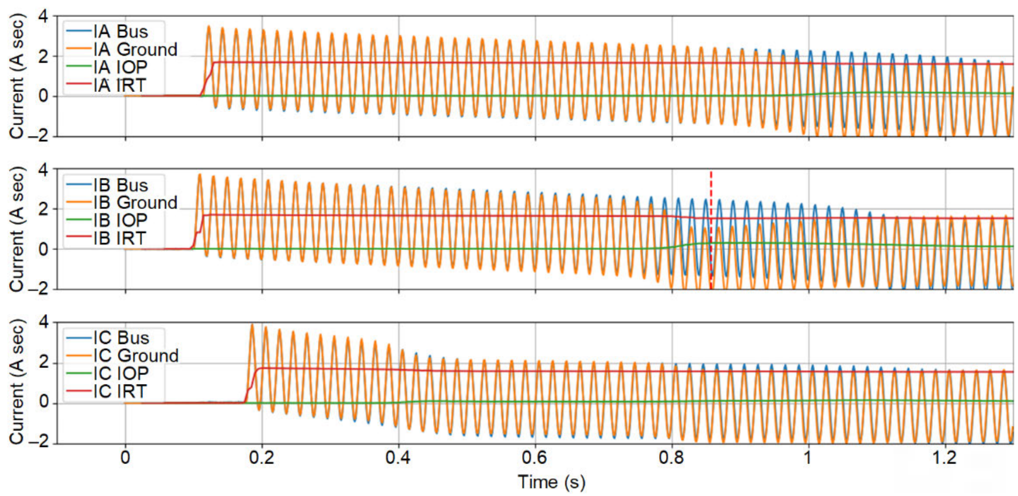

Fig. 9. Fully offset currents cause different behavior in the different phases, likely due to remnant flux and different CT lead lengths.

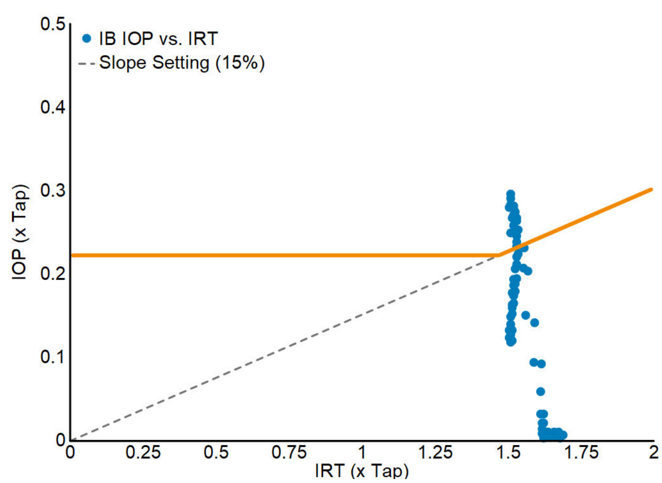

Fig. 10. Field test operate and restraint currents cause the differential element to operate.

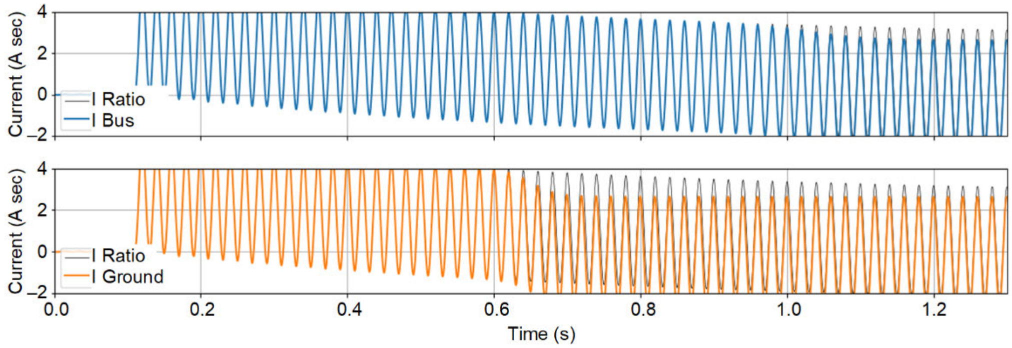

Fig. 11. Reconstruction of B-phase field event using power system model.

V. Mitigation Techniques

From a power system operation perspective, the best approaches to mitigate this problem are the following:

- Minimize the likelihood of a POW energizing the shunt reactors at the wrong time.
- Minimize the CT and CT burden mismatch between the bus and ground CTs.

Both of these approaches are pursued by electric utilities, but economic considerations often limit their application.

When the POW device fulfills its task and energizes the shunt reactor at the right time (at the peak of the voltage signal for single-phase reactors), no dc component appears in the primary current, and the differential protection is not challenged. The full set of event reports in the appendix show that when no dc component is present in the raw signal, the operate current remains close to zero.

Similarly, when the CTs and CT burdens are adequately matched, the secondary current measured by the protective relay also matches, the operate current remains close to zero, and no differential trips are issued (assuming that CTs are degaussed after installation and internal faults) [1] [2].

As the number of POW devices increase, the likelihood of a misoperation grows. This is particularly true for installations with three to four switching operations a day, because the higher number of switching operations can expose CT and CT burden mismatches.

Substation design can make matching the CTs and CT burden challenging. For example, at Site 1 in our study, the distance between the ground-side CT and the relay, 120 meters (393 feet), was three times as long as the distance between the bus-side CT and the relay, which was 40 meters (131 feet). This issue can be mitigated by using a different wire section to balance as much of the total secondary resistance as possible.

From the protection perspective, a simple solution to these UOs exists. Based on our experience, UOs can be avoided on shunt reactors with several taps by energizing the reactors on the lowest current tap. This, in turn, reduces the differential element operate current to some extent, reducing the chances of exceeding the pickup threshold.

The cost of the solution is some loss of sensitivity, which is tolerable in many cases. In case of a fault to ground, the current on the ground-side CT is close to zero, which makes the operate-to-restraint ratio close to 100 percent.

Because these UOs are low-current events (at or below the nominal current of the shunt reactor), one option is to raise the pickup level of the differential element. At the all three sites, we raised the percentage differential slope.

Another way to implement this solution—widely applied to black-start generators—consists of first detecting an event external to the protection zone, the energization, and then reducing or blocking the differential element for a period of time [1] [2]. External event detection, for the shunt reactor case, can be made very secure and dependable by wiring the energization signal to the relay or by detecting a jump from zero current to some current below the minimum burden of the shunt reactor.

Notably, harmonic restraint does not work on air-core or air-gapped-core shunt reactor types because few harmonics (and sometimes no harmonics) are generated during switching.

VI. Conclusion

Differential protection faces challenges presented by the slowly decaying dc component in current signals, which results from closing the breaker at a voltage zero-crossing. We examined data from shunt reactor energization, actual differential UOs, and field tests that we conducted to study the UOs.

We conclude that secondary currents in shunt reactor differential protection schemes present signatures that, because of the low magnitude and slowly decaying dc component, are unique to this application. These secondary current signatures are not widely studied, likely because they only manifest in the POW device as a problem *after* a problem.

Harmonic blocking and harmonic restraint are not suitable for this application. However, adequate performance of the POW device avoids the UOs. Matching the CTs and the CT burden avoids the UOs, assuming that the CTs are degaussed after installation and internal faults.

On the three sites we studied, we found that raising the percentage differential slope to 30 percent was enough to avoid all of the recorded UOs in our data.

VII. Appendix

A. UO Event Data

In this section, we show event data for UOs recorded at three different sites. Site 1 is the case studied in the body of this paper. The Site 2 and Site 3 UOs are similar but show different amounts of dc component associated with phase error at energization time.

Fig. 12 shows data recorded at Site 1.

At Site 1, the B-phase is the farthest away from the protective relay, while the A-phase is closest to the relay, as previously indicated in Table I.

Fig. 13 shows data recorded at Site 2. In the Site 2 UO, the C-phase exhibits the largest dc offset and trips, while the B-phase shows no dc component, implying that the POW device closed the B-phase at the correct angle.

Fig. 14 shows the data from Site 3. Although we do not have the differential event data for the Site 3 UO, a dc signature similar to the signatures at the previous two sites is present.

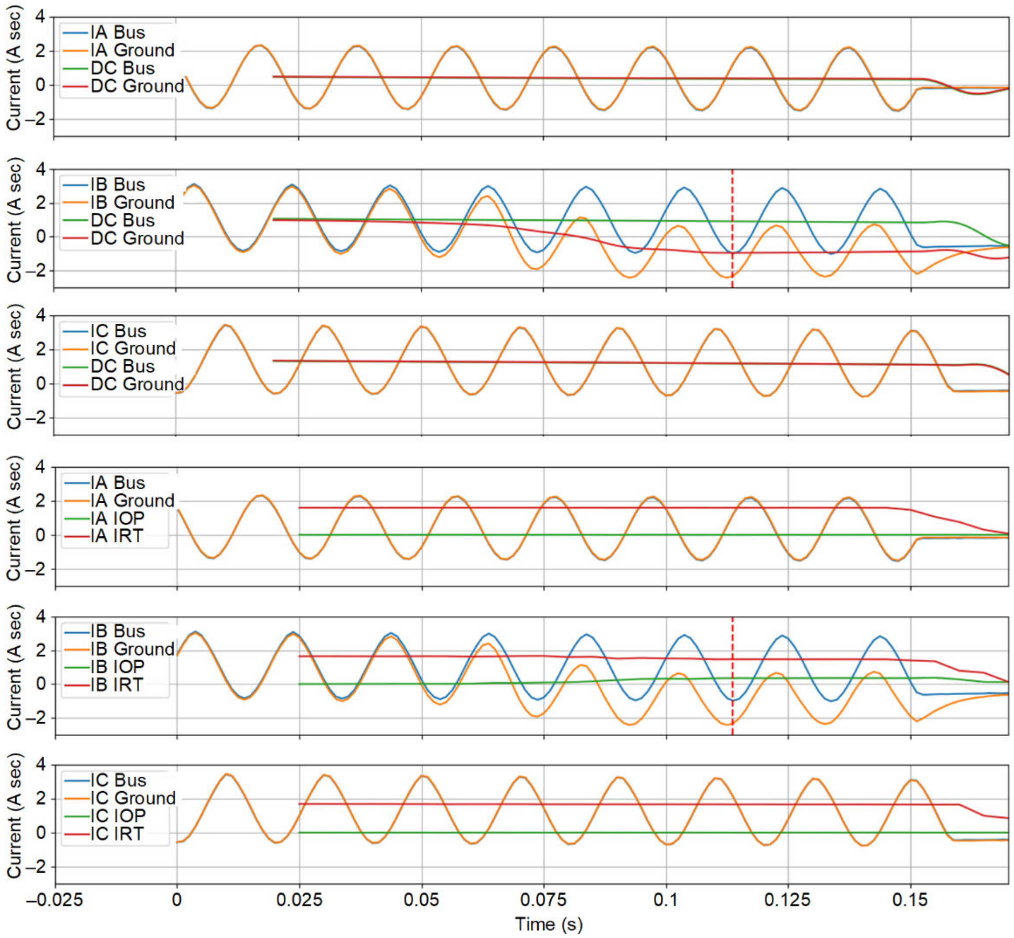

Fig. 12. Site 1.

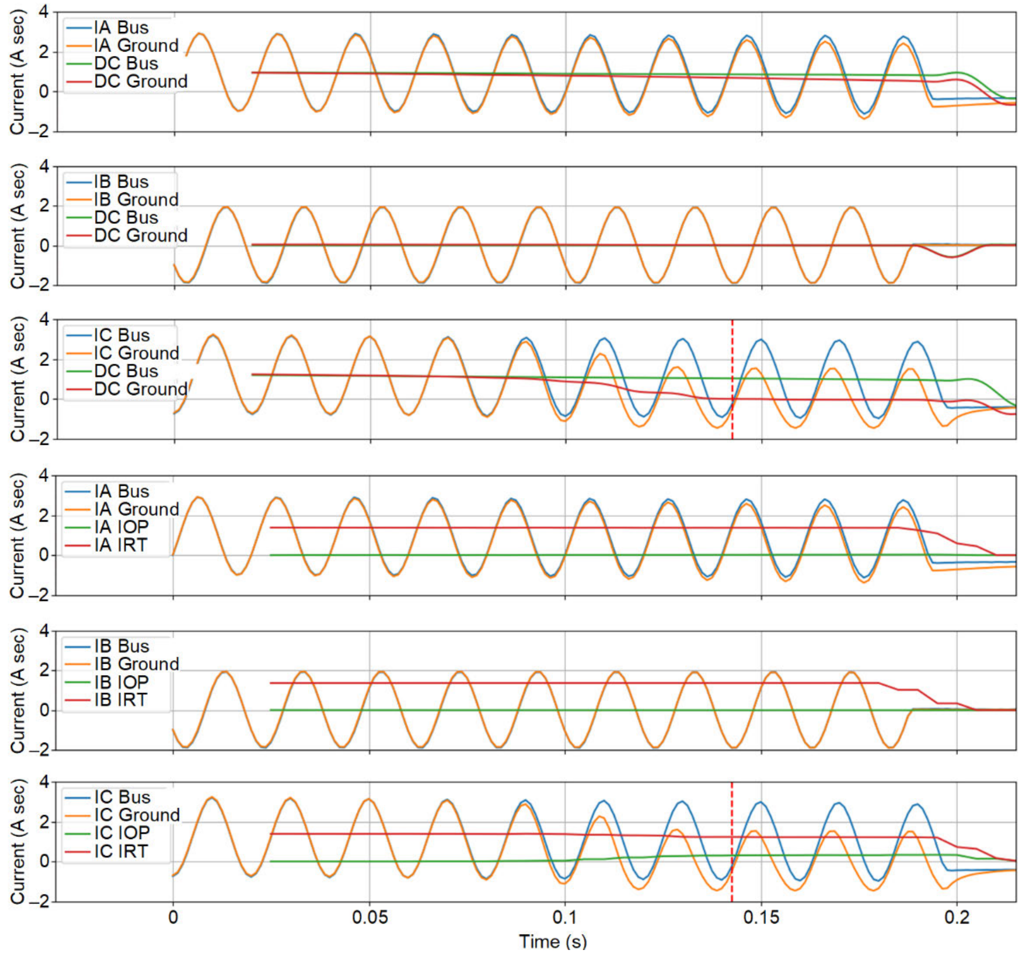

Fig. 13. Site 2.

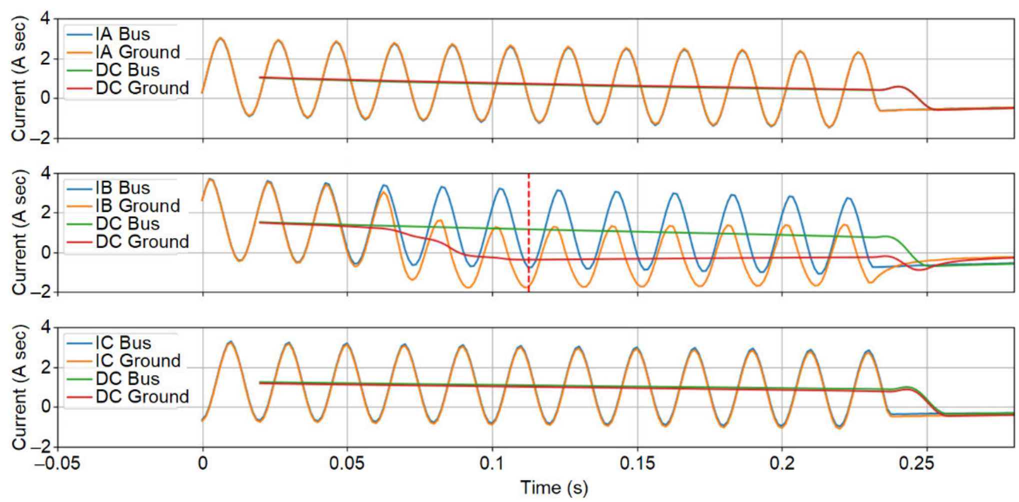

Fig. 14. Site 3.

B. Field Tests

In addition to the case presented in the body of this paper, we recorded a number of other tests at Site 1. In this section, we show the event data from some of these tests.

The event data for Test 1 are shown in Fig. 15. In Test 1, we recorded a differential operation in C-phase. While B-phase has the greatest total secondary resistance, it was close to adequately introducing low-dc component. In this test, the B-phase differential element operates within 600 ms of the energization, indicating that remnant flux might have played an important role.

In the Test 2 data, shown in Fig. 16, the B-phase and C-phase show a minimal dc component, and the A-phase shows only a small amount.

The event data for Test 3 are shown in Fig. 17. The B-phase differential operation in Test 3 was recorded less than 400 ms after energization.

The event data for Test 4 are shown in Fig. 18. The C-phase differential operation in Test 4 was recorded about 1 second after energization.

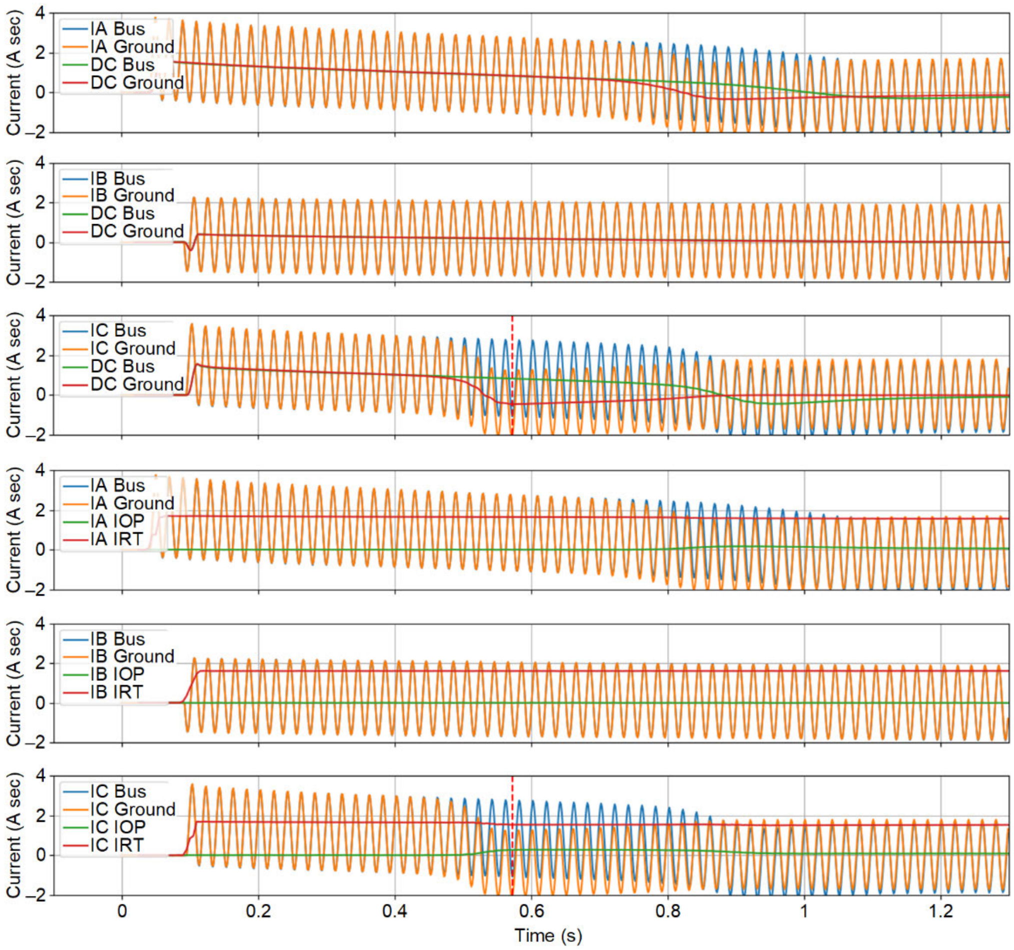

Fig. 15. Test 1.

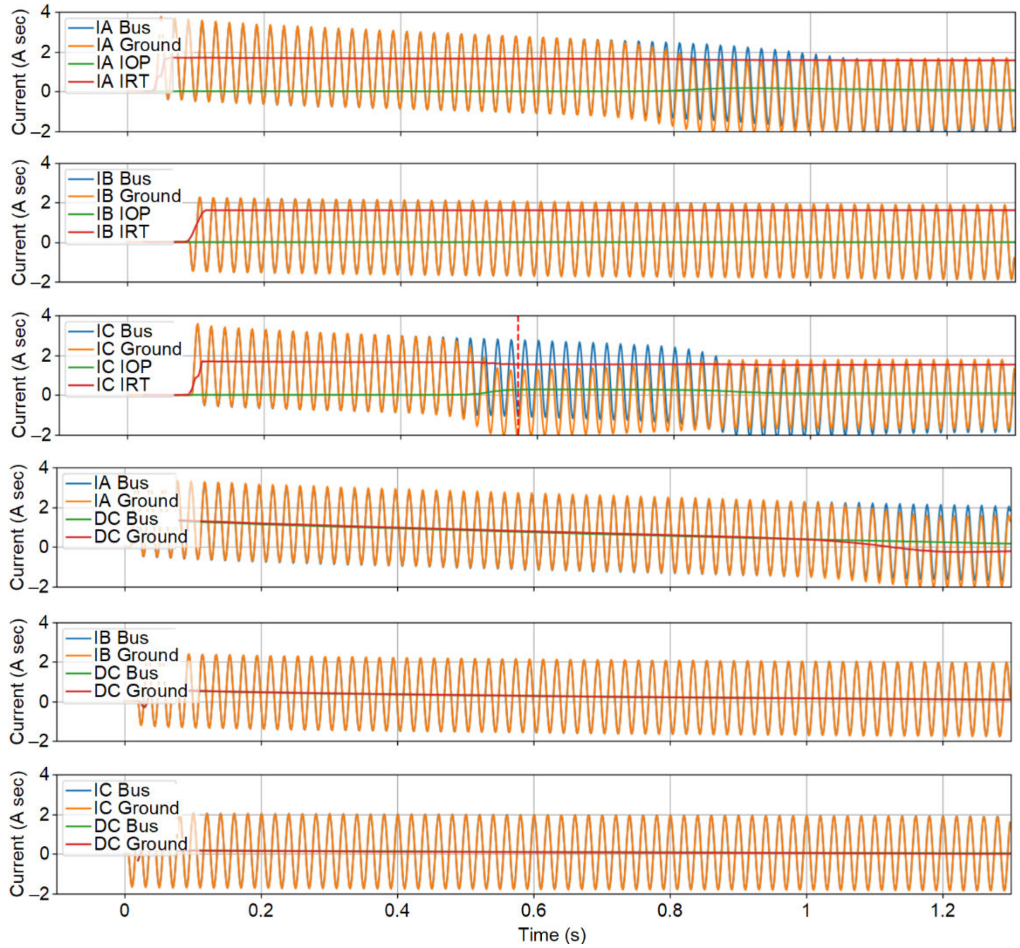

Fig. 16. Test 2.

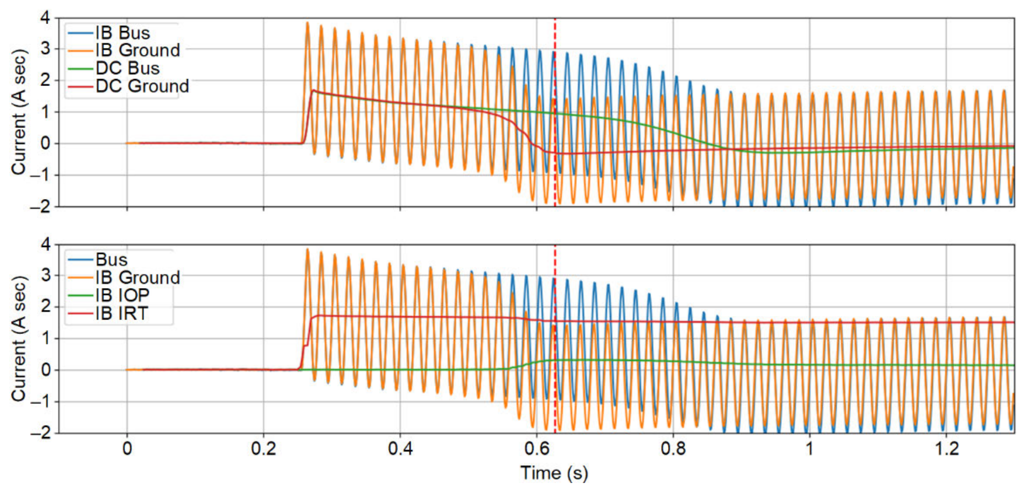

Fig. 17. Test 3.

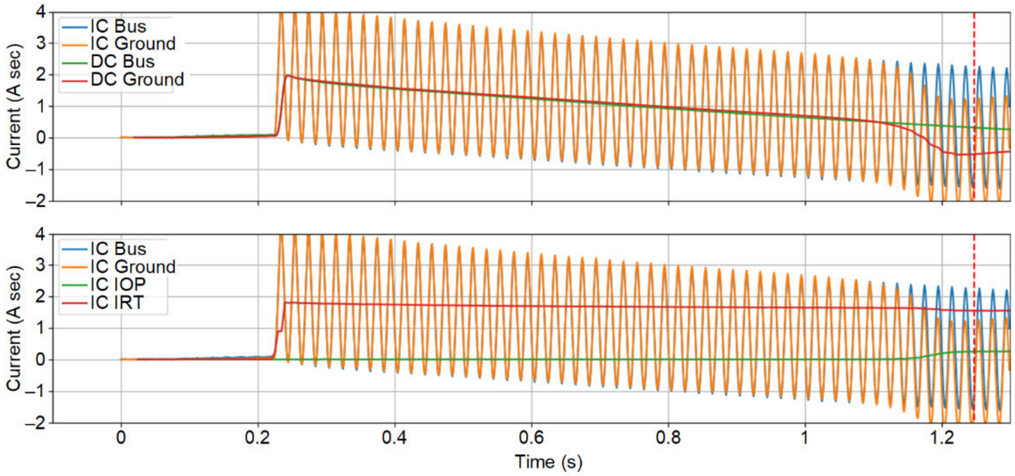

Fig. 18. Test 4.

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IX. Biographies

Fabio Bassi received his doctor of electrical engineering degree from the University of Pisa in 2003. In 2004, he began working for the Italian system operator Gestore della Rete di Trasmissione Nazionale, developing tools and operational rules for the opening of the Italian electricity market. In 2005, he began working for the Italian transmission system operator Terna. He worked for some years as an expert in network analysis and as project manager for the development of dynamic rating optimization and reporting tools for National Control Centre. Currently, he is responsible for the protection systems unit in the dispatching and operation department. His main topics are protection criteria, distributed generation integration, and dynamic line rating. He participated as a member of international working groups in the International Council on Large Electric Systems (Cigrè), the European Network of Transmission System Operators for Electricity, and GO15, Reliable and Sustainable Power Grids. He has authored papers on power system protection and dynamic line rating.

Gianluca Ramundo received his doctor of electrical engineering degree from the University of Bologna in 2013. Since 2014, he has worked for the Italian transmission system operator Terna. Currently, he works in the protection systems unit in the dispatching and operation department. His main topics are protection settings calculation and fault analysis in the extra-high-voltage grid. He has participated as a member of international working groups in the International Council on Large Electric Systems (Cigrè).

Andrea Di Tomasso received his master degree in electrical engineering at the Politecnico di Milano, Milan, Italy, in 2006. He worked on protection and control schemes for substation and power plant automation systems before he joined Schweitzer Engineering Laboratories, Inc. in 2019.

Yusuf Zafer Korkmaz received his BS in electrical and electronics engineering from the Middle East Technical University, Ankara, Turkey, in 1995. He worked on protection and control schemes, substation automation and telemetry systems, and generator autosynchronization systems before he joined Schweitzer Engineering Laboratories, Inc. in 2013.

Marcos Donolo (S 1999, M 2006, SM 2013) received his BSEE from Universidad Nacional de Río Cuarto, Argentina (2000), and his MS degree in electrical engineering (2002), his MS degree in mathematics (2005), and his PhD in electrical engineering (2006) from the Virginia Polytechnic Institute and State University. Since 2006, he has been with Schweitzer Engineering Laboratories, Inc., where he is presently a principal engineer. He holds several patents and has authored numerous papers related to power system protection.