Restricted Earth Fault Protection in Low-Impedance Grounded Systems With Inverter-Based Resources

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Restricted Earth Fault Protection in Low-Impedance Grounded Systems With Inverter-Based Resources

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***Abstract*—A restricted earth fault (REF) protection element provides sensitive detection of ground faults near the neutral of a transformer or a generator. The sensitivity gains from the REF element are especially more valuable when the equipment is low-impedance grounded when the transformer phase differential element (87T) is ineffective. However, the REF element faces several challenges in low-impedance grounded systems, which are becoming more prevalent in inverter-based resource (IBR) plants. Dependability of the REF element may be compromised if the zero-sequence current at the transformer terminal is capacitive for an internal ground fault. Security of the REF element may be jeopardized for external faults, such as a phase-to-phase-to-ground or an evolving fault with current transformer (CT) saturation. Using field events from low-impedance grounded IBR plants and simulations, this paper discusses the challenges and design improvements to an REF element for low-impedance grounded systems. CT selection criteria and setting guidance for reliable operation of the REF element are provided. Finally, the coverage provided by the REF element is compared with the 87T element to highlight its benefits in low-impedance grounded systems.**

***Index Terms*—arcing, collector, CT saturation, differential, feeder, field experience, generator, ground fault, GSU, IBR, intermittent, low-resistance, negative-sequence, REF, resistance-grounded, sensitivity, transformer, WTG, WTGSU, wind.**

I. Introduction

TRANSFORMER ground faults near the neutral can result in large fault currents and cause significant damage. For these faults, the current measured by a neutral current transformer (CT) can be quite large, whereas the currents measured by the phase CTs at the transformer terminals may not change significantly [1]. The restricted earth fault (REF) element utilizes this neutral current measurement to provide sensitive protective coverage for ground faults that remain undetected by the transformer phase differential element (87T) [2]. The REF element provides sensitive ground fault protection to the transformer wye winding in effectively grounded and low-impedance grounded systems. The zone of protection for the REF element is restricted by the CTs, making it selective in determining the faulted transformer winding.

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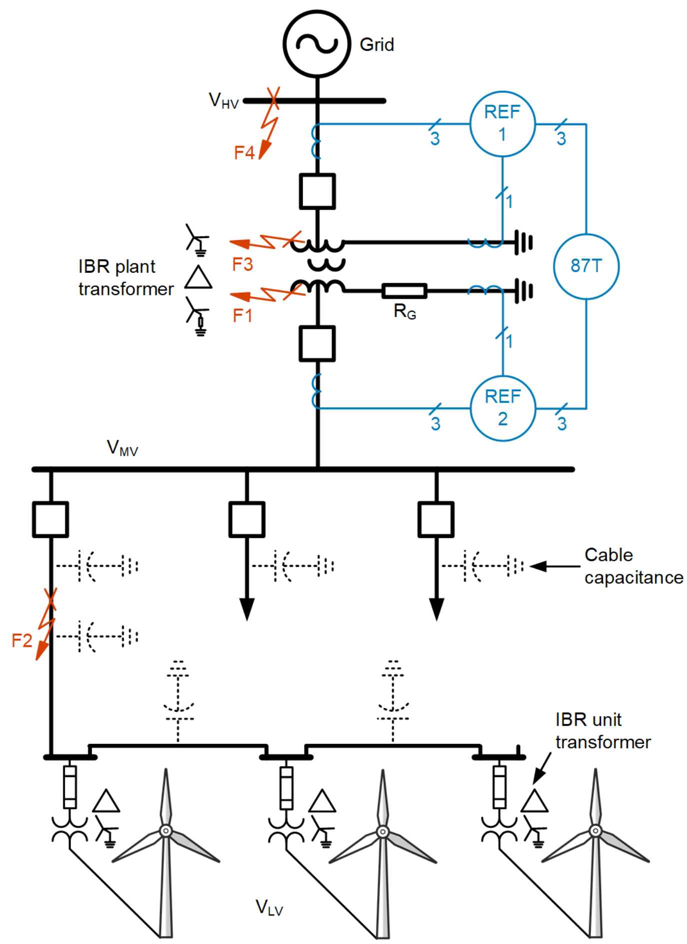

Fig. 1. REF elements applied to an IBR plant transformer application.

Low-impedance grounding may be applied in inverter-based resource (IBR) plants using a grounding resistance [3] at the neutral of the IBR plant transformer medium-voltage (MV) winding, as shown in Fig. 1. Low-impedance grounding may be applied to reduce fault current levels and lower voltage sag during ground faults, which reduces equipment damage and benefits operation. The sensitivities of the REF element and the 87T element in effectively grounded and low-impedance grounded systems are compared in Section V.B.

Wind power plants can have long MV cables in the collector feeder circuits that connect to the individual wind turbine generator (WTG) units. These cables can present a significant amount of capacitance, which can challenge REF element dependability for a transformer phase-to-ground (PG) fault at Location F1 of Fig. 1 [4]. Security considerations in these systems include possible misoperations for an external phase-to-phase-to-ground (PPG) fault on the collector circuit at Location F2 of Fig. 1 due to CT saturation.

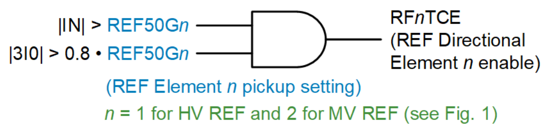

Fig. 2. REF directional element enable simplified logic.

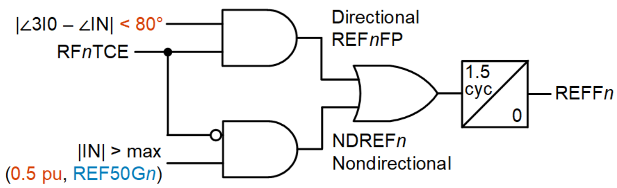

Fig. 3. REF element logic with directional and nondirectional paths.

This paper discusses the challenges (Section III) and presents an improved REF element (Section IV) that resolves the dependability and security issues in low-impedance grounded systems. While this paper focuses on the IBR plant transformer application, the challenges and solutions are applicable to other low-impedance grounded systems, such as a generator or an auxiliary transformer in a conventional generating plant. The improved REF element has been implemented in transformer and generator relays with good operating experience [5].

II. REF Element Overview

The REF element discussed in this paper uses the per-unit residual current measured at the transformer terminals (3I0) and the per-unit neutral current (IN) measured at the transformer neutral to detect a fault in the protected winding. The per-unit normalization is performed with respect to the neutral CT ratio (CTRN). The REF element consists of a directional path and a nondirectional path, which are described in this section.

A. REF Element Security for External Faults

If there is sufficient 3I0 and IN (see Fig. 2) and the angle difference is less than 80 degrees (see Fig. 3), the directional REF path, REF*n*FP, can trip for a forward fault by asserting REFF*n*. This path can operate when the terminal breaker of the protected winding is closed. A 1.5-cycle pickup timer provides security for possible operation of an in-zone surge arrester or possible CT subsidence current during the asymmetric opening of breaker poles following an external fault [5] [6].

During an external PG fault or a steady-state zero-sequence system unbalance, the angle difference between 3I0 with respect to IN is ideally 180 degrees based on the CT polarities shown in Fig. 4a. CT saturation can result in an angular error that is typically less than 75 degrees [7]; this translates to an angle between 3I0 and IN greater than 105 degrees, which is in the restraint region of the REF directional element described in Fig. 3. The phase comparison scheme is one implementation that has been adopted [4] [5], since it provides a simple approach to provide adequate security for CT saturation for PG faults (i.e., we have a known maximum angular error). This is unlike the differential scheme, which has to account for a possible mismatch in saturation level due to application of CTs with different ratios and excitation characteristics at the neutral versus the terminals [1].

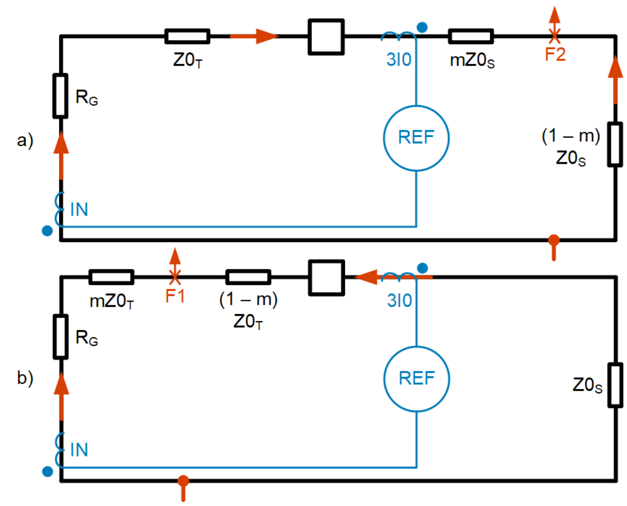

Fig. 4. Relationship of 3I0 and IN shown using a simplified zero-sequence network for an a) external fault and b) internal fault.

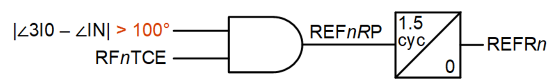

Fig. 5. REF element reverse declaration.

The element uses a coordination multiplier of 0.8, shown in Fig. 2, to ensure that measurement errors near the pickup do not inadvertently allow the nondirectional element (NDREF*n* in Fig. 3) to misoperate for an external ground fault. The element also has a reverse declaration path shown in Fig. 5.

B. Dependability for Internal Ground Faults

For the REF directional path to operate for an internal PG fault, as shown in Fig. 4b, the angle between 3I0 and IN is dependent on the nonhomogeneity associated with the sum of the transformer zero-sequence impedance ($Z0_T$) and transformer grounding impedance (R_G) with respect to the system zero-sequence impedance ($Z0_S$). For solidly grounded systems (R_G = 0 ohm), both $Z0_T$ and $Z0_S$ are expected to be mostly inductive; hence, an operating angle of 80 degrees shown in Fig. 3 is adequate. But as shown in Section III.A and as presented in [4], this is not the case when protecting a low-impedance grounded transformer winding where R_G is sufficiently large.

When there is insufficient 3I0 (i.e., when the breaker shown in Fig. 4b is open), the REF element uses the nondirectional path to provide neutral-side ground fault protection to the transformer. As discussed in Sections III.A and IV.A, the nondirectional path can play a significant role to add dependability in systems with IBRs due to the typical transformer connections.

C. Setting Guidance for REF Element Pickup

The REF element pickup (REF50G*n*) in Fig. 2 should be set greater than both of the following criteria [8]:

1. Natural system 3I0 unbalance—this value could be in the range of 10 percent of the system nominal current (I_{NOM_SYS}) for solidly grounded transformers. For low-impedance grounded systems, this value is small.

2. Steady-state CT and relay errors—this value is assumed to be 0.05 pu of the CT nominal current of the phase CTs at the terminal (I_{NOM_CTR}), multiplied by the mismatch between the CT ratio at the terminal (CTR) and the neutral (CTRN), and finally normalized by the neutral CT nominal current (I_{NOM_CTRN}) as shown in (1) [8].

$$\text{REF50Gn} = 0.05\text{ pu} \cdot \left(\frac{I_{NOM\_CTR}}{I_{NOM\_CTRN}}\right) \cdot \left(\frac{CTR}{CTRN}\right) \quad (1)$$

III. Challenges to the REF Element

The REF element described in Section II encounters certain dependability and security challenges in low-impedance grounded systems with IBRs. The challenges are presented in this section with respect to the commonly applied 87T element.

A. Dependability Issue

1) Field Event 1

In April 2021, in a wind farm that was online, a transformer relay did not operate for an internal fault at the MV terminal bushings of the transformer (F1 in Fig. 1), as shown in Fig. 6. As seen from the MV voltages of Fig. 6, this is a BG fault that restrikes near the voltage peaks and extinguishes near the voltage zeros. This intermittent, arcing behavior is an important consideration in high-impedance grounded systems [9].

What is interesting about this application is that the MV network is a cable network that is capacitive in nature and terminates at the various IBR unit transformers that have an MV delta winding. The IBR unit transformer MV winding is typically delta-connected (as shown in Fig. 1) in wind farms and in some solar farms [10]. The MV delta winding does not provide a path for 3I0, and therefore, appears as an open circuit to the 3I0. After the fault restrikes near the B-phase voltage peaks, there is a capacitive fault current contribution from the MV cable network (3I0 = 474 A or 0.13 pu). There is a larger resistive fault current contribution from the low-impedance grounded IBR plant transformer neutral (IN = 1,116 A or 0.31 pu). When the arc extinguishes near a voltage zero and the B-phase voltage regains a sinusoidal characteristic, the IN does not immediately go to zero but has a smooth decay since it charges the cable network exponentially for a few milliseconds. The intermittent nature of the fault results in the lower fundamental neutral current magnitude of 1,116 A compared to the expected 1,500 A (as shown in Table I) we would expect from a fault at the MV transformer terminal. But the neutral current has a peak value of 2,100 A, hence, an associated root-mean-square (rms) value of around 1,500 A, which is consistent with the fault location.

Considering protection system performance, the 87T element operate current is 0.28 pu, slightly lower than the pickup of 0.30 pu; hence, it does not operate as evident by the lack of assertion of the restrained differential element (87R) in Fig. 6. The MV winding REF element has sufficient current to operate on the directional path, but it does not operate since the angle of 3I0 with respect to IN is 91 degrees, which is outside the 80 degree operating region shown in Fig. 3. The nondirectional REF path is inactive since there is sufficient 3I0 and IN for the directional path (see Fig. 2). The nondirectional REF path is also incapable of operating for this system since the maximum possible neutral current for this system is 1,500 A as limited by the grounding resistor, which is 0.42 pu and lower than the 0.50 pu minimum requirement shown in Fig. 3.

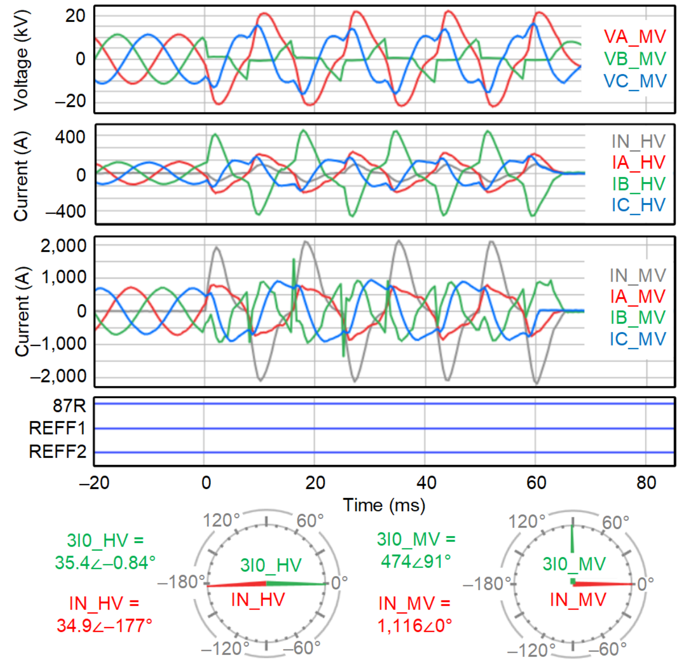

Fig. 6. Inadequate dependability from transformer protection elements for a terminal fault on the MV, low-impedance wye-grounded winding.

Table I
Relevant System Parameters Associated With Field Event 1

Parameter	Value
Voltage rating HV/MV	110 kV/13.8 kV
MVA (ONAN/ONAF) and frequency	50/67 MVA, 60 Hz
Leakage impedance	22% at 50 MVA
Winding configuration	YNyn0d1
MV grounding resistance and current	5.3 Ω, 1,500 A
HV CTR, CTRN	600/1 and 600/1
MV CTR, CTRN	3600/1 and 3600/1
87T pickup, Slope 1, Slope 2	0.30 pu, 21%, and 75%
REF pickup (REF50G) HV, MV	0.08 pu and 0.08 pu

Given that this fault is at the MV winding terminals in the bushings and none of the protection elements operated, we can infer that the entire MV winding of this transformer will remain unprotected for ground faults, which may be considered a catastrophic failure of the protection system.

2) Field Event 2

In August 2019, on a different continent, the REF element did not operate, while the 87T element did, for an internal fault on a transformer. The associated event is shown in Fig. 7. There are indications of arcing on the currents. The MV A-phase current is small and shows severe signs of arcing. The HV A-phase current and MV neutral current show signs of extinguishing near the current zero crossings followed by a restrike shortly after. The voltages wired to the relay are from the HV winding and are unaffected.

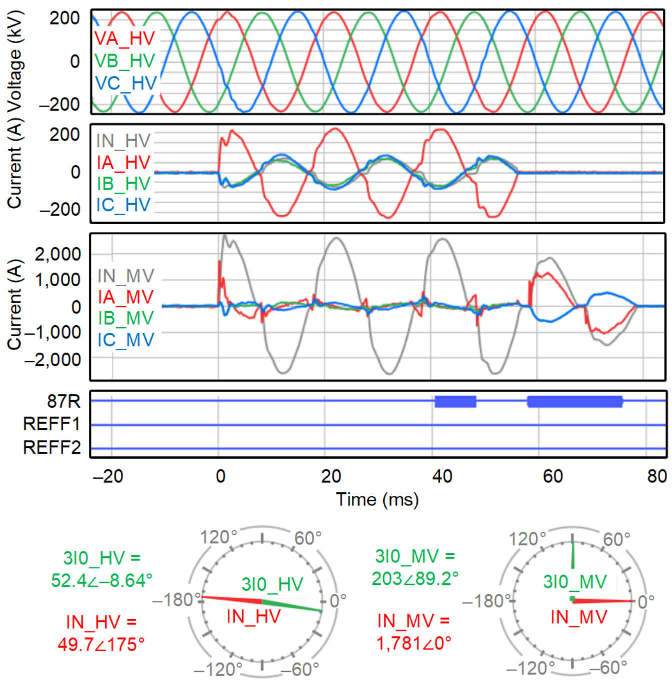

Fig. 7. Inadequate dependability from REF protection for a transformer internal fault on the MV, low-impedance grounded wye-grounded winding.

TABLE II
RELEVANT SYSTEM PARAMETERS ASSOCIATED WITH FIELD EVENT 2

Parameter	Value
Voltage rating HV/MV	275 kV/33 kV
MVA and frequency	130 MVA and 50 Hz
Winding configuration	YNyn0d5
MV grounding resistance and current	10 Ω and 1,905 A
HV CTR, CTRN	500/1 and 500/1
MV CTR, CTRN	2500/1 and 500/1
87T pickup, Slope 1, Slope 2	0.20 pu, 30%, and 40%
REF pickup (REF50G) HV, MV	0.10 pu and 0.10 pu

As with the previous field event, the 3I0 is relatively small (3I0 = 203 A or 0.41 pu) and capacitive as contributed by the MV cable network that terminates at the various IBR unit transformer delta windings. The transformer neutral supplies most of the resistive fault current (IN = 1,781 A or 3.56 pu). As expected and as is consistent with the previous event, the capacitive 3I0 leads the resistive IN by close to 90 degrees. We do not know where the fault is, but since the nonsinusoidal fault current of 1,781 A is close to the maximum current of 1,905 A (as shown in Table II), we can infer that the fault is at the transformer terminal.

The nondirectional REF element can perform well for this case since there is sufficient neutral current, but it does not operate since the directional REF path is enabled due to the presence of adequate 3I0 and IN relative to the pickup of 0.10 pu (as shown in Table II).

In this event, the 87T element operates since the differential current is 0.49 pu, which is higher than the minimum pickup of 0.20 pu (Table II).

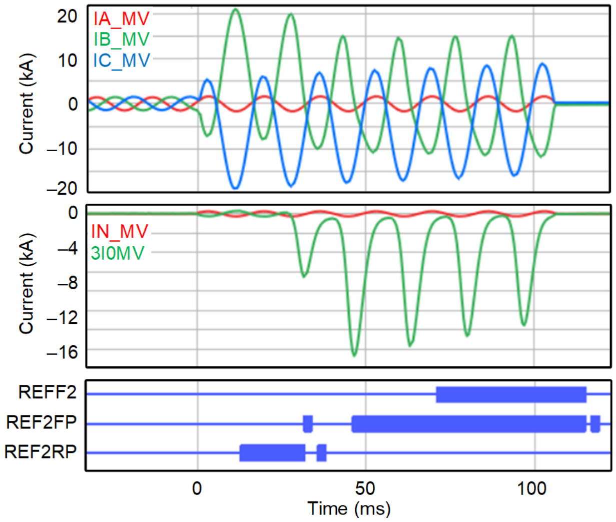

Fig. 8. REF element misoperates for a simulated external BCG fault.

B. *Security Issue*

The REF element may also encounter security issues in a low-impedance grounded system. This is shown in Fig. 8 using an external PPG fault simulation at Location F2 of Fig. 1 with a strong grid at the HV bus. Initially, after the fault occurs, 3I0 and IN are 180 degrees out-of-phase, and the direction reported by the REF element is reverse (REF2RP). However, 25 ms into the fault, when B-phase saturates, the 3I0 erroneously becomes nearly in-phase with the IN, and REF misoperates. We are also aware of a similar misoperation from the field.

This security issue is less likely to occur in solidly grounded transformers, since 3I0 for an external bolted PPG fault is much larger and dominates the error from CT saturation, but it can occur if the PPG fault resistance to the ground is significant.

IV. DESIGN IMPROVEMENTS FOR LOW-RESISTANCE GROUNDED SYSTEMS

To improve the performance of the REF element described in Section II for the challenges presented in Section III, the following improvements are made, which are also marked in the green boxes of Fig. 9 and Fig. 10.

A. *Dependability Improvements*

To improve dependability of the directional REF path, the forward comparison angle is increased from 80 degrees to 105 degrees. This covers the 90-degree capacitive region with adequate margin to improve dependability for the cases shown in Fig. 6 and Fig. 7. The reverse fault angle is reduced from 80 degrees to 75 degrees. As explained earlier in Section II.A, later in Section V.A, and in Reference [7], this provides adequate security for CT saturation during PG faults.

To improve dependability of the nondirectional REF path, the 0.50 pu limit shown in Fig. 3 is removed. This allows the nondirectional path to be dependable for ground faults in applications where the 3I0 contribution from the MV cable network is small. Similarly, for low-impedance grounded windings, the nondirectional path adds sensitivity since 3I0 and IN scale with fault location and become smaller for faults near the neutral.

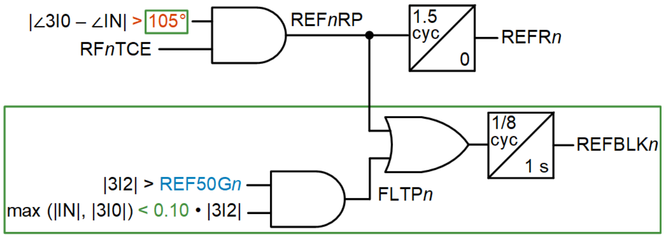

Fig. 9. Logic used to improve security for CT saturation.

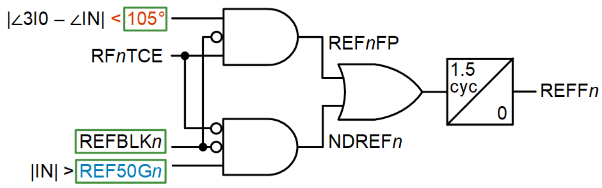

Fig. 10. REF element logic with improved security and dependability.

B. Security Improvements

Security for external PPG faults is improved by use of REFBLK*n* from Fig. 9. CTs take some time to saturate since they need to build up flux, and we expect REF*n*RP to assert initially for external faults involving ground. Once REF*n*RP asserts for an eighth cycle, we assert REFBLK*n*, which blocks and secures the REF element for 1 second to address CT saturation. This short eighth cycle delay provides an optimum balance between dependability and security. It helps ensure that for internal faults, especially those that exhibit arcing behavior and nonsinusoidal characteristics (see Fig. 6 and Fig. 7), do not inadvertently assert REFBLK*n* due to an imperfect response from the phasor estimation. The eighth cycle delay is similar to that used in the external fault detector for differential elements [6]; a longer pickup delay could penalize the CT requirements detailed in Section V.A.

The REF element provides dependability for internal PG faults that may not be detected by the 87T element, as will be discussed in Section V.B. The 87T element is dependable for multiphase faults that involve ground; therefore, these faults do not need to be detected by the REF element. However, external multiphase faults that involve ground can reduce security of the REF element. An example of this is shown in Section III.B. Additional scenarios can include an external phase-to-phase (PP) fault that evolves to the ground. CT saturation can occur prior to ground involvement, and the REF element can lose security once ground is involved and there is sufficient neutral current. Three-phase-to-ground faults can also have some zero-sequence current due to system asymmetries that are larger than the REF50G*n* pickup setting. To avoid any security issues from multiphase faults, the FLTP*n* path in Fig. 9 blocks REF element operation for faults that do not have ground involvement. This is accomplished by checking for sufficient negative-sequence current (3I2) and significantly less 3I0. All multiphase faults produce 3I2; three-phase faults develop 3I2 (but negligible 3I0) during fault initiation during the transient measurement period since each faulted phase current develops differently.

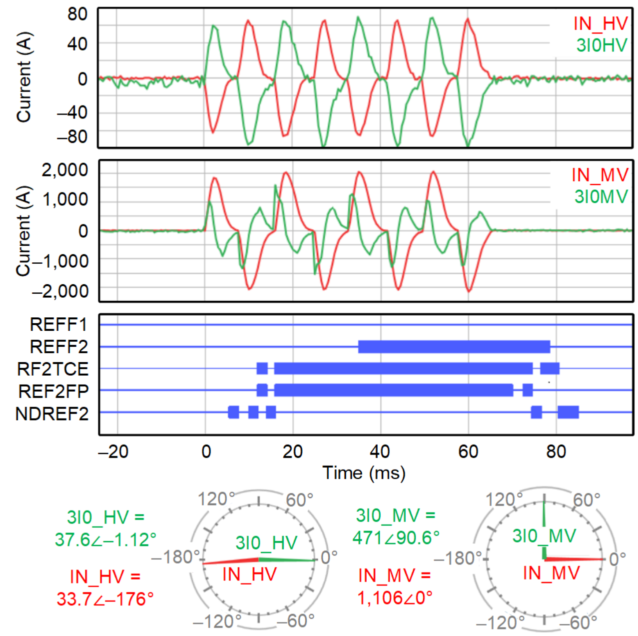

Fig. 11. Improved REF element is dependable (cf. Fig. 6).

For external faults at Location F4 (see Fig. 1) where 3I2 is limited or exhibits poor behavior due to the IBR response [11], it is possible for FLTP*n* to not assert. In such cases, the fault current has a large 3I0 component and any possible CT saturation is adequately addressed by the phase comparison scheme.

Initially, we thought of increasing security by supervising with the external fault detector available from the differential element, but we did not do this, because for a PG fault, the external fault detector for one of the unfaulted phases can assert [6] [7]. An assertion of the external fault detector of one of the unfaulted phases inadvertently blocks and reduces the REF element dependability. This does not impact the differential element since it is typically phase-segregated. Other considerations include inadequate security if the external fault detector does not assert due to the availability of only one current in the differential zone due to open breakers [7]. The improvements here are well adapted to each zone of the REF element and does not depend on the 87T element, which involves multiple windings.

C. Performance of Improved Algorithm for Events

The performance of the improved algorithm described in Sections IV.A and IV.B is verified by replaying the events of Section III. A different set of signals are shown to provide a slightly different amount of information in the figures.

1) Field Event 1 Dependability Improvement

The field event shown in Fig. 6 is dependable from the improved REF element, as shown in Fig. 11. Initially, there is a slight dropout in the RF2TCE during the transient, and the nondirectional element (NDREF2) provides dependability due to the lower pickup threshold. Since REF2FP and NDREF2 are passed through an OR gate to the common 1.5-cycle pickup timer, the element operates without having the timer reset. A common pickup timer adds dependability for intermittent faults where 3I0 can pick up and drop out due to the arcing behavior.

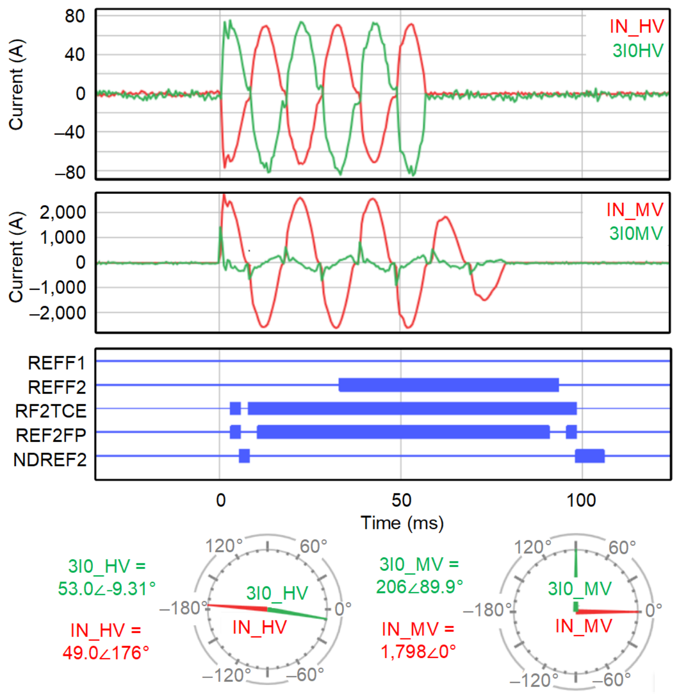

Fig. 12. Improved REF element is dependable (cf. Fig. 7).

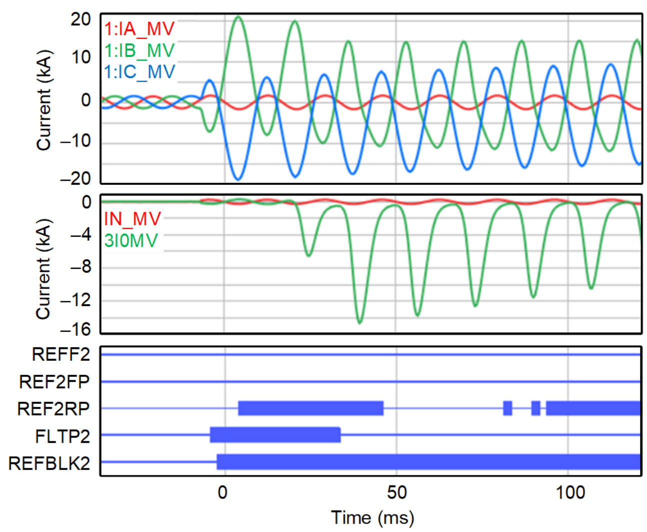

Fig. 13. REF element remains secure for an external BCG fault (cf. Fig. 8).

2) Field Event 2 Dependability Improvement

The field event initially shown in Fig. 7 is dependable from the improved REF element as shown in Fig. 12.

3) Simulated Event Security Improvement

The improved REF element retains security for the external BCG fault with CT saturation, as shown in Fig. 13. REF2RP and FLTP2 both assert prior to CT saturation, which then asserts REFBLK2, keeping the element secure.

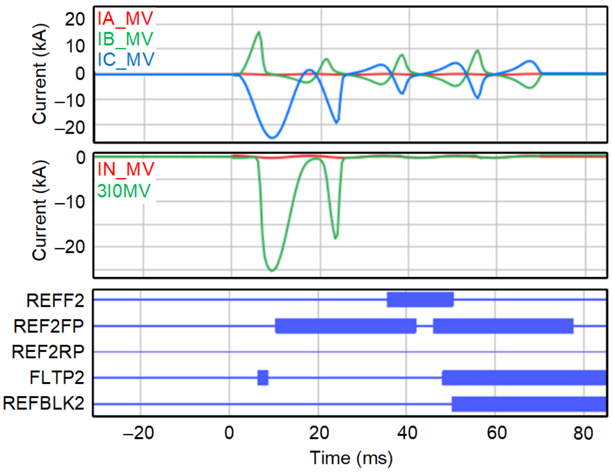

Fig. 14. REF element simulated misoperation due to heavy CT saturation.

V. Application Considerations

A. CT Requirements

The phase comparison implementation of the REF element described in Section II is resilient to CT saturation for PG faults but, as explained in Section III.B, can lose security due to CT saturation even with well-sized CTs for PPG faults in low-impedance grounded systems.

The REF element in Section IV.B overcomes the challenge associated with PPG faults or evolving faults. For IBR plants, there are no considerations associated with HV external faults since the IBR does not contribute sufficient fault current and ground faults (both PG and PPG) have a significant zero-sequence component. For MV external faults, where the terminals CTs see a possibly large PPG fault current contribution from the grid, the REFBLK2 path of Fig. 9 needs some saturation-free time to ensure that the element remains secure. The associated minimum total CT dimensioning factor (K_{TOT}) is 5, which considers the transient dc offset and a remanence level up to 80 percent [6] [7]. An example of simulated misoperation (with K_{TOT} of 4), shown in Fig. 14, corresponds to the security limits of the improved REF design. The saturation is quick and REFF2 misoperates since REFBLK2 does not assert until later. A K_{TOT} requirement of 5 is much lower than the case of Fig. 8, which had well-sized CTs with a K_{TOT} of 20.

The guidance is applied to an example IBR plant. For a PPG fault at Location F2 with maximum faulted phase current (I_F) of 10 kA, CT ratio of 400, internal CT resistance (R_{CT}) of 1 Ω, and burden resistance (R_B) of 1 Ω, the minimum saturation voltage (V_{SAT}) required by the CT is 250 V per (2) and (3). A C200 CT with an R_{CT} of 1 Ω would have a V_{SAT} greater than 300 V and is adequate for this application [6] [7].

$$V_{SAT} = K_{TOT} \cdot I_F \cdot \left(R_{CT} + R_B\right) \tag{2}$$

$$V_{SAT} = 5 \cdot \left(\frac{10{,}000\ \text{A}}{400}\right) \cdot \left(1\,\Omega + 1\,\Omega\right) = 250\ \text{V} \tag{3}$$

Unlike the terminal phase CTs that have a sizing requirement, the 75-degree margin provides adequate security for neutral CT saturation. This has also been shown in the past using field data [12].

TABLE III
SYSTEM PARAMETERS USED TO COMPARE REF VS. 87T ELEMENT COVERAGE

Parameter	Value
Voltage rating HV/MV	138 kV/34.5 kV
MVA, frequency, and impedance	100 MVA, 60 Hz, and 14%
Winding configuration	YNyn0d1
MV grounding resistance and current	25 Ω and 800 A
HV CTR, CTRN	500/5 and 500/5
MV CTR, CTRN	2000/5 and 2000/5
87T pickup, Slope 1, and Slope 2	0.30 pu, 25%, and 75%
REF pickup (REF50G), HV, and MV	0.10 pu and 0.05 pu

B. *REF vs 87T Element Coverage*

Transformers are typically protected by the 87T element, which can detect most internal faults. In this section, we share results of the hardware-in-the-loop tests used to compare the relative sensitivities of the REF and the 87T element, more specifically, the restrained phase differential element (87R) [5]. While the negative-sequence differential element (87Q) is also tested, the results are not significantly different than the 87R element for the ground faults applied, and hence, are not presented.

The system parameters are based on a real-world IBR plant with a few modifications and are shown in Table III [13]. Since CTR and CTRN are equal, the HV REF and MV REF pickup settings are set to 0.10 pu and 0.05 pu, respectively, per Section II.C. The HV REF settings can be set more sensitively since the phase CT primary current rating (500 A) is higher than the full load current (418 A), but it is not considered here for simplicity.

The coverage comparison for faults on the solidly grounded transformer HV winding (F3 in Fig. 1) and the low-impedance grounded MV winding (F1 in Fig. 1) are shown in Fig. 15 and Fig. 16, respectively. For the HV winding, both the 87T element and the REF element can detect faults near the transformer neutral, although the REF provides greater resistive coverage. For the MV winding, the REF element covers down to 12.5 percent of the winding, whereas the 87T element only detects faults near the terminal, 79 percent or higher. Arcing faults that reduce the fault current contribution or capacitive current leaving the 87T zone can further reduce this coverage possibly making the 87T element ineffective, as is the case in Fig. 6. It is evident that without the REF element, a large percentage of the low-impedance grounded winding remains unprotected.

For low-impedance grounded windings, the REF element coverage can be estimated using (4). Using the parameters in Table III, we obtain a coverage of 12.5 percent from (5), consistent with what is shown in Fig. 16. As mentioned in Section IV.A, when 3I0 is very small for faults near the neutral, the coverage is determined by the nondirectional path.

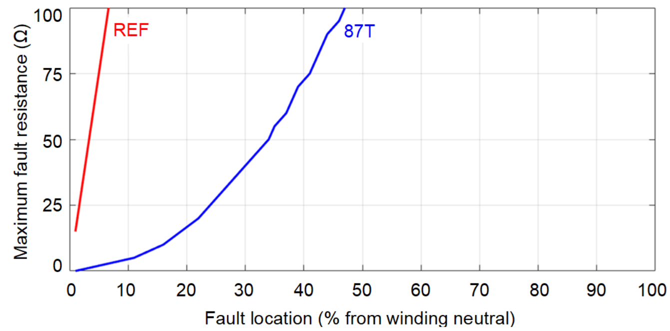

Fig. 15. REF vs. 87T coverage for the solidly grounded transformer winding.

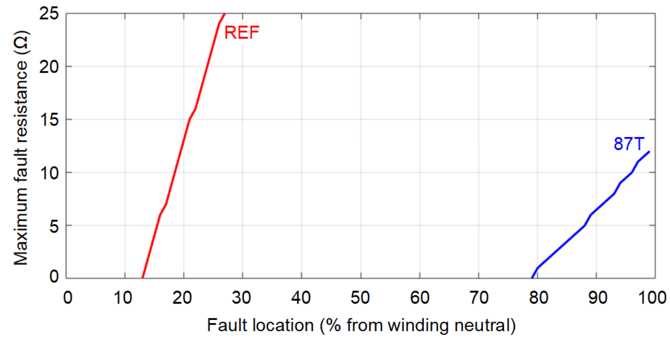

Fig. 16. REF vs. 87T coverage for the low-impedance grounded transformer.

$$\text{Coverage} = \text{REF50G (pu)} \bullet \frac{\text{CTRN} \bullet \text{I}_{\text{NOM\_CTRN}}}{\text{V}_{\text{LL}} / \left(\sqrt{3} \bullet \text{R}_{\text{G}}\right)} \bullet 100\% \quad (4)$$

$$\text{Coverage} = 0.05 \text{ pu} \bullet \frac{400 \bullet 5 \text{ A}}{800 \text{ A}} \bullet 100\% = 12.5\% \quad (5)$$

The REF element with the improvements from Section IV adds a significant level of sensitivity to transformer protection. While the REF element adds resistive coverage for solidly grounded windings, this section highlights how it shines when protecting low-impedance grounded windings.

VI. CONCLUSION

Ground faults are the most common types of transformer faults and can cause significant damage if undetected. For low-impedance grounded systems, the REF element can provide adequate ground fault protection coverage to a transformer unlike the 87T element. However, REF elements can be challenged in low-impedance grounded systems with IBRs.

A dependability challenge results from the relatively small zero-sequence current that may be intermittent in nature as shown using field events of internal transformer faults. The current is capacitive and originates from the MV cable network that terminates on the delta winding of the different IBR unit transformers. The directional and nondirectional paths of the REF element are improved to add dependability for these ground faults. A security issue may result for external PPG faults due to CT saturation. Using the reverse indication and a negative-sequence current reference, the REF element security is improved. The simple REF element design improvements increase reliability of the REF element in many low-impedance grounded systems, such as an IBR plant, a generator, or an auxiliary transformer in a conventional generating plant.

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IX. Biographies

Ritwik Chowdhury received his BS degree in engineering from the University of British Columbia and his MS degree in engineering from the University of Toronto. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2012, where he is presently a senior engineer in research and development. Ritwik holds 8 patents and has helped author 25 technical papers. He was recognized as an exceptional reviewer for IEEE Transactions on Power Delivery for 2019 and 2021. He is the vice chair of the Protection and Control Practices Subcommittee (I-SC) of the IEEE PSRC Committee, the chair of two IEEE Standards Working Groups, and the recipient of the 2021 PSRC Outstanding Young Engineer Award. Ritwik is a senior member of the IEEE and a registered professional engineer in the province of Ontario.

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Satish Samineni received his bachelor of engineering degree in electrical and electronics engineering from Andhra University, Visakhapatnam, India, in 2000. He received his master's degree in electrical engineering from the University of Idaho in 2003; and a PhD from the University of Idaho in 2021. Since 2003, he has worked at Schweitzer Engineering Laboratories, Inc., where he is a principal engineer in the Research and Development Division. He has authored or coauthored several technical papers and holds multiple U.S. patents. His research interests include power electronics and drives, power system protection, synchrophasor-based control applications, and power system stability. He is a registered professional engineer in the state of Washington and a senior member of IEEE.

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