CT Saturation on Transformer Energization: Ensuring Your Black-Start Generator Stays Online

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***Abstract*—The IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes recommends selecting current transformers (CTs) with identical characteristics for use in generator differential relaying applications.**

With a new installation under a single entity, a reasonable expectation is that CT selection and matching are accounted for during the initial project scope, design, and construction. However, many black-start generators and industrial backup generators are connected to switchgear provided under different contracts or projects, preventing CTs from being selected and matched properly. Often this is overlooked until startup testing, when black-start operational tests show unintended stator differential trips from inrush during transformer energization due to the large dc offset or show unintended stator differential trips during heavy external faults, causing CT saturation.

This paper shows why correct CT selection is important for reliable operation of generator differential protection. For instances where the CTs cannot be matched properly, this paper provides insight into different mitigation strategies using hardware changes and/or relay logic changes to prevent differential misoperations. Advancements in generator protection have led to adaptive slopes where the differential characteristic is put into a high-security mode when an external fault or CT saturation is detected. Using hardware-in-the-loop testing with a real-time digital simulator, this paper investigates, evaluates, and compares the different strategies, highlighting complexity and implementation costs. Finally, the paper examines a case from a user who encountered a generator relay misoperation during black-start conditions and discusses how the problem was solved using the strategies presented in the paper.

I. Introduction

In this paper, the term black start applies to energizing the power system of a facility when the main generation source has been lost. On the loss of utility voltage, the generator must be started up and the generator breaker closed to start re-energizing transformers, system auxiliary power, and all other critical loads associated to keep the facility in working order until primary power can be restored.

When a power plant is built, the scope, design, specification, and construction are typically completed under the supervision of a power plant engineer. The same goes for specifying the machines, the switchgear and breakers, the instrumentation devices, and the protection and control devices. With a new installation under a single entity, it is a reasonable expectation that the current transformer (CT) selection and matching are accounted for during initial project scope and design. However, many black-start generators and industrial backup generators are connected to switchgear provided under different contracts or projects, often preventing CTs from being selected and matched properly. This is generally overlooked until black-start operational testing, when the tests show unintended differential trips from inrush during transformer energization. These unintended trips are due to the large dc offset from an external event that leads to CT saturation.

This paper provides insight into common problems associated with CT saturation for black-start generators and practical solutions that can be implemented if the problem is discovered during startup testing.

II. CT Saturation

This paper does not provide an exhaustive background on CT saturation, which can be found in [1], [2], [3], and [4]. A concise overview is provided in this section as a reference point.

Fig. 1 shows the CT equivalent circuit. The primary current I_P, the primary winding resistance R_P, and the primary leakage reactance X_P are reflected to the secondary winding via turns ratio 1:n. The secondary winding resistance and leakage reactance are given by R_S and X_S, respectively. The magnetization branch impedance Z_E is shown as R_E and jX_M. Z_E is a nonlinear impedance, and its magnitude depends on the voltage across it. The excitation current I_E is comprised of the core losses and the flux in the CT core [5].

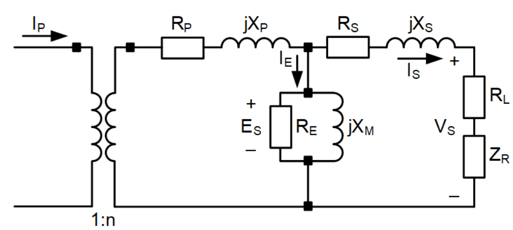

Fig. 1. CT Equivalent Circuit Referred to the Secondary Winding

E_S is the secondary excitation voltage induced in the secondary winding. The impedances R_L and Z_R are the total burden connected to the CT secondary, consisting of the CT lead length and connected devices. The CT secondary terminal voltage V_S appears across the CT burden.

Fig. 2 shows the CT excitation characteristic, which depicts the relationship of the excitation current I_E and the excitation voltage E_S. At low values of E_S, there is a linear relationship between E_S and I_E, with I_S giving almost a perfectly scaled replica of I_P while in the unsaturated region. However, as I_P continues to increase, so does E_S and I_E. As E_S exceeds the knee point, the core enters saturation and a disproportionate amount of I_E is required to produce further increases in E_S. As the CT crosses into the saturated region, the relationship between E_S and I_E is no longer linear, and thus the secondary current is no longer a replica of the primary current.

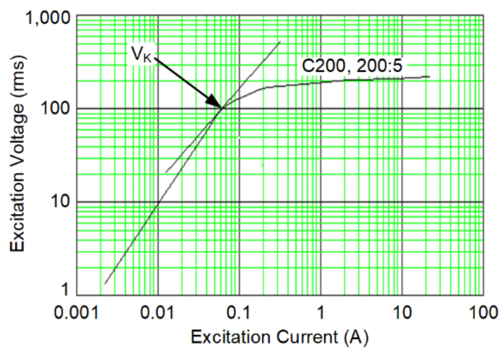

Fig. 2. Diagram of CT Excitation Characteristic [5]

This distortion is shown in Fig. 3, which displays the actual CT secondary current and the ratio secondary current. The actual CT current is in saturation and does not match the ratio CT current. As the dc offset decays, the CT moves out of saturation and the actual CT starts to produce a near replica waveform as the ratio current.

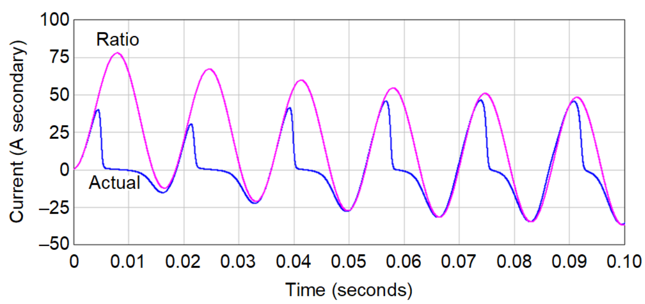

Fig. 3. Actual vs. Ratio (Ideal) CT Secondary Current

When CT saturation cannot be avoided, [6] states that the goal is for both CTs making up the differential zone to enter into saturation at the same current, or to minimize the difference in the time-to-saturation. The ratio of the saturation voltage to the excitation voltage is defined as "the saturation factor K_S and is an index of how close to saturation a CT is in a given application" [6].

K_S is used to calculate the time-to-saturation under transient conditions, as shown in (1).

$$K_S = \frac{V_K}{E_S} = \frac{V_K}{I_S \bullet (R_S + Z_B)} \tag{1}$$

For a distortion-free secondary waveform from the CT, the K_S factor should meet the criterion shown in (2).

$$K_S \geq \left(1 + \frac{X}{R}\right) \tag{2}$$

However, because of the large X/R ratio of a generator, it is difficult to specify a CT size for a generator differential that meets this criterion. If the criterion is not met, CT saturation will occur. The duration before saturation is called the time-to-saturation [6] and is calculated in (3).

$$T_S = \frac{-(X/R)}{2\pi f} \bullet \ln\left(1 - \frac{K_S - 1}{X/R}\right) \tag{3}$$

Note that this calculation assumes that the core flux starts to build up from zero. However, this hardly ever occurs in practice [7].

III. IEEE Guide for Generator CT Selection

According to IEEE C37.110, "the differential CTs on both sides of a generator should be of the same ratio, rating, and connected burden, and preferably should have the same manufacturer so that the excitation characteristics are the same" [6].

This guideline is intended to ensure that the two CTs forming the differential zone saturate similarly, thus minimizing the possibility of a spurious differential current. Section 7.2.2 in IEEE C37.110-2007 provides guidelines for selecting CTs that are used in generator differential applications. The guideline states the following:

- The primary current rating should be 120 to 150 percent of the generator current rating.
- The CTs should be tapped at full winding.
- CTs with fully distributed windings should be used.
- The highest practical C class secondary voltage rating should be used.
- Dedicated CTs should be used for differential protection if not using low-burden digital multifunction relays [6].

Following these guidelines ensures that the CTs forming the generator differential zone have similar excitation characteristics, especially the knee-point voltage.

The goals for the CTs forming the differential zone, in order of importance, are as follows:

- Avoid CT saturation for asymmetrical currents.
- Prevent saturation for symmetrical currents.
- Go into saturation at the same time if dc saturation occurs.
- Minimize the difference in time-to-saturation for dc saturation [6].

A common misconception is that matching the C class of the CTs guarantees that the CT excitation characteristics will be the same [6].

IV. Generator CT Selection

A. Accuracy Class

IEEE C57.13 recognizes three classes of CTs for relaying purposes, but typically only C class is used in the electric power industry because this is the common class in North America. The C classification states that the CT can deliver 20 times rated current with less than 10 percent ratio error at one of four standard burden values: 1, 2, 4, and 8 ohms [8]. For Class C CTs with a ratio greater than 250:5 (50 secondary turns), the CT must deliver less than 3 percent ratio error at rated current, as calculated in (4).

$$\text{Ratio Error } (\%) = (I_E / I_S) \bullet 100 \tag{4}$$

The standard burden values 1, 2, 4, and 8 ohms are relaying burdens with a power factor of 0.5. The code for this accuracy classification is the letter C followed by the voltage across the burden at the specified burden. For example, using (5), if a 5 A CT is selected with a 1-ohm burden, the accuracy classification is C100, 100 A. I_S develops 100 V_S across 1 ohm [8].

$$V_{RATED} = 20 \bullet I_{S\ RATED} \bullet Z_{STD} \quad (5)$$

where:

V_{RATED} is the rated secondary terminal voltage.

$I_{S\ RATED}$ is the rated secondary current.

Z_{STD} is the standard burden (0.1, 0.2, 0.5, 1, 2, 4, or 8 ohms).

B. CT Burden

When designing a system and selecting a CT, the goal is to minimize the total burden connected to the CT. The total burden consists of the internal resistance of the CT windings, the resistance of the CT leads from the CT to the relay and back, and the burden of the connected relays, as shown in (6).

$$Z_B = R_S + R_L + Z_R \quad (6)$$

where:

Z_B is the total burden in ohms.

R_S is the CT secondary resistance in ohms at 75ºC.

R_L is the resistance of the leads in ohms (total loop distance).

Z_R is the connected device impedance in ohms.

1) CT Secondary Resistance

Table I lists the typical secondary resistance of Class C CTs in ohms at 75ºC per IEEE C57.13. The resistance of the CT secondary winding between the secondary terminals should be provided by the manufacturer at a specified temperature.

TABLE I
CT SECONDARY RESISTANCE

Current Ratio	Turns Ratio	Secondary Resistance
100:5	20:1	0.05
200:5	40:1	0.10
300:5	60:1	0.15
400:5	80:1	0.20
500:5	100:1	0.25
600:5	120:1	0.31
800:5	160:1	0.41
900:5	180:1	0.46
1000:5	200:1	0.51
1200:5	240:1	0.61

2) Leads

CT leads are typically the largest burden on CTs when microprocessor-based relays are involved. In new installations, the designer can choose the wire size to control the CT circuit resistance. To calculate the CT resistance of American Wire Gauge (AWG), the log resistance of 1,000 ft of wire is proportional to the AWG of the wire. For example, #10 AWG wire is 0.9989 ohms/1,000 ft. This log relationship means that decreasing the gauge by three decreases the resistance by half, and increasing the gauge by three doubles the resistance. Remember that the loop length, not the physical distance between the relay and CT, is the important distance used to calculate the resistance.

The formula for resistance versus AWG is shown in (7).

$$\Omega / 1{,}000\,\text{ft} = e^{0.232G - 2.32} \quad (7)$$

where:

Ω/1,000 ft is the resistance in ohms per 1,000 ft.

G is the AWG number.

A good practice is to size the leads to limit the lead resistance to 0.5 ohms or less. Using this rule, #10 AWG wire is the correct choice if the CTs are located up to 250 ft from the relays, for a total run of 500 ft to and from the CTs [9]. For CT leads, #12 AWG wire is considered the minimum acceptable wire size.

3) CT Connections

Because of the use of digital relays and the ability to compensate for delta-wye transformers, it is uncommon to wire CTs in delta. System designers should understand that in three-phase CT connections, the burden on the individual CT varies depending on the CT connection type and the fault type, as shown in Table II [6].

TABLE II
EFFECTS ON BURDEN FOR DIFFERENT FAULT TYPES

Connection (location)	Line-to-Line or Three-Phase Fault	Single Line-to-Ground Fault
Wye (connected at CT)	$Z = R_{CT} + 0.5R_L + Z_R$	$Z = R_{CT} + R_L + Z_R$
Wye (connected at switchboard)	$Z = R_{CT} + R_L + Z_R$	$Z = R_{CT} + R_L + Z_R$
Delta (connected at switchboard)	$Z = R_{CT} + R_L + 3Z_R$	$Z = R_{CT} + R_L + 2Z_R$
Delta (connected at CT)	$Z = R_{CT} + 1.5R_L + 3Z_R$	$Z = R_{CT} + R_L + 2Z_R$

The variables in Table II are defined as follows:

Z is the effective impedance seen by the CT.

R_{CT} is the CT secondary winding resistance and the CT lead resistance, including any relay impedance that is inside the delta connection (ohms).

R_L is the circuit loop lead resistance (ohms).

R_R is the relay impedance in the CT secondary current path (ohms).

C. Criterion to Avoid CT Saturation

A commonly used criterion to determine CT saturation and burden limits is shown in (8) [9].

$$20 \geq (X / R + 1) \bullet I_F \bullet Z_{STDB} \quad (8)$$

where:

I_F is the maximum fault current in per-unit of CT rating.

Z_{STDB} is the CT burden in per-unit of standard burden.

X/R is the X/R ratio of the primary fault circuit.

Reference [10] uses (8) in terms of per-unit saturation, as shown in (9). This criterion is used for evaluation in the case study discussed in Section VII.

$$V_S = \left(1+\frac{X}{R}\right) \bullet \frac{I_{MAG}}{I_{SEC} N} \bullet \frac{\left|R_B + \omega \bullet L_B\right| \bullet 20}{V_{RAT}} \quad (9)$$

where:

V_S is the per-unit saturation voltage.

X/R is the X/R ratio of the primary fault circuit.

I_{MAG} is the root-mean-square (rms) magnitude of the CT primary current.

I_{SEC} is the CT secondary rating (1 or 5 A).

N is the CT turns ratio.

R_B is the resistive burden of the leads and connected devices.

L_B is the inductive burden.

V_{RAT} is the CT C class rating.

$\omega = 2 \bullet \pi \bullet$ frequency.

For added simplicity, both the resistive and inductive burdens can be ignored when using (9) with digital relays, as the result would be in the range of several milliohms. A per-unit saturation voltage less than 20 satisfies the criterion to avoid CT saturation.

However, note that these equations consider fully offset sinusoidal fault currents and not nonsinusoidal currents produced during transformer inrush. Additionally, during transformer energization, unipolar inrush currents contain a significant dc component. Subsequently, dc saturation of CTs is a concern for generator relaying applications [5].

V. Mitigation Methods for Unequal CT Saturation

A. Heavy-Gauge or Parallel CT Leads

If the relay is a great distance from the generator neutral or terminal CT, a heavy-gauge cable can be used for the CT leads to increase performance. Fig. 4 is helpful for selecting wire size if the lead lengths are known.

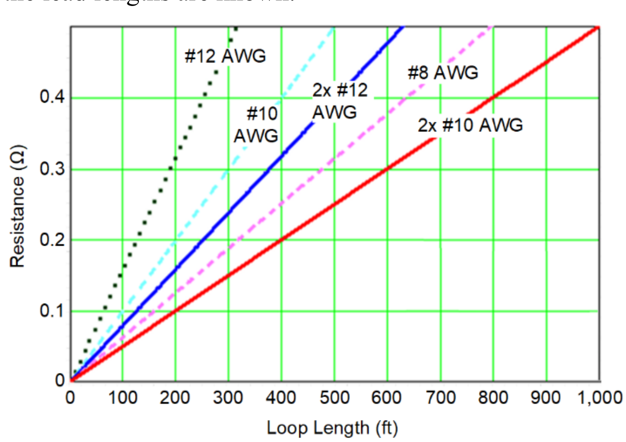

Fig. 4. Burden for Different Lead Lengths and Sizes

If Fig. 4 yields a wire size too difficult to handle, running an additional similar gauge lead in parallel is a good alternative, as this can halve the impedance. For example, Fig. 4 shows that parallel #10 AWG cable is lower resistance than a single #8 AWG cable.

B. Auxiliary CT to Reduce Burden

Auxiliary CTs are traditionally used to adjust the secondary current by the turns ratio, allowing a 1 A relay to be connected to a 5 A CT, and vice versa. However, per IEEE C37.110, auxiliary CTs can also be used to change the apparent impedance on the CT by the square of the CT ratio [6], as denoted by (10).

$$Z_T = Z_P + \left(Z_B + Z_A\right) \bullet \left(I_S / I_P\right)^2 \quad (10)$$

where:

Z_T is the total impedance seen by the primary CT.

Z_P is the impedance on the primary of the auxiliary CT.

Z_B is the impedance on the secondary of the auxiliary CT, including leads and connected devices.

Z_A is the impedance of the auxiliary CT winding resistance and leakage reactance.

To accomplish this, the auxiliary CT is placed in the secondary circuit of the primary CT, as shown in Fig. 5.

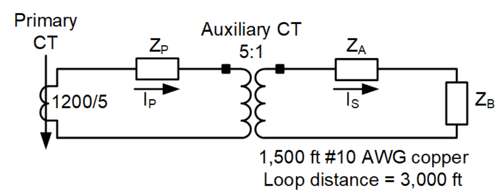

Fig. 5. Auxiliary CT to Reduce Apparent Leads Burden

Fig. 5 shows an application where an existing 1200/5 CT must be connected to a new relay located 1500 ft away. In this scenario, a 1 A relay can be selected and the auxiliary CT used to reduce the 5 A to 1 A and also to reduce the apparent burden seen by the primary CT.

While this approach can help mitigate issues with CT burden, it should be used only after extensive consideration of additional factors, including dc offset in the primary current, CT remanence, and settings complications.

C. Increasing Burden to Match Time-to-Saturation

Another option that does not help with saturation prevention but does affect the CT transient performance is decreasing the time-to-saturation to closer match differential CTs on the neutral and terminal side. This is accomplished by attempting to match burdens for both CTs making up the generator differential.

1) Adding CT Lead Length to Create Similar Burden

This method takes the shortest CT lead and makes it match the longest CT lead by running additional cable to match lengths. For example, if the breaker CT lead lengths are 50 ft and the generator CT leads are 300 ft, an additional 250 ft would be used for the breaker CT. A suitable location would then need to be found to coil up the additional cable. If space is not available, then this option would not be suitable.

2) *Increasing the Burden With a Resistor*

This method is probably easier to implement than previous options but is undesirable for reliability and safety reasons. The time-to-saturation for the CT becomes very short with high fault currents as the burden is increased, so the relay may not operate as expected on internal faults. Also, a failure of this resistor can cause an open CT circuit, causing serious damage. The resistor in the CT circuit reduces the reliability of the scheme, so this solution is not recommended.

VI. Relay Selection and Internal Methods for Black-Start Security

A. *Percentage Differential Element*

Most percentage differential elements operate on a per-phase magnitude of the vector sum of the currents (see (11)) entering a protected zone called operate current. To provide sensitive yet secure protection, the percentage differential element uses a restraint current and the magnitude sum of currents, as shown in (12). Restraint provides security for when the CTs making up the differential zone respond differently. Causes for these differences include magnetizing current, relay measurement errors, CT ratio errors, and CT mismatch errors.

$$I_{OP} = \left| I_{TERM} + I_{NEUTRAL} \right| \tag{11}$$

$$I_{RT} = \left| I_{TERM} \right| + \left| I_{NEUTRAL} \right| \tag{12}$$

where:

I_{OP} is the operate current.

I_{RT} is the restraint current.

I_{TERM} is the terminal current.

$I_{NEUTRAL}$ is the neutral side current.

B. *High-Security Mode*

Many digital relays have advanced algorithms to secure generator differential elements from CT saturation caused by external events.

The example generator relay discussed in this section has a differential high-security mode (HSM) that changes the characteristic of the differential element. When the HSM differential element is enabled due to a detected external event, the relay uses a higher restraint pickup and a steeper slope characteristic, as shown in Fig. 6.

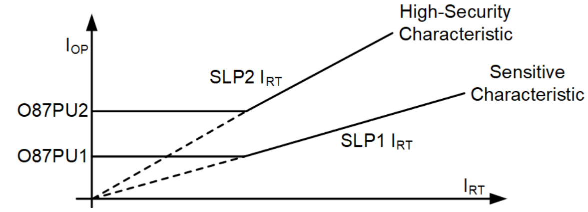

Fig. 6. Percentage Restraint Differential With HSM

For applications where CT saturation is known to occur, such as black-start generators that must energize large transformers, the relay includes a logic equation to enable and disable the HSM in real time, as shown in Fig. 7.

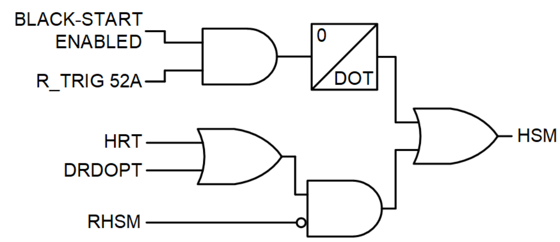

Fig. 7. HSM Enabled on Breaker Closing

In the logic, the HSM is enabled automatically for closure of the generator breaker. Once the breaker is closed, HSM is enabled for a user-defined duration after closure, and the HSM reset logic then resets in the same fashion shown in Fig. 8.

To ensure quick operation in cases when external events evolve into internal events, the relay provides a phase comparator logic that can be used to reset HSM [5]. Fig. 8 shows the phase comparator logic along with its current supervision. It also shows that the reset bit (RHSM) will assert three cycles after all currents fall below 0.2 pu of tap.

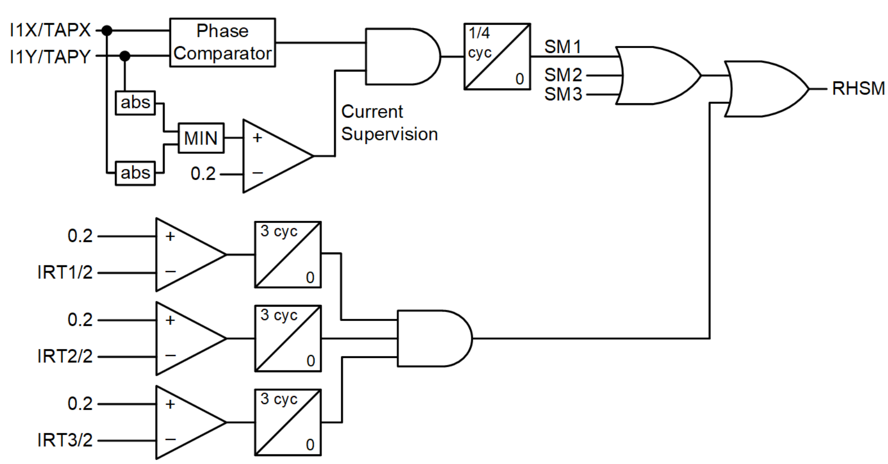

Fig. 8. HSM Reset Logic

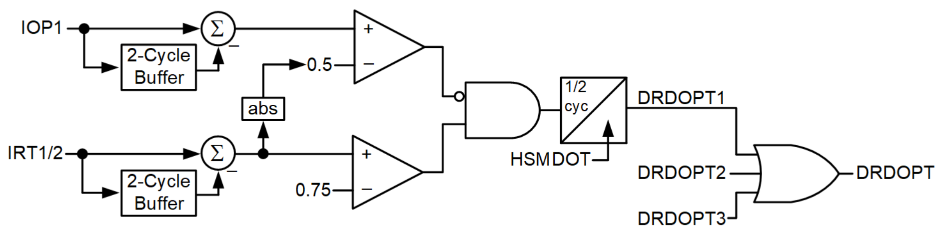

Fig. 9. Incremental Comparator External Event Detector

The relay provides two dedicated external event detectors: an incremental comparator event detector logic [11] and a second-harmonic event detector.

The incremental comparator external event detector (Fig. 9) calculates the incremental differential current and compares it to the incremental restraint current. If there is a large enough increment in restraint current without a simultaneous increment in differential current, the logic declares an external event and enables the HSM differential element.

The second-harmonic external event detector (Fig. 10) compares the fundamental compensated current to the second-harmonic compensated current. It requires the second-harmonic compensated current to be greater than 20 percent of tap and greater than 15 percent of the fundamental compensated current for five cycles. This is completed on a per-phase basis in the generator differential zone.

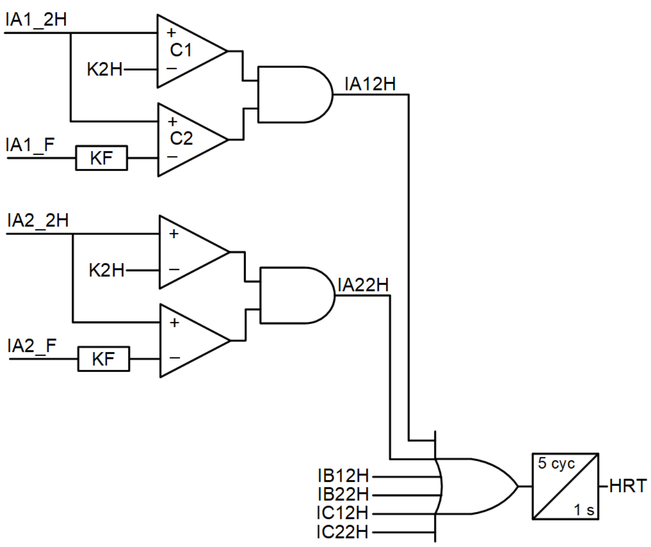

Fig. 10. Second-Harmonic External Event Detector

For high-impedance grounded generators where the generator step-up transformer is outside of the differential zone, the relay can further improve protection by computing the differential element pickup threshold (O87P2) in real time, as shown in Fig. 11.

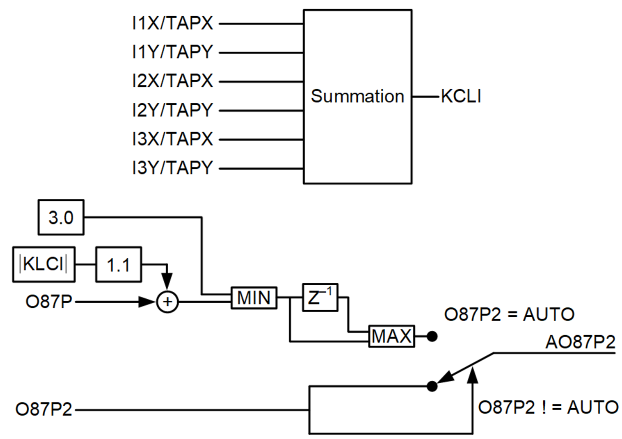

Fig. 11. Adaptive HSM Minimum Restraint Pickup Logic

Note that setting an O87PU2 value too high delays operation for external events evolving into internal faults. For external events evolving into low-current faults, where the (I_{OP}, I_{RT}) location falls between the two characteristics, tripping is delayed considerably.

The adaptive logic in Fig. 11 determines a vector sum of all the compensated fundamental currents and adds it to the sensitive minimum restraint pickup threshold. Under normal conditions, the vector sum of all currents should be 0, but as any uneven saturation occurs, the logic automatically increases the threshold. As the CTs recover and come out of saturation, the adaptive threshold decreases and provides increased security for evolving internal faults.

C. Harmonic Blocking and Restraint

For generator differential applications that include the transformer in the differential zone (see Fig. 12), the relay still has HSM but does not use the adaptive minimum restraint pickup AO87P2 element.

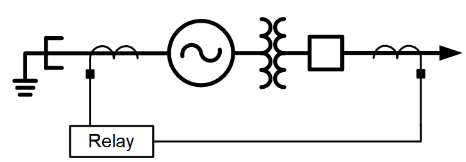

Fig. 12. Generator Differential With Transformer in Zone

Differential elements meant to protect transformers or generator step-up units often include second- and fourth-harmonic restraint and/or blocking. It is important to note that these harmonic methods look for harmonics in the differential currents and will not help avoid undesirable operations when picking up a transformer external to the protection zone. References [12] and [13] provide more insight into harmonic blocking and restraint.

D. Delay 87 Element

If a relay is used that does not provide HSM, harmonic restraint, or blocking, additional logic can be programmed to increase security during energization at the expense of sacrificing protection for a short duration. The proposed logic in Fig. 13 blocks the restrained differential element 87R for a few cycles after closing the generator breaker. This logic completely blocks restrained differential, preventing misoperation for CT saturation and inrush scenarios while leaving the unrestrained element free to trip for a severe internal fault. This should be used cautiously and after all other mitigation techniques have been exhausted.

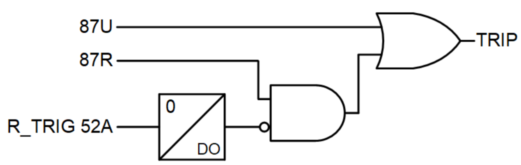

Fig. 13. Custom Blocking Logic for 87R Element

E. 87N Considerations

The 87N is a differential element that uses the zero-sequence (3I0) of the terminal currents and compares it to the measured neutral current. It is applied on solidly grounded or resistance-grounded systems that limit the fault current to no less than 200 A and cannot be used on high-impedance grounded systems. While this scheme can be sensitive for internal faults, there are security concerns when the terminal CTs saturate. The saturation creates a false 3I0 that is summed with the measured neutral current, which will be zero, potentially causing the 87N to operate. To avoid misoperation, the element must be delayed or blocked for the worst-case fault clearing time for an external fault that can cause the CTs to saturate.

Alternatively, if the protective relay has HSM, this logic can be used to supervise the 87N element. This allows 87N to be used for internal faults and to provide the required security to ride through CT saturation for external events. This is more ideal than delaying the element. Reference [14] provides further details and guidelines for increasing 87N security.

F. Restricted Earth Fault Considerations

The restricted earth fault (REF) element shown in Fig. 14 is an alternative to the 87N element and is applied in a similar configuration. REF is a comparison between the measured neutral current and the residual of the terminal-phase CTs, where the current from the neutral CTs is used for operate current and the residual of the phase CTs is used for polarization. The REF element is secure from CT saturation because the 3I0 generated is present only in the terminal CT measurement while no current flows in the neutral. Thus, there is no operate quantity to trip.

VII. Generator Black-Start Design Considerations

A. When Generator and Switchgear Are Under One Procurement

It is common for black-start generator protection to include the generator breaker as part of the differential zone. It protects the cables and reduces the number of CTs required for generator and cable protection. However, the designer must be aware that with metal-clad switchgear, the CT voltage rating options may

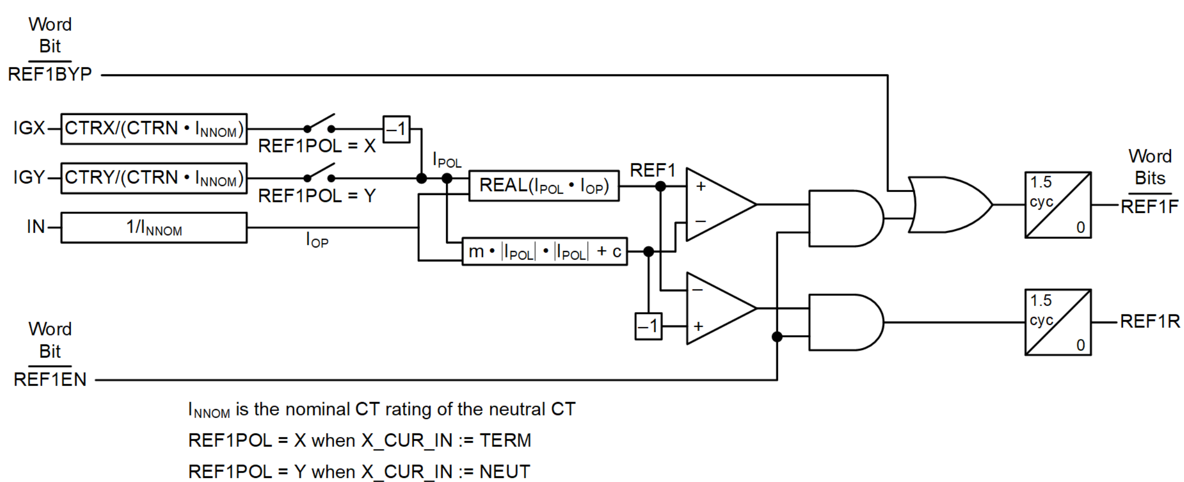

Fig. 14. REF Element

be limited due to the physical space constraints. This style of installation typically has two configurations, as shown in Fig. 15.

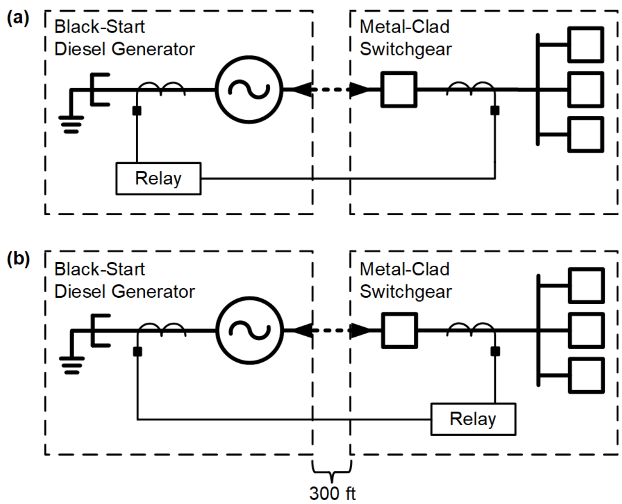

Fig. 15. Black-Start Generator Connected to Switchgear

In each of these configurations, the CT lead length can be significantly different. In Fig. 15a, with the differential relay near the generator, the neutral leads are short and the terminal CT leads are long. In Fig. 15b, with the differential relay at the breaker, the generator terminal CT leads are short and the neutral leads are long. If the designer matches CT size and characteristics per IEEE C37.100 but does not consider the difference in burden from CT leads, unequal saturation may occur.

For example, if 300 ft is the distance between the generator and the breaker, using a #10 AWG cable at a total loop length of 600 ft for the terminal (see (13)) and 50 ft for the generator neutral (see (14)), there is a 0.55 ohm difference in burden between the neutral and terminal CTs, as shown in (15).

$$CT_{NEUT} := \left(\frac{50}{1000}\right) \bullet e^{(0.232 \bullet 10 - 2.32)} = 0.05 \tag{13}$$

$$CT_{TERM} := \left(\frac{600}{1000}\right) \bullet e^{(0.232 \bullet 10 - 2.32)} = 0.6 \tag{14}$$

$$CT_{DIF} := CT_{TERM} - CT_{NEUT} = 0.55 \tag{15}$$

To help ensure that the black-start generator does not have any CT saturation issues, consider the following:

- Specify the same make and model CT for the neutral and terminal.
- Consider the length and size of the leads.
- Use a relay with HSM.
- Add logic for HSM and enable it for black-start mode, if required.

B. Generator and Switchgear Are Different Projects

If the black-start generator is connected to a spare cubicle in existing switchgear or is provided as a separate contract, it is often discovered that the CTs are not matched in the field. This mismatch may lead to saturation issues that reduce the security of the differential elements.

If this is a new design, the issue can be mitigated by the design engineer specifying a CT that accounts for the correct sizing and particular CT model for both contracts.

For a design that is incorporating a black-start generator into an existing cubicle, it is critical that the design engineer determine the following CT characteristics: ratio, excitation curve, and winding resistance. Using these characteristics, the CT must be evaluated with the proposed generator differential design.

In addition, it is important to consider doing the following when adding a black-start generator to existing switchgear:

- Use the excitation curve for existing CTs and try to match terminal CTs with neutral CTs.
- Use CTs larger than C20. We have experienced problems that required multiple mitigation techniques to ensure black-start security, as explained in the case study in Section VIII.
- Estimate the saturation using (6) and (9) to determine if parallel leads or larger leads are required. Generator X/R can be estimated using the method described in the Appendix.
- Use a relay with HSM, and add logic for HSM to be enabled for black-start mode, if required.

VIII. Case Study: Generator Trip for Black-Start Conditions

One user discovered a problem with a black-start generator tripping when performing startup testing on site. The user normally ran connected to the utility, as shown in Fig. 16. In the event of a utility loss, one of two black-start generators were required to start the energization process.

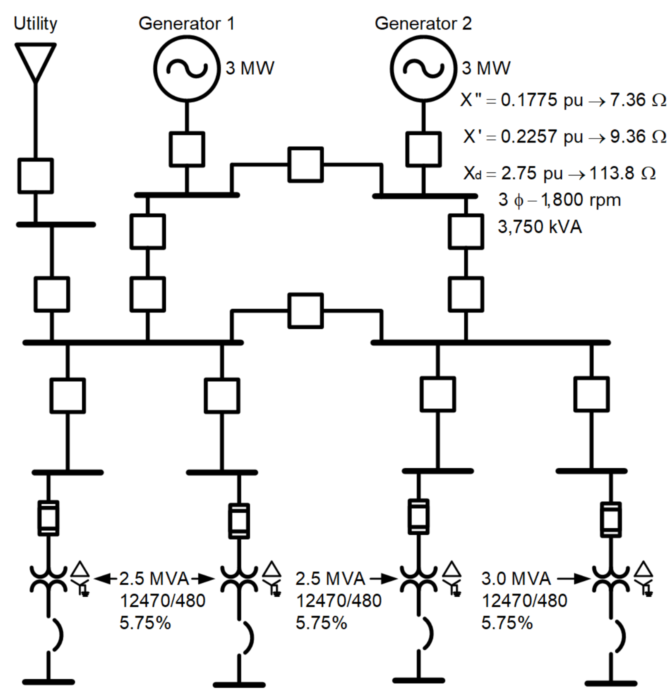

Fig. 16. System One-Line

The original intent was to bring the generators online, and then one-by-one energize the power transformers. However, there was a life safety requirement that all fire pumps be back online within 10 seconds. Because the fire pumps were all around the campus, this requirement practically forced all four power transformers to come online simultaneously. This led to investigation of the differential relay and CT circuits to evaluate their performance during energization and ensure that the black-start generator stays online.

A. CT Analysis

The machines in this system are diesel generators; their parameters are listed in Table III.

TABLE III
GENERATOR PARAMETERS

Description	Values
Machine rating	3.750 MVA
Voltage level	12.47 kV
Positive-sequence impedance	7.37 ohms
Positive-sequence angle	86.78 degrees
Negative-sequence impedance	9.48 ohms
Zero-sequence impedance	1.28 ohms
X/R ratio	17.75

To gauge the performance, the CTs were modeled in a Mathcad CT simulation based on [10].

The parameters for CT1 that measured the generator neutral currents are listed in Table IV.

TABLE IV
CT1 CHARACTERISTICS

Description	Values
CT class	C20
Secondary-side resistance	0.054 ohms
Secondary-side inductance	1E-6 henries
Turns ratio	40
CT lead length	300 ft
Burden series resistance	0.32 ohms
Burden series inductance	1E-6 henries

These parameters were then used in (16) to calculate the per-unit saturation voltage. A voltage of <20 satisfies the criterion to avoid CT saturation.

$$V_S := \left(1+\frac{X}{R}\right)\bullet\frac{I_{MAG}}{I_{SEC}N}\bullet\frac{\left|R_B+\omega\bullet L_B\right|\bullet 20}{V_{RAT}} = 75.368 \quad (16)$$

For these parameters, there was a significant chance that the CT would saturate. Fig. 17 shows what the ratio and actual current waveforms would be.

The CT shows indication of saturating in the first 1/8 cycle. As the dc offset decays, the CT secondary starts to become a replica of the ratio current.

The parameters for CT2 that measured the generator breaker currents are listed in Table V.

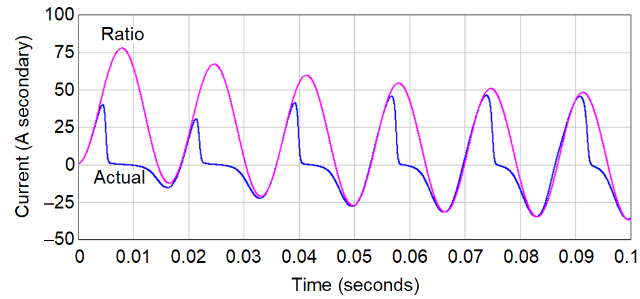

Fig. 17. Neutral CTs: CT1 Ratio and Actual Secondary Current

TABLE V
CT2 CHARACTERISTICS

Description	Values
CT class	C20
Secondary-side resistance	0.06901 ohms
Secondary-side inductance	1E-6 henries
Turns ratio	40
CT lead length	50 ft
Burden series resistance	0.07 ohms
Burden series inductance	1E-6 henries

These parameters were then used in (17) to calculate the per-unit voltage. Recall that a voltage of <20 satisfies the criterion to avoid CT saturation.

$$V_S := \left(1+\frac{X}{R}\right)\bullet\frac{I_{MAG}}{I_{SEC}N}\bullet\frac{\left|R_B+\omega\bullet L_B\right|\bullet 20}{V_{RAT}} = 19.54 \quad (17)$$

For these parameters, it was a close call on whether the CT would saturate. The graphical representation of this is shown in Fig. 18.

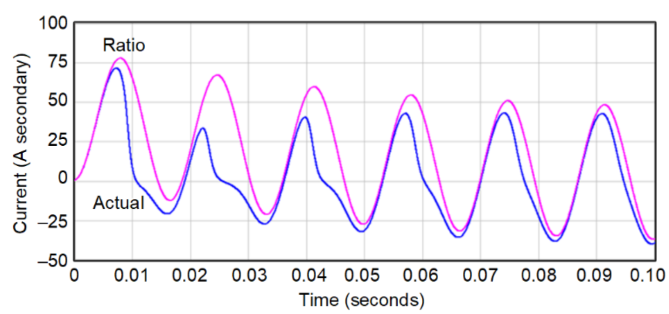

Fig. 18. Terminal CTs: CT2 Ratio and Actual Secondary Current

The CT shows indication of saturating in the first 1/4 cycle. As the dc offset decays, the CT secondary starts to become a replica of the ratio current. Because the two CTs saturate at different times, the relays will likely measure a false differential current.

Table VI lists the excitation characteristics for the two CTs.

TABLE VI
CT1 AND CT2 EXCITATION CHARACTERISTICS

Current (A)	CT1 Voltage (V)	CT2 Voltage (V)
0.01	0.3	0.4
0.02	0.6	0.8
0.04	1.3	1.6
0.05	1.8	2.1
0.08	3.4	3.8
0.1	4.5	5
0.2	11.1	12
0.4	21.1	23.5
0.5	23	25.6
0.8	25.4	28

The excitation characteristics for the two CTs can then be plotted on a logarithmic graph to see how they compare, as shown in Fig. 19.

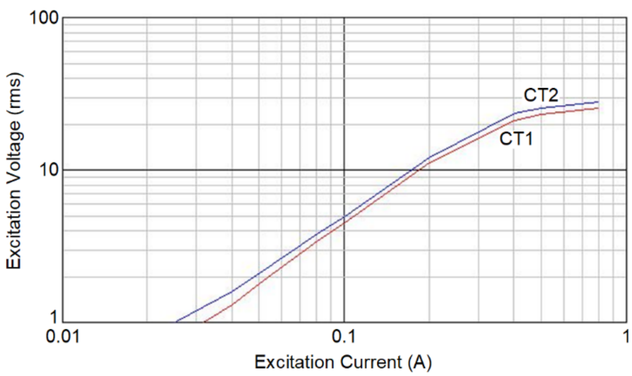

Fig. 19. CT1 and CT2 Excitation Characteristics

This graph shows that the excitation characteristics are practically identical.

B. Hardware-in-the-Loop Testing

Hardware-in-the-loop testing was performed using a real-time digital simulator, which is an Electromagnetic Transients Program (EMTP) that runs in real time and allows the integration and testing of the relay with the exact firmware version and settings that will be used in the field. The intent for this project was to validate that the relays would be secure for external faults and transformer inrush. To perform the validation required accurate models of the CTs and the power transformers. The CTs were modeled using the characteristics previously discussed, while the power transformers were modeled with the parameters listed in Table VII and the magnetization characteristics to accurately model the inrush current.

With the model setup, external faults were simulated to validate the performance of the CTs and to ensure they matched the Mathcad simulations. An external single line-to-ground fault is shown in Fig. 20. The top graph is the ratio and secondary current of CT1, and the bottom graph is the ratio and secondary current of CT2. Comparing Fig. 20 to Fig. 17 and Fig. 18 shows that the current waveforms closely match. The main difference is that a static simulation is being compared to an EMTP simulation.

TABLE VII
TRANSFORMER PARAMETERS

Description	Values
Transformer rating	2.5 MVA
Leakage inductance	0.0575 pu
No-load losses	0.0101 pu

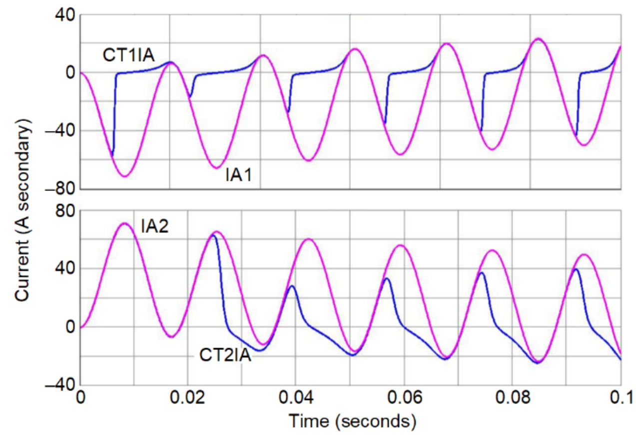

Fig. 20. Waveforms From an External Single Line-to-Ground Fault

C. Test Results

The relays were connected to the simulation and exercised appropriately. We started by simulating an external single line-to-ground fault on the generator bus and capturing the event record from the relay, as shown in Fig. 21.

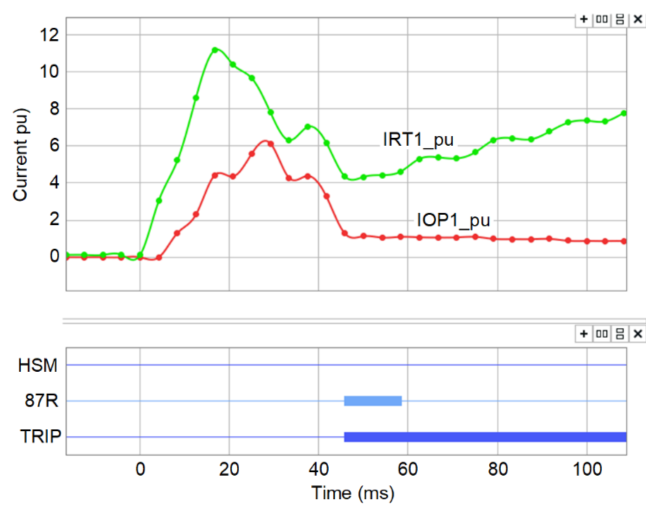

Fig. 21. External Single Line-to-Ground Fault With HSM Disabled

The top plot shows the operate and restraint current, and the bottom plot shows the digital elements that operated. Initially, the operate and restraint current are nearly equal, and the digital elements show that both 87R and TRIP asserted. From an external single line-to-ground fault, it was immediately required to enable HSM to prevent a misoperation.

With HSM enabled and O87P2 set to AUTO, the fault was reapplied, with the results shown in Fig. 22. HSM asserted during the fault and prevented the relay from misoperating.

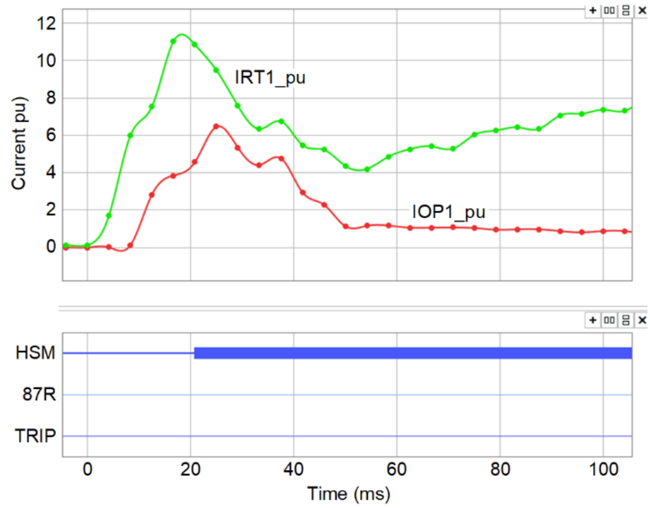

Fig. 22. External Single Line-to-Ground Fault With HSM Enabled

Fig. 23 shows the event record of the operate and restraint currents, as well as the HSM and 87R for a transformer energization event. With HSM disabled, the 87R element operated and tripped the generator approximately 200 ms into energization.

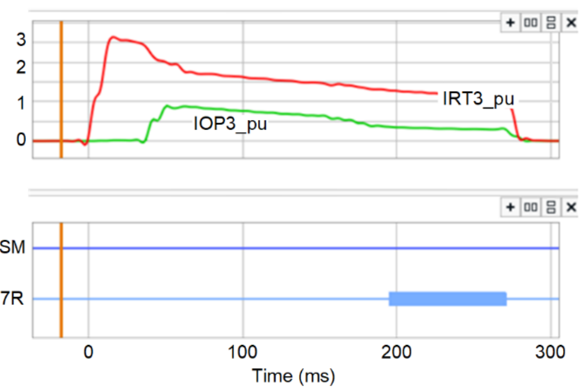

Fig. 23. Single Transformer Energization With HSM Disabled

Fig. 24 is a replay of the same event, this time with HSM enabled. Upon transformer energization, HSM asserts and stays asserted for about 600 ms, riding through the transformer energization and blocking the differential element.

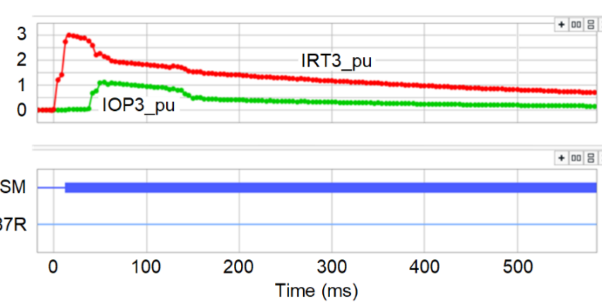

Fig. 24. Single Transformer Energization With HSM Enabled

Since the requirement is to energize four transformers, we moved to that next. Fig. 25 shows the energization of four transformers with HSM enabled.

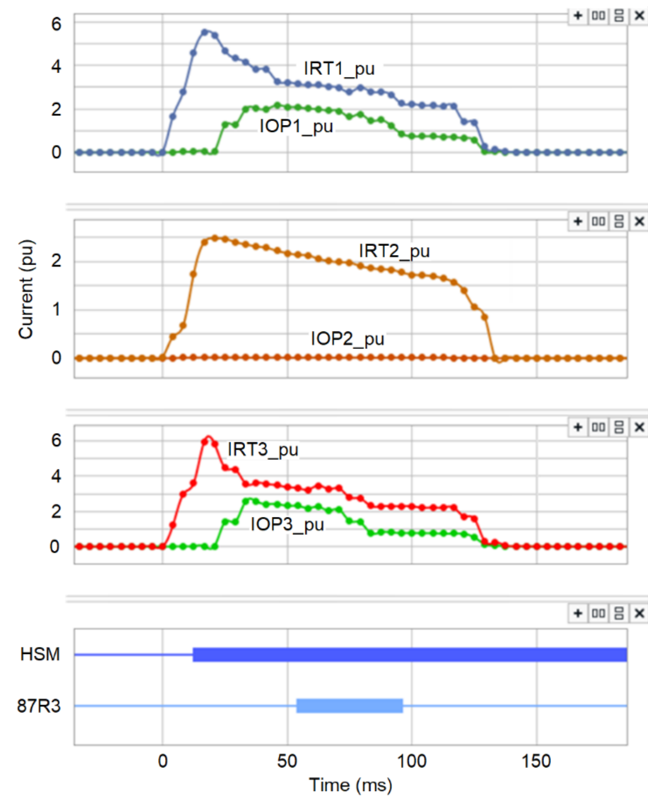

Fig. 25. Four Transformers Energized With HSM Enabled

Unfortunately, just using HSM was not enough to prevent tripping on the energization of four transformers. Going back to the mitigation techniques discussed previously, we investigated using parallel CT leads for the longest run on CT1 to reduce the burden by half. The result of secondary current compared to the ratio current is shown in Fig. 26.

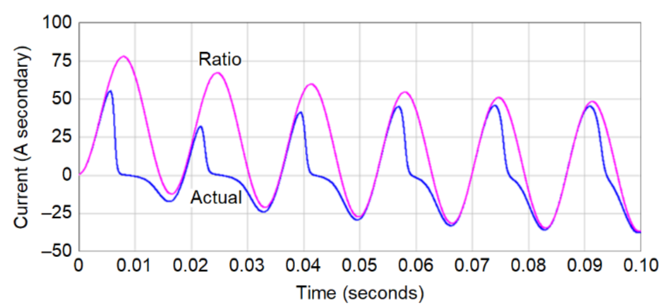

Fig. 26. CT1 Ratio and Actual Secondary Current With Parallel CT Leads

Paralleling the CT leads decreased the effect of the CT saturation. The burden was adjusted in the real-time digital simulator model, and the same four transformers were energized again. The event record is shown in Fig. 27.

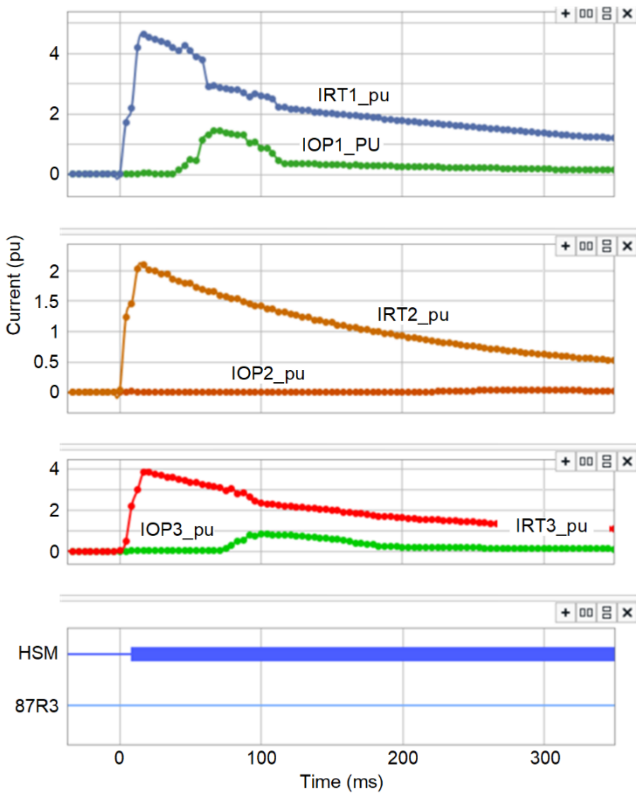

Fig. 27. Four Transformers Energized With Parallel Leads and HSM Enabled

The combination of using HSM in the relay and paralleling the leads from CT1 allowed the differential protection to remain secure during the energization of four transformers. Another option would be to investigate the use of C50 CTs. However, there was a physical limitation in space, so C50 CTs would not have fit.

Performing the simulations and using hardware-in-the-loop testing allowed for an effective solution prior to commissioning. This no doubt saved countless hours of commissioning time and investigation to get the system to the desired point of operation.

IX. Conclusion

This paper shows that correct CT sizing is important to generator differential protection. Improper selection can lead to many issues, several of which are addressed in this paper to provide mitigation techniques.

Following are the main takeaways:

- Proper CT selection is the highest importance when considering security for generator differential protection.
- In applications where CT saturation is likely to cause differential trips, generator relays with external event detectors and HSM greatly reduce unwanted trips.
- HSM can be enabled for known transformer energization using custom relay logic.
- It is difficult to size CTs so that they do not saturate during transformer inrush on smaller black-start units. The traditional CT criterion for saturation may not be feasible due to high X/R ratios, and physical space constraints may prevent the use of a higher C class.
- If the criterion cannot be satisfied, the next important goal is to minimize differences in time-to-saturation. This can be accomplished by using the same manufacturer for both neutral and terminals CTs and by considering the difference in lead burden.
- For issues discovered during startup, there are several mitigation solutions that can be implemented without large expenses or time.
- Hardware-in-the-loop testing allows for realistic comparison of different mitigation techniques.

Table VIII provides a high-level overview of the mitigation techniques and their effectiveness as well as implementation cost comparisons.

Table VIII
Black-Start CT Saturation Mitigation Techniques and High-Level Cost Comparison

Mitigation Technique	Cost Prior to Installation	Cost After Installation	Effectiveness
Correct CT specification	Low	High	Very high
Relay with HSM	Low	Low	High
Logic to enable HSM	Low	Low	High
Using parallel lead	Low	Medium	Low to medium
Increasing resistance to match burden	Low	Medium	Low
Introducing 87 delay during inrush	Low	Low	Medium

X. APPENDIX: ESTIMATING GENERATOR X/R RATIO

During the design phase, the generator X/R ratio may not be available for CT calculations and selection. Reference [15] provides a figure (Fig. 28) that can be used to estimate X/R ratio based on the kVA rating of the synchronous machine.

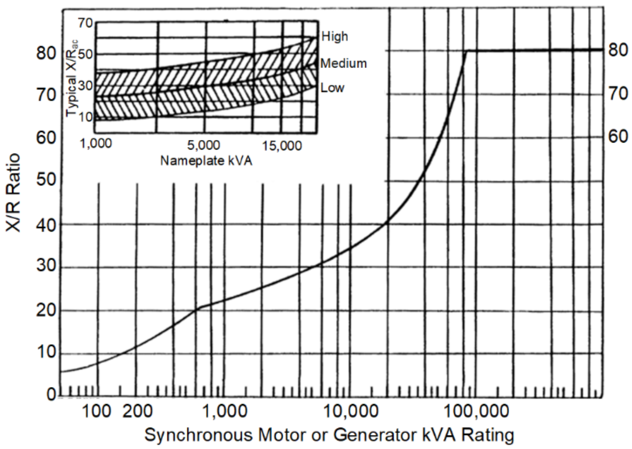

Fig. 28. IEEE X/R Ratios for Synchronous Machines [15]

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XII. BIOGRAPHIES

Austin Wade received his BS in Electronic and Electrical Engineering, summa cum laude, from California State University, Sacramento, in 2013. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2012. He is presently working as the automation group manager in the Pullman branch of the SEL Engineering Services, Inc. group. He is a registered professional engineer in the state of California and is a member of the IEEE Power and Energy Society.

Jordan Bell received his BSEE from Washington State University in 2006. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2008 as a protection engineer in the SEL Engineering Services, Inc. group. He is currently a senior engineer and supervisor in that group, working on event report analysis, relay settings and coordination, fault studies, and model power system testing with a real-time digital simulator. He is a registered professional engineer in the state of Washington and a member of IEEE.

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 senior research engineer. He holds several patents and has authored numerous papers related to power system protection.