Transformer Differential Protection Revisited

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***Abstract*—This paper takes a fresh look at transformer differential and restricted earth fault protection. The paper provides a new way to rule out magnetizing inrush as a source of the differential current, allowing tripping for most transformer faults in as fast as a quarter of a power cycle. The paper also provides a new way to restrain the differential element for ratio errors and by doing so allows increasing protection sensitivity. Some of the presented ideas require the transformer relay to have access to the voltage signal, but today, such access is not a limiting factor. The paper also addresses protection dependability for faults that occur during or prior to transformer energization.**

I. Introduction

Power transformers are expensive assets with long lead times and complicated onsite delivery and installation steps. Transformer faults may result in limited damage, allowing the transformer to be repaired, or in a catastrophic failure, resulting not only in scrapping the damaged transformer but also in a substation fire with collateral damage and environmental costs due to the potential for an oil spill. The speed and sensitivity of the transformer protective relay can be the difference between a routine trip and extensive, costly damage.

Transformer differential (87T) protective relays follow the operating principles devised many decades ago within the limitations of the electromechanical relay technology. This backward compatibility and intentionally restrained innovation contributed to the fast adoption of microprocessor-based 87T relays but resulted in no or only limited protection performance improvements. Today's 87T protection elements take a power cycle or more to operate, have limited sensitivity to turn faults, and may face both security and dependability problems during transformer energization.

This paper takes a fresh look at the speed and sensitivity of transformer differential protection. Magnetizing inrush current is the single most critical obstacle to the 87T protection speed: having to rule out inrush slows down the 87T protection to about 1.5 cycles. Current transformer (CT) ratio errors and the onload tap changer operation are key obstacles to the 87T protection sensitivity.

The paper proposes a new way to rule out the magnetizing inrush as the cause of the differential current, offering an opportunity to reduce the 87T protection operating time to about a quarter cycle. The paper discusses the new method and proves that it works well during voltage recovery inrush (clearance of a nearby external fault) and sympathetic inrush (an energized transformer drawing a gradually increasing inrush current because of dc offset in the voltage that is caused by the initial energization of a nearby transformer).

The paper proposes a new way to restrain the 87T protection for CT and transformer ratio errors, including the onload tap changer operation. The new method is not concerned with fast and deep CT saturation during external faults, because the tried-and-true external fault detection logic solves this challenge very well. Instead, the paper focuses on small CT ratio errors during load or remote fault conditions and the challenge of attributing the small differential current either to an internal fault or to CT and relay measurement errors or transformer ratio changes.

The paper also discusses the challenges and solutions for detecting internal faults during transformer energization.

Section II is a short tutorial on transformer differential protection. It reviews the sources of spurious differential current and methods to secure the transformer differential protection. Section III reviews the fundamentals of restraining transformer differential protection. It is a refresher on the ampere-turn balance principle and how it drives the proper differential current formulation. The section introduces a new method of restraining for enhanced sensitivity. It also shows how to track the transformer ratio online to minimize the standing differential current and improve protection sensitivity. Section IV reviews the challenges and solutions to the magnetizing inrush current during initial energization, voltage recovery after clearing an external fault, sympathetic inrush, and sudden overexcitation. Section V addresses security during external faults, including the principle of external fault detection logic. Section VI reviews arming logic that supervises the fast and sensitive modules in the enhanced transformer differential protection element. Section VII discusses challenges and solutions to transformer protection dependability for faults that occur during or prior to transformer energization. Section VIII includes examples of operation of the proposed protection methods.

II. Short-Circuit Protection for Power Transformers

Power transformers require protection against a range of abnormal conditions ranging from an internal short circuit to a thermal overload. This paper focuses on short-circuit protection and is concerned with 1) phase and ground terminal faults, 2) interwinding faults, 3) turn-to-turn faults, and 4) winding-to-ground (winding-to-core or winding-to-tank) faults.

A fault arc inside the transformer tank decomposes the oil and creates gases while moving the oil. These fault byproducts facilitate the application of oil and gas protective relays. Because the oil and gas relays respond to byproducts of faults, they tend to be dependable and sensitive, especially for incipient and low-current faults, but relatively slow because gases and oil movement are lagging fault indicators. Because of their relatively slow operation, the oil and gas relays are often considered as backup for electrical transformer protection: transformer differential (87T) and restricted earth fault (REF) protection elements. Sudden pressure relays are fast and therefore considered redundant to electrical transformer protection. Because currents are instantaneous indicators of faults, electrical protection – especially in the form of differential protection – has a high potential for speed. In the case of protecting a power transformer, however, this potential is not fully realized.

Transformer differential protection is based on an ampere-turn balance between pairs of legs of the transformer core [1]. Therefore, it can detect changes in the ampere-turns, including 1) current diverted away from any part of any winding and 2) an effective change in turns of any winding. These two scenarios cover turn-to-turn faults, interwinding faults, and winding-to-ground faults. Transformer differential protection covers all fault types, although with varying and sometimes limited sensitivity.

Restricted earth fault protection monitors Kirchhoff's current balance between the currents at the winding terminals and the grounded neutral of a wye- or zigzag-connected winding. Therefore, it protects a winding (not the entire transformer) and is only able to detect ground terminal faults and winding-to-ground faults. REF protection has limited coverage compared with transformer differential protection, but its application is beneficial because it is more sensitive to ground faults close to the winding neutral point. Also, REF protection security is not affected by the transformer magnetizing current. Therefore, REF protection can operate faster than transformer differential protection and is more dependable when energizing a faulted transformer.

A. Causes of Spurious Differential Current

Current differential protection is the strongest protection principle at our disposal. However, when applied to a specific power apparatus, it faces specific security challenges. In the case of a power transformer, it is the magnetizing current that demonstrates itself as a spurious differential current and causes security issues. Additionally, tap changers (onload or offline) vary the turns ratio of a transformer, upset the nominal ampere-turn balance, and by doing so cause a spurious differential current to appear.

The following are generic as well as transformer-specific sources of a spurious differential current.

1) Transformer Magnetizing Current

The ampere-turn balance equations that underpin the transformer differential protection do not account for the magnetizing current, and therefore the magnetizing current demonstrates itself as a spurious 87T differential current. We distinguish the following categories of the magnetizing current: initial energization inrush current, voltage recovery inrush current, sympathetic inrush current, sudden voltage change inrush current, and overexcitation (overvoltage and/or underfrequency) current. Section IV discusses the magnetizing current challenges and solutions in detail. Traditionally, harmonic blocking or restraining are used to secure the 87T element during magnetizing current conditions.

2) CT Ratio Errors

An 87T differential current comprises three or more measured currents (see Subsection II.A.4) for example). When using breaker bushing CTs in dual-breaker applications, more than five measured currents typically make up the 87T differential current. Each of these currents is measured with a small CT ratio error. These errors can accumulate or partially cancel and yield a small standing differential current. Traditionally, a minimum pickup threshold and a small percentage restraint (e.g., 15 percent) address the CT ratio errors in 87T elements.

3) Transformer Ratio

The ampere-turn balance equations that establish the 87T protection assume numbers of turns that correspond to nominal winding voltages. In reality, the transformer voltage ratio has a finite tolerance due to flux variations near the winding edges and proximity effects. A small difference in the transformer ratio demonstrates itself as a small standing differential current. Traditionally, a small percentage restraint addresses the transformer ratio error in the 87T elements. A tap changer further exacerbates this problem by contributing to ratio changes on the order of 10 percent.

4) CT Saturation During External Faults

When CTs saturate during external faults, the CT errors increase far beyond small ratio errors. CT errors elevate the spurious differential current considerably during external faults. The transformer impedance limits the external fault current to about 10 times the nominal current, and by doing so, it alleviates the danger of severe CT saturation during through-faults. However, in dual-breaker applications, the transformer impedance does not limit the current passing through the two breakers (in and out of the 87T zone if using breaker bushing CTs). In these cases, the through-fault current can be very high. Also, in systems with large X/R ratios, the slowly decaying dc component in the fault current can cause CT saturation even if the transformer impedance limits the ac component in the external fault current.

The long-lasting dc component in the initial energization inrush current also causes CT saturation. External faults immediately following transformer energization may cause the transformer CTs to saturate because the preceding inrush current elevates the CT flux.

Traditionally, 87T elements use a high percentage restraint to address CT saturation. An 87T element can apply such increased restraint permanently, or it can engage a high restraint when it detects an external fault by using an external fault detection logic.

External faults that do not produce zero-sequence current (phase-to-phase and balanced three-phase faults) but cause CT saturation may affect REF protection security. Traditionally, the REF element balances the neutral-point winding current with the tripled zero-sequence current (3I0) at the winding terminals. The 3I0 component in the secondary currents is spurious during phase faults with CT saturation. As a remedy to this problem, REF elements often require the presence of the neutral-point current before they operate (the neutral-point current is zero during external phase faults).

B. Transformer Differential Protection

Fig. 1 shows a simplified diagram of a generic 87T element. The following description serves as a brief tutorial on 87T protection while highlighting obstacles to 87T element speed and sensitivity.

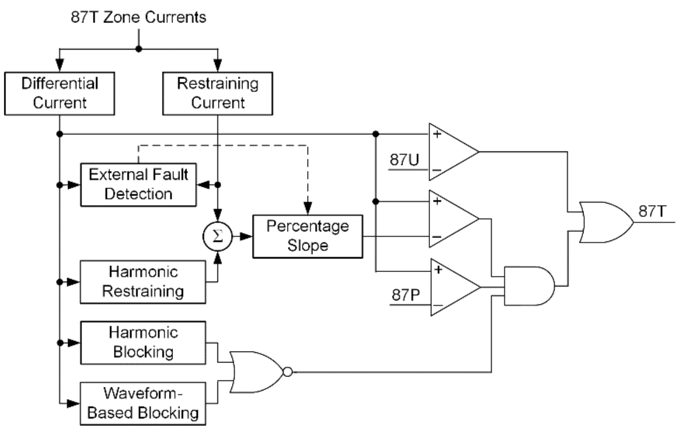

Fig. 1. 87T element simplified logic diagram.

The 87T element derives the differential (operating) and restraining currents by using all currents that form the boundary of the 87T zone. In dual-breaker applications with breaker bushing CTs, currents from both breakers should contribute to the restraining current. The 87T protection is typically implemented as a three-phase ("phase-segregated") element, but it may also include a negative-sequence differential element [1] [2]. The term phase-segregated is not strictly correct because the transformer differential current equations mix currents from two or all three phases (see Subsection II.A.4) for example). In the rest of this paper, we refer to 87T "loops" rather than 87T "phases" (similar to a distance protection element).

The 87T element operates if the differential current is above the minimum pickup threshold (87P) and above a percentage of the restraining current. These two comparators can be implemented on waveform samples (lowpass-filtered) or the fundamental-frequency phasor (bandpass-filtered) quantities.

The harmonic-blocking module ensures security during magnetizing inrush and overexcitation conditions. If the differential current is rich in harmonics, the logic blocks. Even harmonics (primarily the second harmonic) indicate inrush. Odd harmonics (primarily the fifth harmonic) indicate stationary overexcitation. Harmonic blocking is preferably performed on a per-loop basis to avoid jeopardizing the 87T element dependability. In certain applications, the level of harmonics during inrush conditions can be low [3]. This forces protection engineers to 1) lower the harmonic blocking thresholds (i.e., make the harmonic blocking logic more sensitive to harmonic content) and risk affecting protection speed and dependability, 2) apply cross-phase harmonic blocking with even more concerns about speed and dependability, or 3) use additional methods to address magnetizing inrush, such as waveform-based inrush detection [4] [5].

Harmonic restraining, like harmonic blocking, is also based on high harmonic content in the differential current during inrush. However, instead of blocking the 87T logic, harmonic restraining uses harmonics in the differential current to boost the restraining current. The gain factor between the differential harmonics and the restraining current is selected in such a way that during the initial energization inrush, which is a single-end feed, the increase in the restraining current is sufficient – given the percentage slope setting – to prevent the 87T element from operating. Harmonic restraining and harmonic blocking face similar issues in applications with low harmonic content during inrush. Typically, either harmonic blocking or harmonic restraining is used.

Both harmonic blocking and restraining slow down the 87T logic. During internal fault conditions, the harmonic filters are excited with a sudden change in current and, as a result, they output spurious harmonics. For example, when using a full-cycle filter, a spurious harmonic signal lasts for one cycle before the filter correctly outputs zero as the value of that harmonic. Moreover, during inrush conditions, the harmonic filter is also subjected to the sudden change in current, and therefore it may temporarily underestimate the harmonic or the harmonic ratio. A harmonic ratio that momentarily falls below the blocking threshold would result in 87T element misoperation. Therefore, practical 87T element implementations add a dropout security timer in the harmonic blocking logic: if the harmonic ratio is above the blocking threshold for a certain time, such as a quarter cycle, a short dropout timer is engaged to ride through the temporary low harmonic content due to the transient response of the filters. This additional dropout timer further delays the unblocking action during internal fault conditions.

As a result, the differential unit of the 87T element may be ready to operate for an internal fault in a quarter cycle, yet the harmonic blocking or restraining unit holds it back for more than a full cycle.

The unrestrained differential element remedies this situation but only for high-current internal faults. The unrestrained element uses a high-set threshold (87U) instead of using the percentage restraint. The threshold is set above the highest possible inrush current, removing the need to use harmonics for security during inrush conditions.

Waveform-recognition methods address inrush by detecting the presence of dwell-time intervals in the differential current [4] [5]. These dwell-time intervals are present during inrush conditions but not during internal faults. However, the first dwell-time interval is visible in the inrush current only at the end of the first power cycle following energization. Therefore, the waveform-recognition methods must block the 87T element for just over one cycle, similarly to the harmonic-based methods. The waveform-recognition blocking methods are not used for speed but to address the security concern related to the low second-harmonic content during energization.

The relatively slow 87T element operation may inadvertently impact dependability. To ensure the 87T element operates for internal faults, the CT secondary currents must faithfully represent the primary currents without adding distortions that may cause the harmonic-based methods to assert and block the 87T element. As a result, the 87T protection CTs must be rated to provide saturation-free operation for as long as it takes the 87T element to operate. The worst-case scenario is when the 87T element is initially blocked by spurious harmonics because of the filter transients and continues to be blocked because of actual harmonics arising from CT saturation.

The external fault detection logic monitors the rise in the differential and restraining currents. During external faults, the restraining current increases immediately while the differential current – if it increases because of CT saturation – increases after a time delay because the CTs initially operate without saturation. During internal faults, the differential and restraining currents increase simultaneously. Some external fault detection implementations may also monitor the decaying dc components in the measured currents and operate in anticipation of CT saturation because of the large and slowly decaying dc component rather than the large ac component in the fault current. Typically, the external fault detection logic engages a higher percentage slope in order to provide more restraint. The external fault detection logic does not block the 87T element, so the element continues to provide some protection should an internal fault develop during, and as a result of, the external fault.

Concerns related to voltage recovery inrush, sudden voltage change inrush, and sympathetic inrush prevent practitioners from applying very sensitive 87P pickup thresholds. Concerns with CT ratio errors, transformer ratio tolerance, and onload tap changers drive higher slope settings. As a result, the 87T element cannot be very sensitive. The negative-sequence transformer differential (87TQ) element has a potential for higher sensitivity but only because it intentionally lowers the restraining signal [2]. The standing spurious differential signal is not guaranteed to be symmetrical, and the 87TQ element cannot be set to provide extremely sensitive protection.

C. Restricted Earth Fault Protection

The REF element implementation may follow a phase-comparison principle, a differential restraining principle, or a combination of the two as Fig. 2 illustrates. The following description serves as a brief tutorial on REF protection while highlighting obstacles to REF protection speed and sensitivity.

The phase-comparison implementation treats the REF element as a ground directional element in which I_N is the operating signal and 3I0 is the polarizing signal. These two signals are out of phase during external faults and approximately in phase during internal faults. The phase-comparison implementation verifies that the neutral-point current (I_N) is above the minimum pickup threshold (INP) before allowing the REF element to operate.

The differential REF implementation derives the differential (operating) current as the sum of the neutral-point current (I_N) and the 3I0 in the phase currents (I_A, I_B, and I_C) of the protected winding. Strictly speaking, REF protection is a four-current differential element, but often it is implemented and analyzed as a two-current differential element (I_N and 3I0) when used as a low-impedance scheme. The REF logic verifies that the differential current is above a minimum pickup threshold (REFP), but it should also verify that the neutral-point current (I_N) is above a minimum pickup threshold (INP).

Requiring I_N to be above a minimum pickup threshold contributes to REF security during phase-to-phase and balanced three-phase external faults with CT saturation. Practical implementations must also address security during external phase-to-phase-to-ground faults with CT saturation.

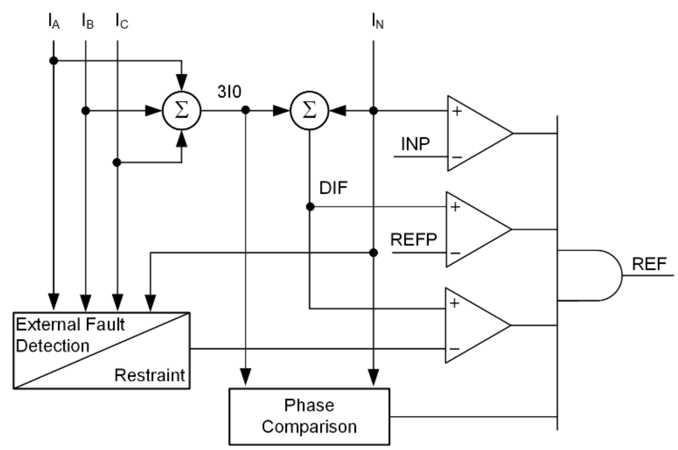

Fig. 2. REF element simplified logic diagram.

The differential restraining implementation derives a restraining current from the I_N and 3I0 currents. To address phase-to-phase and three-phase balanced faults, this implementation may also derive additional restraint from the phase currents or the positive- or negative-sequence current components.

It is beneficial to realize that the phase-comparison REF implementation and the differential REF implementation that uses the magnitude of the difference between the I_N and 3I0 currents as the restraint are exactly equivalent (see [8] for more information about using the difference of two currents when restraining two-current differential elements).

The REF element may use an external fault detection logic for additional security: either the external fault detection logic associated with the 87T element or a dedicated external fault detection logic that works with the four currents that form the boundary of the REF zone: I_A, I_B, I_C, and I_N.

The REF element is primarily applied for sensitivity to ground faults close to the winding neutral. Therefore, in dual-breaker applications, it is advantageous to use the REF element with the transformer bushing CTs rather than with two sets of breaker bushing CTs. If applied with two sets of breaker CTs, the REF element should restrain for external faults that draw large current across the two breakers. The errors in the two CTs do not necessarily cancel, and the sum of the two currents has a larger error than the winding current measured directly through a transformer bushing CT. Therefore, applications with breaker CTs must apply a higher restraint and are therefore less sensitive.

Because the zero-sequence current is both a phasor and time-domain signal, REF protection can be implemented by using instantaneous signals: i_A, i_B, i_C, and i_N.

The REF element is not affected by magnetizing inrush or overexcitation. Therefore, it can be faster than the 87T element. The REF element is not affected by the onload tap changer. Therefore, it can be more sensitive than the 87T element. Of course, the REF elements only detect faults that involve ground (core or tank) in grounded windings of the transformer.

III. Enhanced Transformer Protection

A. *Simplified Logic Diagram*

When enhancing a protection element for speed and sensitivity, it is beneficial to retain the traditional element logic and add separate modules that address speed and sensitivity independently (see Fig. 3).

The traditional 87T element provides the base performance (dependability, speed, and security). Retaining the traditional 87T element reduces the implementation risks and aids adoption. The traditional 87T element provides an entry point for commonly used and well-understood settings. The new functional modules aimed at speed and sensitivity use these settings directly or derive their operating thresholds based on these settings.

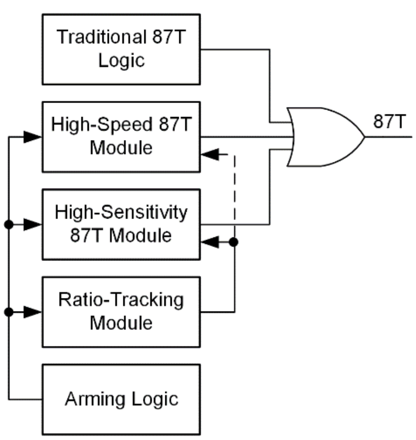

Fig. 3. Simplified logic diagram of the enhanced 87T element.

The high-speed 87T module is designed and optimized for speed while maintaining security. Not having to be perfectly dependable, this module can be kept simple and can achieve fast operation under typical conditions while disregarding difficult internal fault cases. To achieve fast operation, the high-speed 87T module uses current samples rather than phasors. More importantly, this module does not use harmonics in the differential current to address the magnetizing current security challenges (see Section IV).

The high-sensitivity 87T module is designed and optimized for sensitivity while maintaining security. Not having to be perfectly dependable or fast, this module can be kept simple and can achieve sensitive operation under typical conditions while disregarding difficult internal fault cases. The high-sensitivity module applies transformer ratio-tracking to minimize the standing differential current (the high-speed 87T module can optionally use the online estimated ratio as well). The high-sensitivity module uses a novel restraining signal.

Of course, security of all three modules is paramount. An arming logic supervises the high-speed and high-security modules. This logic is a proven method for maintaining security by explicitly allowing the supervised logic to operate only under the conditions considered when designing that logic [6]. The arming conditions for the high-speed 87T module and the high-sensitivity 87T module are slightly different. The arming logic also supervises the transformer ratio-tracking algorithm to ensure that internal faults or inrush conditions do not lead to an incorrect estimation of the transformer ratio.

Fig. 3 illustrates the enhanced 87T element. The enhanced REF element takes a similar approach by using the traditional REF logic as a base and adding the high-speed and high-sensitivity REF modules.

B. *87T Differential and Restraining Currents*

1) *87T Differential Current*

The 87T differential current is based on an ampere-turn balance between a pair of core legs [1]. Following this rule, the proper transformer winding compensation must use:

- Wye-type compensation for, and only for, delta-connected windings.
- Single-delta compensation for, and only for, wye-connected windings.
- Double-delta compensation for, and only for, zigzag-connected windings.

Historically and in some retrofit applications, connecting CT secondaries provides the compensation. Microprocessor-based relays use wye-connected CTs and compensate for transformer winding connections in software. The rule from [1] applies regardless of the approach taken. Any deviation from the rule signifies a settings error that may result in a loss of security during an external fault, including a misoperation in healthy 87T loops due to lack of restraint if one or more CTs saturate.

While the definition of transformer differential current is grounded in physics and is therefore unambiguous, the restraining current is design-driven and may take various forms [7] [8].

We use an example to make this concept clear and later leverage the example to illustrate other parts of the paper. Consider the YNd1 transformer in Fig. 4, and assume CT polarities as indicated in the figure (all currents measured toward or away from the transformer).

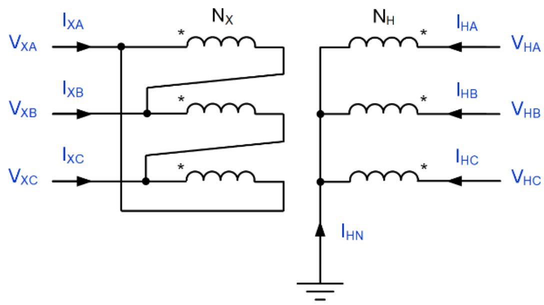

Fig. 4. YNd1 transformer connections and current polarity convention.

The ampere-turn balance in primary amperes between the top and bottom core legs is as follows:

$$N_H \cdot (i_{HA} - i_{HC}) + N_X \cdot i_{XA} = 0 \tag{1}$$

The nominal voltage ratio allows us to substitute for the turn ratio as follows:

$$\frac{N_X}{N_H} = \sqrt{3} \cdot \frac{V_{XNOM}}{V_{HNOM}} \tag{2}$$

We insert (2) into (1) and obtain the following balance equation:

$$\frac{1}{\sqrt{3}} \cdot (i_{HA} - i_{HC}) + \frac{V_{XNOM}}{V_{HNOM}} \cdot i_{XA} = 0 \tag{3}$$

If the left-hand side expression differs from zero, it may signify an internal fault. Therefore, we use it as a differential current:

$$i_{DIF1} = \frac{1}{\sqrt{3}} \cdot (i_{HA} - i_{HC}) + K \cdot i_{XA} \tag{4}$$

where K is the transformer voltage ratio.

Subscript 1 denotes the first loop of the differential current. Again, we do not refer to it as a phase because it mixes currents from two phases of the wye-connected winding. As expected, the delta-connected winding currents (subscript X) use wye-type compensation, and the wye-connected winding currents (subscript H) use single-delta compensation. We obtain the loop 2 and 3 differential currents by rotating phase indices in (4).

It is convenient to express the differential current in per unit of the transformer nominal current. Equation (4) is written in primary amperes on the H side. The H-side nominal current is:

$$I_{HNOM} = \frac{S_{NOM}}{\sqrt{3} \cdot V_{HNOM}} \tag{5}$$

Dividing (4) by (5), we obtain the per-unit differential current. However, we can continue to use (4) for convenience if the right-hand side currents are in per unit on the base (5).

2) *87T Restraining Current*

Historically, users compensated for the transformer winding connections by connecting CT secondaries before supplying the compensated currents to an electromechanical differential relay. That electromechanical relay developed a restraining quantity from the currents connected to it, following, for example, (6) for the example transformer in Fig. 4:

$$i_{RST1} = \frac{1}{2} \cdot \left(\frac{1}{\sqrt{3}} \cdot |i_{HA} - i_{HC}| + K \cdot |i_{XA}| \right) \tag{6}$$

where the | | symbol denotes a signal magnitude, and the 2 factor is the number of windings used to normalize the restraint with respect to the number of transformer windings.

Strictly speaking, (6) does not follow the common rules for obtaining a secure restraining current. Equation (6) does not obtain one restraining term from each of the three involved currents. Instead, it derives a restraining term from the difference of two currents. In any other application, this approach would be referred to as partial restraint and considered not optimal. Microprocessor-based 87T relays never diverged from the traditional application of the transformer restraining current and continue to use (6) even though they have access to all three currents that make up the differential current (4).

3) *Restraining Current for the High-Speed 87T Module*

We redefine the restraining current to follow the common method of obtaining a separate restraining term from each of the currents that make up the differential current:

$$i_{RST1} = \frac{1}{2} \cdot \left(\frac{1}{\sqrt{3}} \cdot (|i_{HA}| + |i_{HC}|) + K \cdot |i_{XA}| \right) \tag{7}$$

The new restraining current (7) provides better restraint than the traditional version (6). Consider the time instant at which $i_{HA} = i_{HC}$. Because the transformer is healthy, the differential current (4) is 0, and therefore $i_{XA} = 0$ when $i_{HA} = i_{HC}$. As a result, the instantaneous restraining current (6) is zero at that point in time. Having a zero restraining current when the transformer carries current ($i_{HA} \neq 0$) is not preferred. When we use the new formula (7), the instantaneous restraining current is $0.58 \cdot |i_{HA}|$ instead of 0.

Equation (7) applies to instantaneous values, and the | | symbol denotes an absolute value of a sample. When using (7) with current magnitudes, we apply additional scaling to (7) with the intent to make (7) identical to (6) under balanced load conditions.

We use (4) and (7), respectively, as the instantaneous differential and restraining currents for the high-speed 87T module. We assume the involved currents are in per unit on a transformer-rated current base, yielding per-unit differential and restraining currents. Table I summarizes the differential and restraining terms for the delta-, wye-, and zigzag-connected windings. We obtain the loop 2 and 3 currents from the loop 1 currents by rotating phase indices.

TABLE I
SUMMARY OF DIFFERENTIAL AND RESTRAINING TERMS

Winding	Differential	Restraining
Delta	i_A	$\lvert i_A \rvert$
Wye	$\frac{1}{\sqrt{3}} \cdot (i_A - i_C)$	$\frac{1}{\sqrt{3}} \cdot (\lvert i_A \rvert + \lvert i_C \rvert)$
Zigzag	$\frac{1}{3} \cdot (2 \cdot i_A - i_B - i_C)$	$\frac{1}{3} \cdot (2 \cdot \lvert i_A \rvert + \lvert i_B \rvert + \lvert i_C \rvert)$

4) *Restraining Current for the High-Sensitivity 87T Module*

Traditionally, a current differential element develops a restraining current, multiplies it by a percentage slope to obtain an estimation of the spurious differential current, and uses that estimate as a variable (adaptive) threshold to verify if the measured differential current is higher than the estimated spurious differential current. If so, the element operates. If not, the element restrains. The percentage slope can be a single-slope function (Fig. 5a), dual-slope function (Fig. 5b and Fig. 5c), or adjustable-slope function controlled by dedicated logic such as external fault detection logic (Fig. 5d).

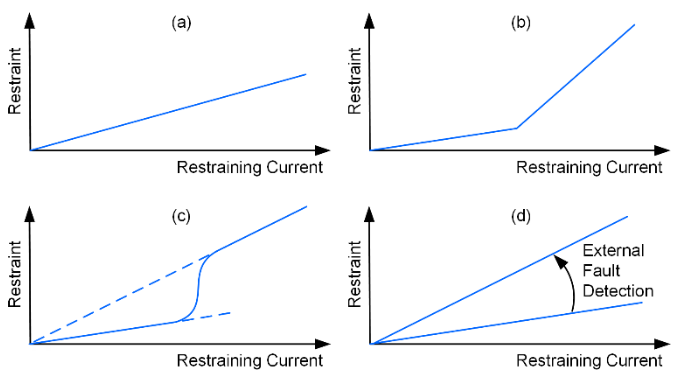

Fig. 5. Types of percentage restraint characteristics.

The traditional approach is simple, but it does not account for the fact that the currents that make up the differential protection zone can be at different levels with respect to the nominal currents of their CTs. Effectively, the traditional approach to restraining uses an average current of all the CTs and estimates an average error caused by CT ratio inaccuracy and CT saturation. Moreover, when we use (6), the H-side Phase A and Phase C currents subtract, yielding a restraining term that poorly reflects the current levels with respect to the CT nominal currents.

A better approach when attempting to provide sensitive differential protection is to obtain a separate restraint from each current that makes up the differential zone and sum these individual restraints. Fig. 6 explains our approach and contrasts it with the traditional approach.

In the traditional approach (Fig. 6a), the restraining current axis and the slope characteristic breakpoint setting relate to the transformer per-unit current. In the enhanced approach (Fig. 6b), the restraining current axis and the breakpoint setting relate to the CT per-unit current. Because the new restraining logic derives the restraint based on the current level relative to the CT nominal current, the slope and breakpoint settings do not have to be set and can be fixed by design.

The new method recognizes where each individual current is in relation to the CT nominal current and applies a higher restraint based on that specific information. Because the new approach uses more information, it provides a more accurate estimation of the possible spurious differential current. This fact, in turn, allows increasing sensitivity of differential protection by lowering the slope values in Fig. 6b as compared with Fig. 6a. Of course, if the relay uses a single slope (Fig. 5a), the traditional and new restraining approaches yield the same results. In dual-slope implementations, however, the two approaches yield different results.

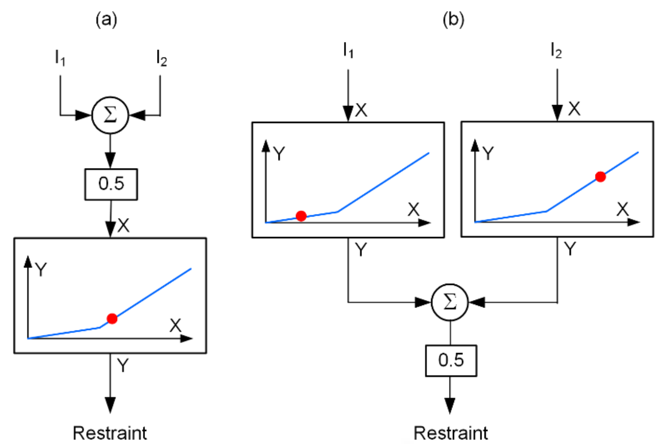

Fig. 6. Traditional (a) and enhanced (b) approach to dual-slope restraining.

Another refinement we propose for the high-sensitivity 87T module is to derive the restraint from the integral of the secondary current rather than the secondary current. CT errors, including saturation errors, depend on the flux in the CT core, i.e., on the voltage across the CT magnetizing branch. We can approximate this voltage by the voltage drop from the secondary current that flows through the total CT burden resistance. Because the flux is the integral of the magnetizing voltage, we can approximate the flux by the integral of the secondary current. If we scale the current integral to have a gain of 1 at the nominal system frequency, we can disregard the CT burden resistance and use the integral of the secondary current in place of the secondary current.

We integrate the current by using the following practical (numerically stable) formula:

$$i_{INT(k)} = A \cdot \left(i_{INT(k-1)} + B \cdot i_{(k)}\right) \tag{8}$$

where:

$$A = \frac{f_S}{f_S + \frac{1}{T_D}} \quad \text{and} \quad B = 2\pi \cdot \frac{f_N}{f_S} \tag{9}$$

where k is a sample index, f_S and f_N are the sampling and nominal frequencies, respectively, and T_D is the design time constant that controls how long the integrator holds the dc component. In this application, use T_D on the order of 0.25 s.

Fig. 7 illustrates the restraining current derivation for the high-sensitivity 87T module.

In the implementation shown in Fig. 7, each current that makes up the differential zone contributes to the restraining current as shown in Table I. The logic integrates an instantaneous current i by using (8) and obtains a replica of the instantaneous flux in the CT core. The logic then derives a one-cycle true root-mean-square (rms) value in order to apply the restraint to a phasor-based differential current. The rms value is applied to the dual-slope restraining function in per unit of the

CT nominal current. The logic then sums the individual restraints.

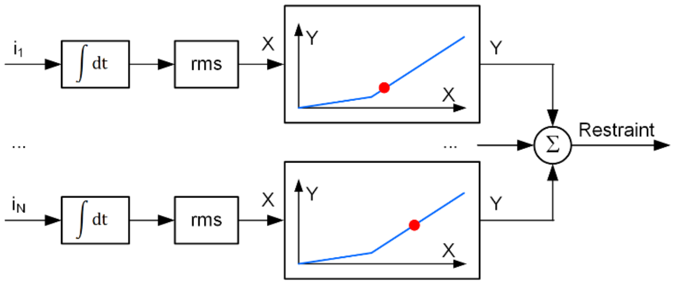

Fig. 7. Deriving restraining current for the high-sensitivity 87T module.

The restraining characteristic can have a first slope setting as small as 2 percent and a breakpoint on the order of 3 times the CT nominal current. The second slope setting can be on the order of 20 percent.

The proposed restraining method for the high-sensitivity 87T module works very well when the current contains a decaying dc component. The calculated integral increases because of the dc component and produces a higher restraint compared with using the current phasor magnitude to obtain the restraint.

C. Tracking the Transformer Ratio

The enhanced restraining method described in the previous subsection accounts for CT and relay errors. To improve sensitivity, we need to apply very small slope values in Fig. 7. However, to do it securely, we must account for the accuracy of the transformer ratio, especially if an onload tap changer is installed. We can track the transformer ratio as long as the transformer is healthy and is not being energized.

Consider the differential current (4), which is a sample case that is valid for a two-winding wye-delta transformer. We generalize it for a multiwinding transformer with any combination of winding connections as follows:

$$i_{DIF} = K_{11} \cdot i_{W1} + K_{12} \cdot i_{W2} + \cdots + K_{1q} \cdot i_{Wq} \qquad (10)$$

where i_{Wn} denotes the compensated winding current of Winding n (where n = 1, …, q) according to Table I (wye, single-delta, or double-delta compensation), and K_{1n} denotes the ratio-matching factor of Winding n with respect to Winding 1.

Of course, K_{11} is 1 but we introduce it to generalize our discussion. The nominal values of the K_{1n} coefficients are calculated from the nominal winding voltages.

Assume that p denotes the winding that has an onload tap changer installed. If there is no onload tap changer, select p to be the winding with the highest and most persistent current (supply side rather than load side). We rewrite (10) as follows:

$$i_{DIF} = K_{1p} \cdot i_{Wp} + \sum_{\substack{k=1 \\ k \neq p}}^{q} K_{1k} \cdot i_{Wk} \qquad (11)$$

In (11), we treat K_{1p} as a variable, and we assume that the K_{1k} scaling coefficients remain at their nominal values. The objective is to find a value for K_{1p} that minimizes the standing differential current. We treat the total current of all the windings other than p as a single equivalent current:

$$i_{EQ} = \sum_{\substack{k=1 \\ k \neq p}}^{q} K_{1k} \cdot i_{Wk} \qquad (12)$$

and write:

$$i_{DIF} = K_{1p} \cdot i_{Wp} + i_{EQ} \qquad (13)$$

We use the least squares method and seek a value for K_{1p} that minimizes the differential current given the measured currents:

$$\sum_{T} \left(K_{1p} \cdot i_{Wp} + i_{EQ}\right)^2 \rightarrow \text{minimum} \qquad (14)$$

The time window parameter T does not need to be a multiple of power cycles and can be as long as a fraction of a second, such as 200 ms.

We solve the least squares problem (14) and obtain:

$$K_{1p} = -\frac{\sum_T i_{EQ} \cdot i_{Wp}}{\sum_T {i_{Wp}}^2} \qquad (15)$$

Operation (15) is very simple, and it involves calculating two sums of sample-by-sample current products over the time interval T. The calculation must be properly supervised (see Subsection VI.C). Also, the ratio-matching coefficient K_{1p} must be clipped at the expected range limits, such as at (1 ± R) per unit, where R is the per-unit regulation interval. For example, with R = 0.1 (10 percent onload tap changer regulation), the expected values of the per-unit ratio-matching coefficient are between 0.9 and 1.1.

IV. Magnetizing Current Security Challenges and Solutions

The 87T differential current formulation does not account for the transformer magnetizing current. Therefore, the magnetizing current appears as a spurious differential current. The high-sensitivity 87T module uses a traditional harmonic-based approach to inrush and overexcitation. To operate fast, the high-speed 87T module must use a different approach. This section describes the new approach to the magnetizing current challenge.

A. Initial Energization Inrush

The high-speed 87T module rules out the initial energization inrush as a source of the differential current based on the presence of voltage at and load current in any of the transformer windings.

Because a transformer carrying load current is already energized, it cannot be subject to initial energization. We use the magnitudes of the compensated winding currents as shown in Table I to detect load. If the magnitude of any of the compensated winding currents is above a certain threshold, on the order of 10 percent of the winding nominal current, the logic declares the transformer energized. Using the compensated winding currents and not the restraining current avoids false operation of the logic if a winding that is terminated on two breakers is de-energized through an open disconnect switch (see the discussion related to Fig. 8 below).

It is also true that the transformer is already energized when voltage is present at least one of the windings.

To explain this principle, Fig. 8 shows an application example. The sum of the CT1 and CT2 currents is the winding current. If the DS3 disconnect switch is open but the CB1 and CB2 breakers are closed and the CB1 – CB2 path carries current, the winding current is still zero and the relay does not declare the transformer energized based on the CT1 and CT2 load currents. If the relay has access to the VT1 voltage, it supervises the use of this voltage with the closed position of the DS3 disconnect switch before declaring the transformer energized. If the relay has access to the VT2 voltage, it supervises the use of this voltage with the closed positions of the DS4 and DS5 disconnect switches and the CB3 breaker. For better security, it is good practice to use a dual-point monitoring of the disconnect switches, i.e., connect both the 89a and 89b contacts to the relay.

Of course, the supervision with the disconnect and breaker status signals is required only when using bus-connected VTs and not when using VTs connected directly to the transformer terminals.

The current and voltage conditions in the initial energization logic can be OR-ed for better dependability of the high-speed 87T module or AND-ed for better security. Section VI provides a high-level explanation of how to rule out the initial energization inrush as part of the arming logic.

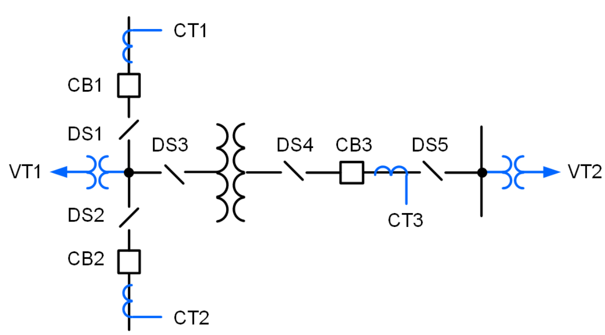

Fig. 8. Application example related to ruling out initial energization inrush.

B. *Voltage Recovery Inrush*

Voltage recovery inrush occurs when a close-in external fault is cleared. The fault depresses the transformer voltage. When the fault is cleared and the voltage suddenly returns to the normal value, the transformer is subject to a form of "partial re-energization". We can address voltage recovery inrush as follows. First, the external fault detection logic triggers for the external fault as long as the system is not extremely weak. The external fault detection logic blocks the high-speed 87T module for the duration of the fault and for some time after the fault is cleared. Second, the voltage decreases during the external fault and disarms the high-speed 87T module. The voltage may remain high if the system is extremely strong. In such a case, the external fault detection logic is guaranteed to assert. A third method uses arming logic described in Section VI. The external fault causes changes in voltages, currents, or both. The arming logic simply allows the transients (changes) in the currents and voltages associated with the inception of the external fault to disarm the high-speed 87T module before the fault is cleared and the return of voltage to its normal value causes an inrush current.

C. *Sympathetic Inrush*

During sympathetic inrush, the magnetizing current increases gradually over several power cycles. It starts with the excitation current on the order of 1 to 2 percent of the transformer nominal current and rises to the level consistent with a magnetizing inrush on the order of several times the transformer nominal current.

When a transformer parallel to the protected transformer is energized, it starts to draw significant unipolar inrush current. This unipolar current creates a unipolar voltage drop across the equivalent system resistance because the voltage drop across the system inductance has a very small decaying dc component. This in turn results in a dc offset in the voltage at the terminals of the protected transformer. This voltage offset persists for the duration of the inrush of the transformer being energized, and it ratchets up the flux in the protected transformer. However, it takes some time for the flux to shift away from the average of zero and into the area that causes the magnetizing branch to draw higher magnetizing currents. This is the reason for the gradual increase of the sympathetic inrush current. In our experience, it takes several cycles for the sympathetic inrush current to develop (see Fig. 9).

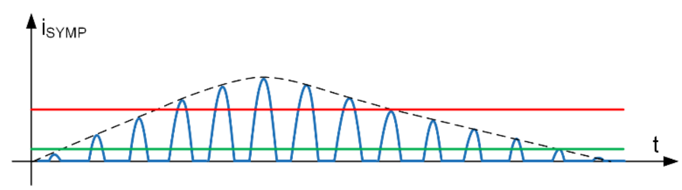

Fig. 9. Sample sympathetic inrush current.

We leverage this gradual increase in the spurious differential current when securing the high-speed 87T module by requiring the differential current to transition above the pickup threshold relatively quickly.

Our sympathetic inrush logic uses an auxiliary threshold of about one-fourth of the minimum pickup threshold (green line in Fig. 9) to detect that the differential current starts increasing. From that moment, the logic allows a short window, on the order of one-third of a power cycle, for the differential current to continue increasing in the same direction (positive or negative) and to cross the minimum pickup threshold (red line in Fig. 9). If the differential current increases within the time window, the high-speed 87T module is allowed to operate. If it does not, the sympathetic inrush logic disarms the high-speed 87T module.

D. *Sudden Voltage Change Inrush*

A sudden change in voltage at the transformer terminals may elevate the flux and cause the transformer to draw an inrush-like current. Consider a switching scenario that does not involve an increase in voltage magnitude but only a small shift in the voltage angle as in Fig. 10. Because switching in the system may delay the voltage zero crossing, the voltage integral (the area under the voltage curve) grows. The increasing voltage integral means that the flux increases potentially up to the saturation region of the core and causes an inrush-like current to flow. Note that the flux in Fig. 10 developed an offset as a result of the switching operation. This offset eventually decays, but the process takes a relatively long time (similar time constant to that of the initial energization inrush).

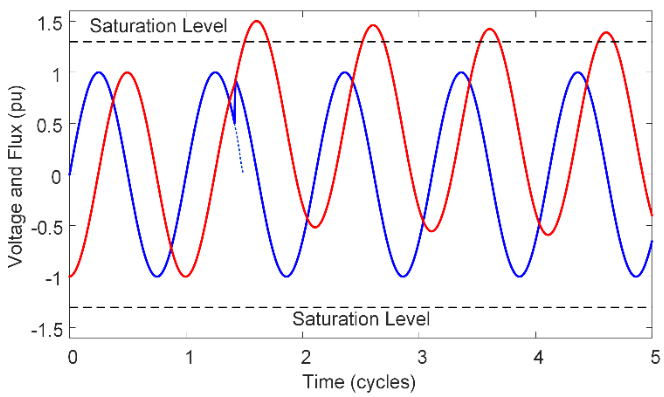

Fig. 10. A switching event may shift the voltage (blue) and increase the flux (red).

Switching events that change voltage (disconnecting loads, capacitor banks, or reactors) can permanently or transiently increase the flux and may cause an inrush-like current. Like the initial inrush current, this magnetizing current eventually decays to the excitation current level that is consistent with the steady-state values of voltage and frequency. If the steady-state voltage magnitude is high, the excitation current may increase well above 1 to 2 percent of the nominal transformer current. However, before the current settles on the excitation level, it may resemble an inrush current even if the voltage magnitude does not increase (see Fig. 10).

We ensure security of the high-speed 87T module by using transformer voltage. The sudden voltage change logic integrates the voltage to obtain flux by using an approach analogous to (8):

$$\mathrm{Flux}_{(k)} = \mathrm{A} \cdot \left(\mathrm{Flux}_{(k-1)} + \mathrm{B} \cdot \mathrm{v}_{(k)}\right) \tag{16}$$

where A and B are coefficients defined in (9).

For simplicity, the gain (scale) in (16) is 1 Wb/V. This way, a voltage threshold can be directly applied to the flux obtained by using (16). The logic compares the flux with a threshold, such as the flux value for 115 percent of the nominal voltage, to detect an imminent inrush current.

We must resolve several implementation details to make this concept practical:

1. The relay may measure the voltage at any winding of a transformer (wye, delta, zigzag). Depending on the winding connection, different voltages are applied to particular windings. The logic must select the right voltages for a meaningful flux calculation.
2. The differential current reflects an ampere-turn balance on a pair of core legs. As a result, high flux in either of the two legs causes a spurious differential current. The logic must select voltages that reflect the flux in a pair of core legs.
3. Voltages at different windings of the transformer can differ because of the voltage drops across the transformer impedance. The voltage drop can be as much as 10 percent of the nominal voltage, and it acts as a phasor, perpendicular to the load current. Depending on which voltage is connected to the relay, the relay may use a voltage that is not the highest compared with the other winding(s), and by doing so, it may underestimate the flux when integrating the measured voltage.
4. During internal ground faults at or close to the grounded-wye or zigzag winding terminals, the healthy-phase voltages may increase during the fault. This increase may result in the transformer drawing an inrush current during the internal fault, which may potentially jeopardize the high-speed 87T module dependability.

We offer the following solutions to resolve these challenges. Further details are beyond the scope of this paper.

1) Winding Connections

We use the following voltages to estimate the flux:

- Phase-to-ground voltages for solidly grounded wye-connected windings.
- Phase-to-phase voltages for delta-connected windings.
- Phase-to-ground voltages minus the voltage drop from the neutral current across the grounding impedance for impedance-grounded wye-connected windings.

We discourage the application of the high-speed 87T module if the only voltage available to the relay is from a zigzag-connected winding.

The above choices follow the principle of using the voltage across a winding regardless of how the winding is connected. The windings on the wye-connected solidly grounded side are subjected to the phase-to-ground voltages, for example, and this is why we use phase-to-ground voltages to obtain the flux.

2) Multiple Phase Currents in Each Differential Loop

The differential current reflects an ampere-turn balance on a pair of core legs. We inhibit the high-speed 87T module if either of the two legs is over-fluxed. Consider the example in Fig. 4. The differential current (4) balances ampere-turns between the top and bottom legs. Therefore, the logic blocks the differential loop (4) for the following conditions:

- If either the v_{AB} or v_{CA} voltages on the delta-side (X) yield elevated flux values.
- If either the v_A or v_C voltages on the wye-side (H) yield elevated flux values.

We can apply the following mapping rule between the measured currents that make up the differential current and the terminal voltages used to derive the flux and block the high-speed 87T module as follows:

- If using voltages from the wye-connected side, use the same phases as in the differential current (v_{HA} and v_{HC}, because i_{HA} and i_{HC} appear in (4)).
- If using voltages from the delta-connected side, use the phase-to-phase voltages that involve the same phases as in the differential current (v_{XAB} and v_{XCA}, because i_{XA} appears in (4)).

The above rule makes the implementation straightforward: the phase indices of the measured currents that make up the differential current also define the voltages that must be used to supervise the high-speed 87T module on a per-loop basis.

3) Voltage Drop Across the Transformer

The relay can solve this problem in the following ways:

- Measuring the voltage at the transformer terminal with the highest per-unit voltage (supply side).
- Letting voltage at any winding block the high-speed 87T module (with all voltages connected to the relay).
- Using the currents to compensate for the voltage drop across the transformer to derive voltages at all terminals and letting voltage at any winding block the high-speed 87T module.

4) Internal Ground Faults and Dependability

Consider an internal AG fault on the wye-connected side of the transformer in Fig. 4. If the B and C phase voltages increase, the transformer can draw magnetizing currents in the B and C phases on the wye-connected side. The i_{HB} and i_{HC} currents are involved in all three 87T loops. The inrush current may increase harmonic content in the differential current and therefore jeopardize the 87T element dependability. Typically, the fault current is large, making the harmonics relatively small, which results in dependable 87T element operation. However, this scenario is one of the reasons to avoid cross-phase harmonic blocking.

In the context of the high-speed 87T module, if an internal fault elevates the B or C phase voltages, they may inadvertently block the high-speed 87T module in all three loops. We solve this problem by monitoring the sequence of events. During internal faults, the differential current increases first and the flux associated with the healthy phases increases to reach the saturation level a few milliseconds later. During switching events that lead to overfluxing, the flux increases first and the differential current follows. This sequence pattern is similar to the pattern the external fault detection logic uses when it monitors the sequence between the differential and restraining currents (see Subsection V.A).

E. Stationary Overexcitation

Stationary overexcitation is not a threat to the high-speed 87T module because the arming logic does not arm the high-speed 87T module if there is a standing differential current, such as the stationary overexcitation current. If the stationary overexcitation condition begins suddenly, the sudden voltage change logic ensures security in the initial few cycles and the arming logic disarms the element afterward.

V. CT Saturation Challenges and Solutions

Historically, CT saturation has been a concern for differential relays, including transformer differential relays. Dual-slope characteristics (see Fig. 5) use the upper slope to accommodate CT saturation errors in secondary currents during external faults. A CT is a nonlinear element, and it is difficult to quantify the error in the secondary current, especially if the decaying dc component is present in the fault current or a residual flux is present in the CT core. The upper slope and the breakpoint of the characteristic are therefore set heuristically rather than by performing rigorous engineering calculations. This lack of rigorous analysis leaves some doubt in the soundness of applications that are based solely on percentage restraint.

Today, many differential relays incorporate an external fault detection (EFD) logic. The EFD logic monitors the sequence in the rise of the differential and restraining currents. During internal faults, the differential and restraining currents increase together because the fault current flows into the protected transformer (the fault current drives both the differential and restraining currents). During external faults, the restraining current increases because the fault current flows through the protected transformer. At that time, the differential current is very small, ideally zero, because the CTs perform without saturation at least for the first several milliseconds of the fault. If the restraining current increases and the differential current does not follow immediately, the EFD logic declares an external fault. By using this principle, the EFD logic asserts before and irrespective of CT saturation.

Like the percentage restraint, the EFD logic works correctly if the transformer winding compensation is correct. Excessive compensation, such as delta compensation for delta-connected windings or double-delta compensation for wye-connected windings, results in an error current due to CT saturation appearing in both the differential and restraining currents of the healthy 87T loops. See Subsection III.B for the fundamentals of transformer winding compensation.

A. 87T External Fault Detection Logic

Fig. 11 shows a simplified EFD logic for the 87T protection element. The logic responds to the changes (Δ) in the instantaneous differential and restraining currents respective to their one-cycle old values. Because these two currents are periodic in the steady state before the fault, the change signals are zeros before the fault. Therefore, using the change signals improves sensitivity of the EFD logic.

The EFD logic verifies that the restraining signal changed, such as by using a constant threshold P_R of 1.5 per unit (1.5 times the transformer nominal current). The EFD logic verifies that the differential current remains small, such as less than the percentage restraint when using the lower slope (S_L) of the restraining characteristic. If the restraining current changed but the differential current did not follow in T_{EFD} (e.g., in 3 ms), the EFD logic asserts.

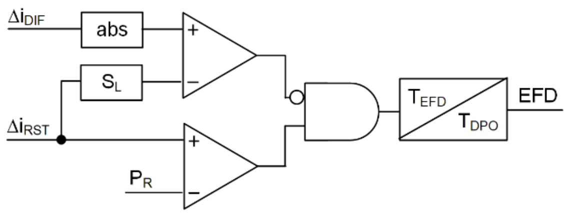

Fig. 11. Simplified EFD logic for the 87T protection element.

The logic maintains the EFD output bit by using the dropout timer T_{DPO} (e.g., 0.5 s). Additionally, the EFD logic can seal in the output and allow the EFD bit to reset only after the external fault is cleared (i.e., after the restraining current drops below about 150 percent of the load current and the differential current falls below the lower slope of the restraining characteristic). The EFD logic can also reset the EFD bit to restore full sensitivity and dependability if the external fault is cleared before the T_{DPO} timer expires. When asserted, the EFD logic enforces high security, such as by increasing the percentage restraint slope as shown in Fig. 5c.

The EFD logic can incorporate a dc saturation path that monitors the level of the dc component in the currents that make up the differential current (not shown in Fig. 11). If any current contains a significant dc component and the differential current remains small, the EFD logic asserts in anticipation of CT saturation resulting from the dc component rather than a high ac component.

Consider the following EFD application factors:

- In dual-breaker applications, the restraining current must include the currents from both breakers. Otherwise, both the percentage restraint and the EFD logic may fail to detect the fault current flowing in and out of the transformer differential zone.
- If the EFD logic asserts, the 87T element may increase the upper slope of the restraining characteristic for better security (see Fig. 5d). This way, the lower slope can be set to address ratio errors (15 to 20 percent) and the upper slope can be set very conservatively (80 percent, for example).
- The EFD logic can be implemented and applied on a per-loop basis. This approach allows retaining sensitivity for internal faults after the external fault has caused the EFD logic to assert.

B. REF External Fault Detection Logic

The REF element can use the 87T element EFD logic. This logic asserts for heavy external faults and provides security for the REF element. However, a more complete approach is to provide a separate EFD logic for each of the REF elements. A dedicated EFD logic provides additional security during heavy ground faults when the transformer through-current is small in terms of the positive- and negative-sequence components (a weak system in terms of the positive- and negative-sequence) and most of the current is the zero-sequence component that flows into the grounded REF winding.

The EFD logic dedicated to the REF element also uses the logic in Fig. 11 except it is based on the following differential and restraining currents:

$$i_{DIF} = i_A + i_B + i_C + i_N \qquad (17)$$

$$i_{RST} = \frac{1}{2} \cdot (|i_A| + |i_B| + |i_C| + |i_N|) \qquad (18)$$

The EFD logic that uses (17) and (18) asserts reliably for phase-to-phase and balanced three-phase faults, which are of particular concern for the EFD logic security. Of course, in dual-breaker applications, the restraining current (18) must use currents from both breakers.

When the EFD logic asserts, the EFD element engages more security, for example, by lowering the limit angle in the phase comparator or increasing the slope of the percentage restraint REF characteristic (see Fig. 2).

For better security, the REF-dedicated EFD logic can also cross-trigger the EFD logic dedicated to the 87T element.

C. Internal Faults and Dependability

CT saturation may create dependability problems during internal faults because of harmonic-based inrush security logic. Typically, CTs used for 87T protection are selected to avoid saturation for as long as the worst-case 87T operating time, on the order of two power cycles. The high-speed 87T and high-speed REF modules reduce the likelihood of a failure to operate should the CTs saturate during an internal fault before the traditional 87T element operates. It is still good practice to rate the CTs to avoid saturation before the 87T element has a chance to operate, but the requirement becomes less critical if high-speed modules are used.

VI. Arming Logic

The purpose of an arming logic is to allow the supervised protection logic to engage only when conditions are satisfactory. More specifically, the arming logic monitors if the transformer conditions are among those that have been considered during the design stage of the supervised logic. By doing so, the arming logic ensures security by inhibiting the supervised logic during conditions that have not been explicitly considered and tested during the design stage. This approach to security yields excellent results in practical applications of ultra-high-speed protection principles [6].

The following subsections provide a high-level description of the arming logic for the high-speed and high-sensitivity 87T and REF modules and the ratio-tracking module.

A. 87T Arming Logic

The high-speed 87T module is armed when all the following conditions occur:

- The transformer winding currents and voltages indicate that the transformer is already energized.

- The standing differential current is small, signifying the transformer is not drawing an inrush current or experiencing a differential current caused by CT problems, tap changer operation, or CT saturation during external faults.
- The transformer voltage and frequency are within the normal operating limits.
- The winding currents are in a steady state.
- The EFD logic is reset, signifying no external fault is present or was present in the recent past.

When armed, the high-speed 87T module remains armed for a short period of time, on the order of one cycle, following a disturbance. The high-speed 87T module provides accelerated tripping. Therefore, keeping it engaged for a longer period following a disturbance has no benefits – only potential disadvantages.

If relay logic detects any of the following conditions when the high-speed 87T module one-cycle operating time window is open, the window immediately closes:

- Sympathetic inrush based on the slow rise in the differential current (Subsection IV.C).
- Overexcitation based on the calculated flux (Subsection IV.D).
- An external fault based on the assertion of the EFD logic (Subsection V.A).

Once the arming logic opens and closes the operating time window, it applies an intentional time-out delay (it disables itself) on the order of 1 s before it verifies the arming conditions and arms again.

The high-sensitivity 87T module is armed using the same basic conditions as the high-speed 87T module. Additionally, the arming logic requires the transformer ratio-tracking module to settle following a tap changer operation. Also, the operating time window is longer to account for the filtering and additional security time delay of the high-sensitivity 87T module.

B. REF Arming Logic

The arming logic for the high-speed and high-sensitivity REF modules is similar to that for the 87T modules. The following exceptions apply:

- The REF element does not see the magnetizing current in its operating current (the magnetizing inrush is a through-fault for the REF element). Therefore, the transformer energized status, the core overexcitation condition, and the sympathetic inrush conditions do not apply.
- The REF element does not balance ampere-turns and does not need the transformer ratio-tracking values for sensitive operation.
- It is beneficial to use the EFD logic in the REF arming logic that is dedicated to the REF element (Subsection V.B). For example, the REF-dedicated EFD logic detects an inrush current as an external fault current and provides additional security for CT saturation during magnetizing inrush conditions.

C. Ratio-Tracking Supervision Logic

The transformer ratio-tracking module assumes a balance between the winding currents and treats the turns ratio as an unknown to be tracked. As a result, the following conditions supervise the ratio-tracking module:

- The arming logic declared the transformer energized based on the winding currents and voltages. Additionally, the two currents involved in ratio matching are above a noise level (e.g., greater than 20 percent of their nominal values).
- The EFD logic did not detect an external fault presently or in the recent past.
- The second- and fourth-harmonic content in the differential current is small, signifying the current is not a sympathetic inrush current or a voltage recovery inrush current.
- The fifth-harmonic differential current is small, signifying the current is not a stationary overexcitation current.
- The differential current is below a value that corresponds to 1 or 2 tap changer steps. Higher values signify an inrush, an overexcitation, or a tap changer failure.

The ratio values of all three differential loops agree under normal conditions. Ratio values that differ by more than one tap changer step signify tap changer problems. The ratio-tracking module can be used to alarm based on discrepancy between the three loops or based on discrepancy between the current-based ratio and the ratio obtained from the tap changer position indicators.

Another consideration is time coordination between the ratio-tracking module and the high-sensitivity 87T module. If a low-current internal fault occurs, the ratio-tracking module eventually rebalances the differential current and effectively erases the legitimate differential signal caused by the fault. The time constant of this operation must be longer than the operating time of the high-sensitivity 87T module. Alternatively, or in addition, the ratio adaptation may be inhibited if the ratios in all three loops differ too much.

The final consideration regarding ratio-matching supervision is the startup procedure. For example, the transformer may be switched on with the tap position significantly different than the neutral position when using an offline tap changer. In this case, the ratio-tracking module would take time to converge on the true ratio. During that time, the small differential current supervisory condition must be waived and the high-sensitivity 87T module must be disarmed.

VII. Protection Dependability During Transformer Energization

Transformer protection dependability is reduced for faults that occur when the transformer is being energized. We cannot dismiss such faults as very rare because moisture and other contamination could have accumulated inside the tank or foreign objects, such as animals, could have encroached on the bushings and breaker connections when the transformer was de-energized.

The dependability challenge for the 87T element stems from the fact that the differential current is composed of the magnetizing inrush current component and the fault current component. As a result, the differential current is distorted and the harmonic blocking or restraining logic could inhibit the 87T element. If the fault current is large, the harmonic content is likely to be small and the 87T element may have a chance to operate. It is also relevant that the magnetizing inrush current is likely to saturate the CTs because of its long-lasting decaying dc component. When the fault occurs during the energization inrush, the CTs may not reproduce the primary currents with accuracy and the harmonic content in their secondary currents may increase.

The dependability challenge for the REF element stems from the fact that the magnetizing inrush current when energizing the REF-protected winding has a large zero-sequence through-current. If a ground fault occurs during energization, the fault components in the two currents that the REF balances may be overshadowed by the zero-sequence current component caused in the inrush current. As a result, the REF element (based on phase comparison or on the percentage restraint principle) may restrain for faults during inrush. If the fault current is large, the fault component in the compared currents is large and the REF element may have a chance to operate.

We differentiate between two scenarios: 1) a transformer fault that occurs during energization but sometime after closing the breaker and 2) energizing a faulted transformer. We address each of these possibilities separately.

A. Transformer Fault During Energization

This scenario is likely if the root cause of the fault is a buildup of moisture or other contaminants in the oil and paper insulation during the time the transformer was de-energized. When the voltage is applied, the compromised insulation holds for a period of time but finally fails.

We have proposed a bipolar differential overcurrent logic to address the 87T element dependability challenge [5] [9]. The logic operates if the differential current falls below a negative threshold shortly after crossing a positive threshold. This approach is insensitive to inrush because the inrush current, if large, is unipolar. CT saturation during inrush can challenge the solution described in [3]. Because of CT saturation, the dc offset in the secondary current is gradually suppressed, yielding a bipolar waveform. Reference [5] and implementation [9] solves this problem by supervising the bipolar overcurrent logic with an overcurrent comparator that uses an incremental current. The incremental current (one- or two-cycle difference in the current) is very small during inrush because the inrush current, despite being distorted, is periodic (neglecting the slow decay factor).

A different solution is to use the incremental current in the bipolar overcurrent logic. Fig. 12 illustrates this approach. During the first cycle of inrush, the incremental differential current (Δi_{DIF}) is the same as the inrush current (i_{DIF}) because the incremental current is obtained by subtracting zeros. However, the CTs do not saturate that quickly on inrush and the incremental current is decisively unipolar in the first few cycles of inrush. The CTs may saturate later, but at that time, the incremental current is very small because the inrush current is periodic. When the fault occurs, the incremental current reflects the fault current and gives the bipolar overcurrent logic a chance to operate (the incremental current crosses the positive and negative thresholds in quick succession).

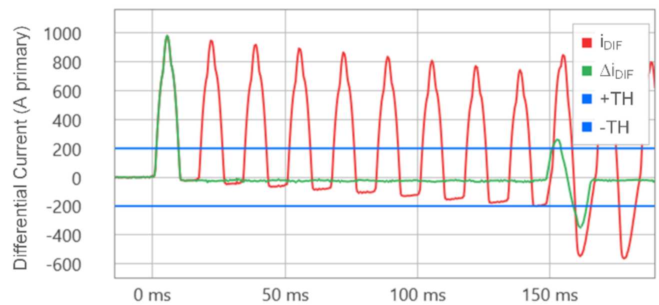

Fig. 12. Using incremental current in the bipolar overcurrent 87T element.

We can also improve the REF element operation for faults during energization by using incremental currents. Comparing the incremental zero-sequence current in the winding terminals with the incremental neutral current in the winding neutral connection restores the maximum sensitivity despite the inrush-caused zero-sequence current flowing through the protected winding.

For better security, the incremental bipolar overcurrent logic in the 87T element and the incremental current-based REF logic can be supervised (armed). The arming logic should enable them only when they are beneficial and when the conditions allow.

B. Energizing a Faulted Transformer

This scenario is likely if the root cause of the fault is a permanent fault that developed during the time the transformer was de-energized. Examples include safety grounds inadvertently left after working on the protected transformer and debris, animals, or other foreign objects making their way to the bushings or breaker connections.

When the transformer is being energized, a short time lag occurs between the moment the voltage is applied and when the inrush current starts to flow. This delay is on the order of 2 to 4 ms and is related to the time it takes the flux to build up and reach the saturation level. When looking at the typical transformer inrush current, we notice the dwell times between the adjacent peaks of the current. We argue that transformer energization starts with such a dwell time.

When the transformer is faulty, the fault current rises immediately after the voltage is applied.

The relay can apply a current derivative to distinguish between the steep rise of the differential current during a fault and the more gradual rise of the current during energization.

Additionally, when using high sampling rates, a transformer relay can determine the exact moment voltage is applied to the transformer by detecting very high-frequency components (on the order of hundreds of kilohertz) in the winding currents, caused by charging the winding stray capacitances. These high-frequency components can be used as a time marker. If the differential current starts building up immediately, then there is an internal fault. If the differential current stays small for about 2 ms, then the subsequent rise in the differential current can be attributed to transformer energization. The relay can also use the voltage signal to determine the energization moment, assuming the voltage transformers are of relatively high fidelity (when using magnetic VTs instead of CCVTs) and are installed on the transformer side of the energizing breaker.

Fig. 13 illustrates the difference between energizing a faulted transformer and a healthy transformer.

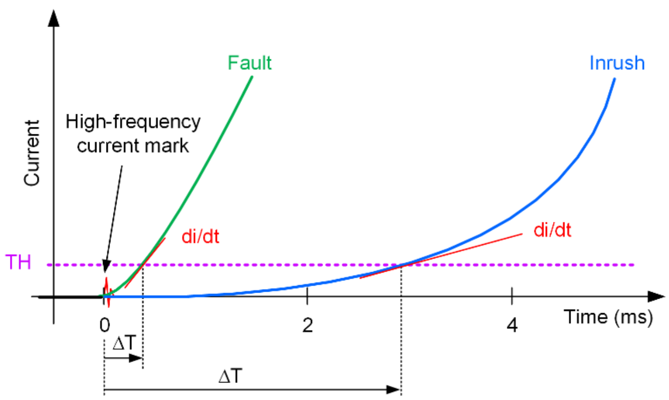

Fig. 13. Transformer energization: the differential current rises sharply and almost immediately for a faulted transformer, and it rises gradually and appears after a short time for a healthy transformer during inrush.

The appearance of the high-frequency current component sets the time mark to zero. The fault current crosses a threshold (TH) after a short time (ΔT); for an inrush, the current crosses the threshold after a longer time. Also, a time derivative (di/dt) taken at the time the current crosses the auxiliary threshold is higher for a fault than for an inrush.

This principle can be used in both the 87T and REF elements to improve dependability when energizing a transformer with a pre-existing fault.

VIII. Examples of Operation

This section uses simulations for a 115/230 kV, 150 MVA, 0.15 pu, wye-delta-connected transformer to illustrate some of the presented transformer protection principles.

A. Internal Fault

Fig. 14 plots the currents and voltages at the transformer terminals for a fault cleared in 1.5 cycles by two-cycle circuit breakers and an ultra-high-speed transformer protective relay that operated in 3 ms. Fig. 15 plots the differential and restraining currents as well as the absolute differential current, the percentage restraint current (75 percent slope), and the minimum pickup current (0.5 pu). The high-speed 87T module is armed and not blocked by any of the security conditions. The high-speed 87T module operates dependably in less than 3 ms.

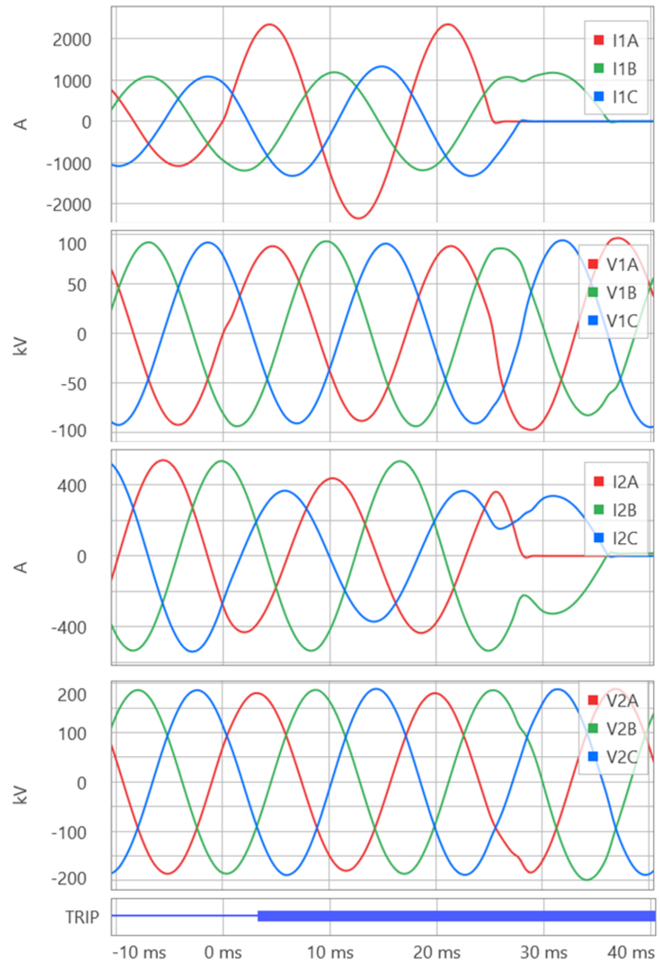

Fig. 14. Internal fault: transformer currents and voltages.

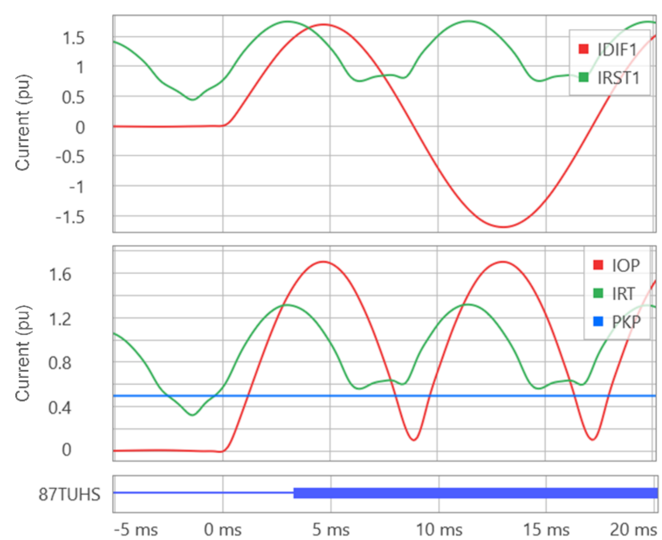

Fig. 15. Internal fault: faulted loop differential and restraining currents, absolute differential current, percentage restraint, and minimum pickup.

B. *External Fault With CT Saturation*

Fig. 16 plots transformer currents and voltages for an external ABG fault on the wye-side of the transformer. The fault has zero fault resistance between the A and B phases resulting in large phase fault current. This high current level saturates – in about 1.5 power cycles – the A-phase CT on the wye-side of the transformer. The ground fault resistance, however, is significant, limiting the neutral-point current to about 20 percent of the transformer nominal current.

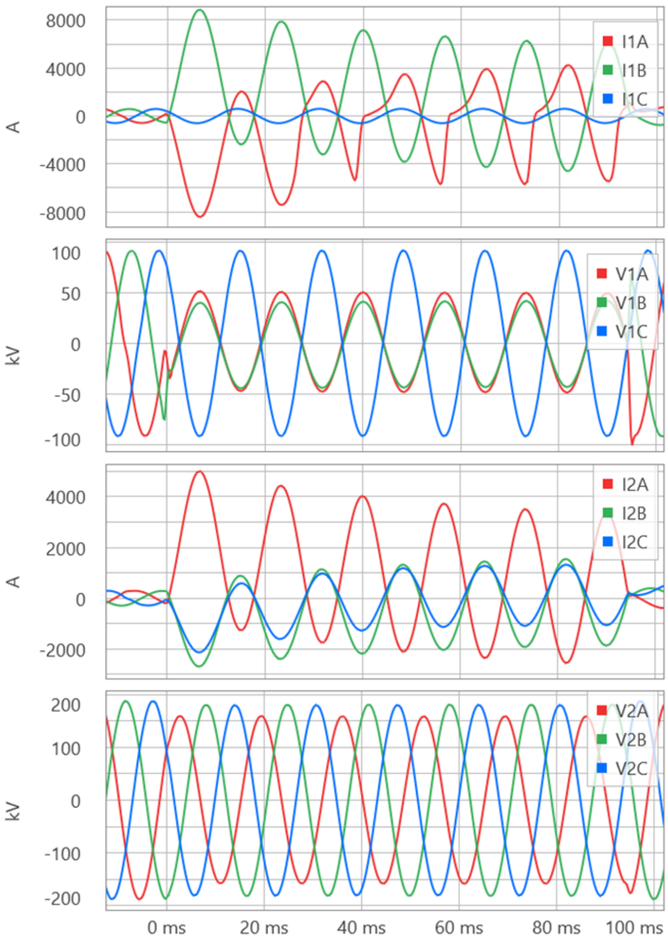

Fig. 16. External fault: transformer currents and voltages.

Fig. 17 plots the 87T and REF currents. The 87T differential current is significant because of CT saturation and cannot be restrained with a 75 percent restraint. The REF element security is also jeopardized because of the legitimate current measured in the transformer neutral. This current allows the REF logic to operate, yet the REF differential current is affected by CT saturation including periods when the neutral current and the spurious 3I0 current at the transformer terminals are in phase at 40 ms, 56 ms, and 74 ms, defeating the phase comparison condition in the REF logic.

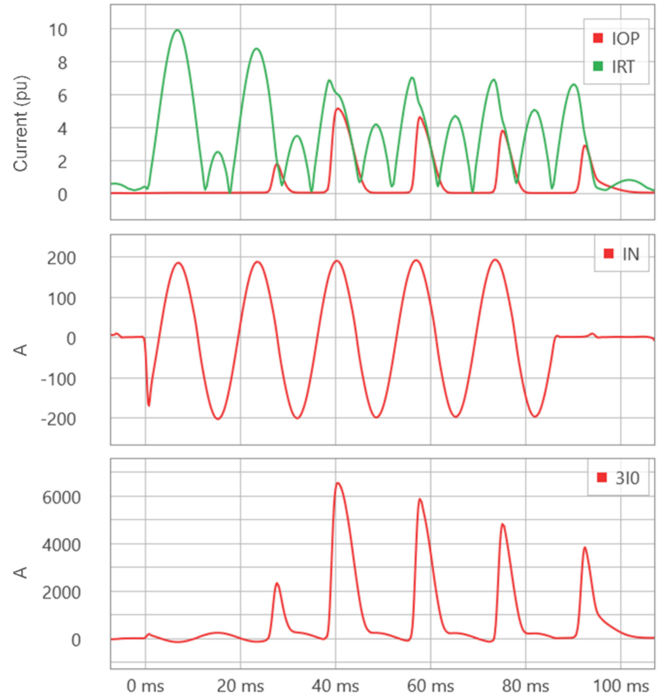

Fig. 17. External fault: 87T and REF currents.

Fig. 18 plots the change in the 87T differential and restraining currents. Because the restraining current increases and the differential current does not follow for more than 20 ms, the 87T EFD logic asserts and secures the high-speed 87T module before the spurious differential current develops.

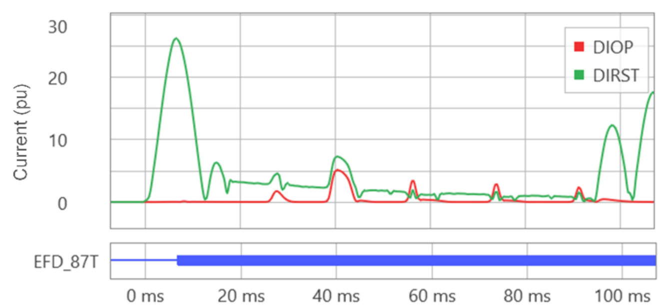

Fig. 18. External fault: change in the 87T differential and restraining currents.

Fig. 19 plots the change in the REF differential and restraining currents. Because the restraining current increases and the differential current does not follow for more than 20 ms, the 87T EFD logic asserts and secures the REF element before the spurious differential current develops.

Of course, the 87T EFD logic and the REF EFD logic can cross-trigger each other for better security.

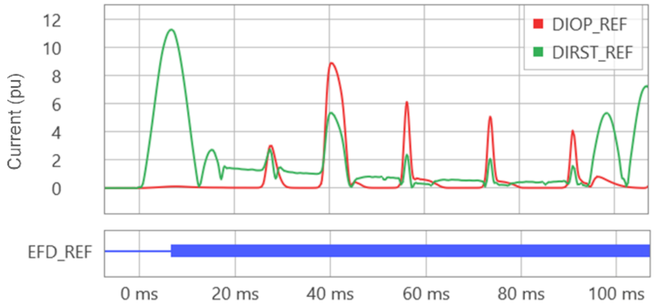

Fig. 19. External fault: change in the REF differential and restraining currents.

C. Sympathetic Inrush

Fig. 20 plots transformer currents and voltages for the case of energizing a parallel transformer.

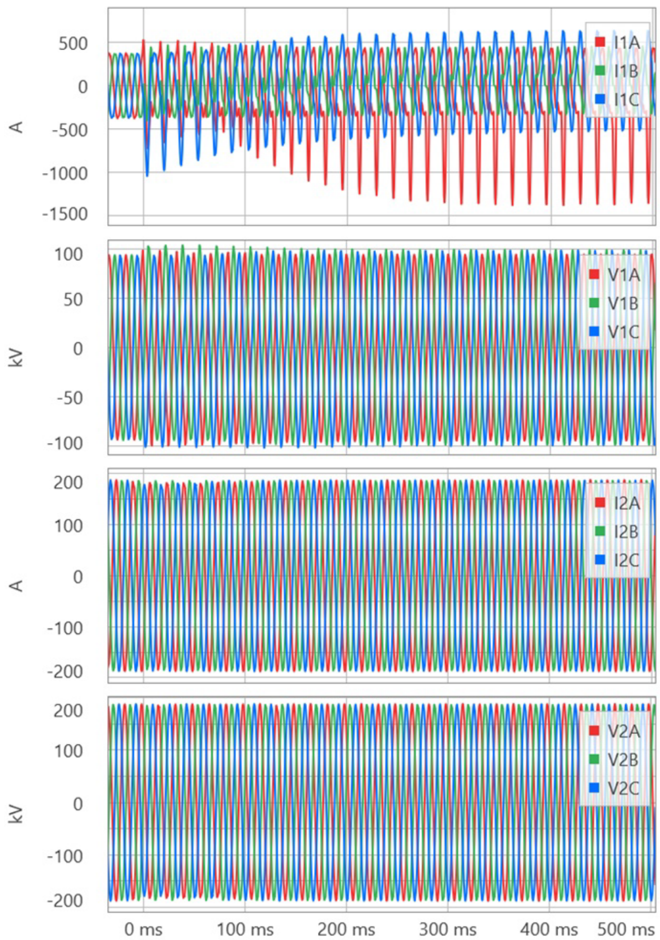

Fig. 20. Sympathetic inrush: transformer currents and voltages.

Fig. 21 plots the differential and currents and the percentage restraint current (75 percent slope). The sympathetic inrush currents develop gradually. The transformer is lightly loaded, and the sympathetic inrush current exceeds the percentage restraint at about 60 ms. It exceeds the minimum pickup of 0.5 pu at about 90 ms. The sympathetic inrush logic has therefore 90 ms to disarm the high-speed 87T module. Once the absolute differential current (blue) in the bottom plot of Fig. 21 exceeds the lower threshold (green) and does not exceed the upper threshold (red) within the prescribed time, the relay disarms the high-speed 87T module at about 70 ms. Additionally, the small differential current at the beginning of the event may open the operating window at about 50 ms. If so, the operating window closes at about 65 ms, well before the sympathetic inrush exceeds the minimum pickup threshold.

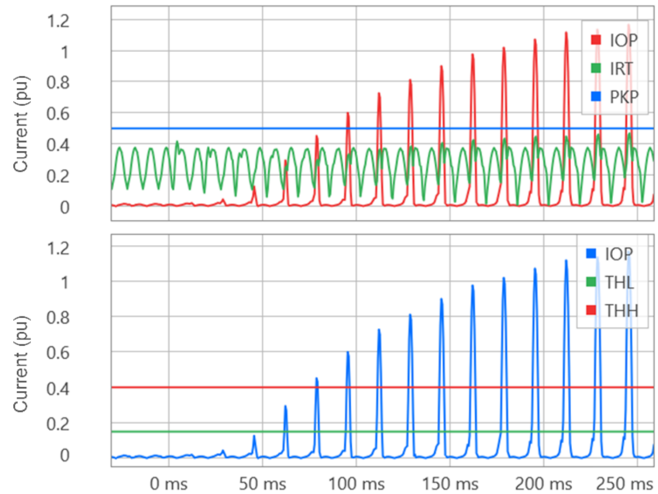

Fig. 21. Sympathetic inrush: differential current and percentage restraint currents (top), absolute differential current and the sympathetic inrush logic thresholds.

IX. Conclusions

This paper introduced several ideas to improve the speed and sensitivity of transformer short-circuit protection. These new ideas are grounded in first principles and in careful analysis of relationships between the transformer currents and voltages. Most of our new ideas require a voltage signal from at least one transformer winding. This requirement is not a major limitation because today's transformer relays provide voltage inputs: the voltages are often used for metering, overvoltage and overexcitation protection, or backup protection for system faults.

Our approach is based on a hybrid logic that retains the traditional 87T and REF modules and adds dedicated high-speed and high-sensitivity 87T and REF modules. This division of labor (dependability, speed, and sensitivity) allows us to optimize each module separately while maximizing protection dependability, speed, and sensitivity and maintaining security. We strengthen protection security by using an arming logic for the high-speed and high-security modules. The arming logic explicitly confirms that the conditions and assumptions used in the design phase are present, allowing secure application of the new logic. This is a powerful concept with an excellent track record in applications to ultra-high-speed line protective relays.

Magnetizing inrush current is the main obstacle to the 87T element speed. Magnetizing inrush may take several forms (energization inrush, fault voltage recovery inrush, sudden overexcitation inrush, and sympathetic inrush). We have analyzed each inrush category and presented solutions for ruling out inrush and tripping fast for internal faults.

Standing differential current caused by CT ratio errors, relay errors, and transformer ratio errors, especially when using a tap changer, is the main obstacle to 87T element sensitivity. We have proposed a new method for deriving the restraining current for the high-sensitivity 87T module as well as a method for tracking the transformer ratio online. These two approaches improve sensitivity without sacrificing security.

When using our new ideas, it is possible to trip for faults in an already energized transformer with speed and sensitivity that exceed those of today's transformer relays. We also discussed faults that develop prior to or during transformer energization. We presented two solutions for improving dependability, speed, and security for faults that occur when an inrush current is also present.

The REF and 87T elements are complementary; however, they see ground faults differently and are exposed to different challenges and limitations. Therefore, optimizing the REF elements for speed and sensitivity and applying them to all grounded windings brings additional benefits.

X. References

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XI. Biographies

Bogdan Kasztenny has 35 years of experience in power system protection and control. In his decade-long academic career (1989–1999), Dr. Kasztenny taught power system and digital signal processing courses at several universities and conducted applied research for several relay manufacturers. In 1999, Bogdan left academia for relay manufacturers where he has since designed, applied, and supported protection, control, and fault-locating products with their global installations numbering in the thousands. Bogdan is an IEEE Fellow, an IET Fellow, a Senior Fulbright Fellow, a Distinguished CIGRE Member, and a registered professional engineer in the province of Ontario. Bogdan has served as a Canadian representative of the CIGRE Study Committee B5 (2013–2020) and on the Western Protective Relay Conference Program Committee (2011–2020). In 2019, Bogdan received the IEEE Canada P. D. Ziogas Electric Power Award. Bogdan earned both the Ph.D. (1992) and D.Sc. (Dr. habil., 2019) degrees, has authored over 250 technical papers, holds over 60 U.S. patents, and is an associate editor of the *IEEE Transactions on Power Delivery*.

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.