Time-Domain Elements Optimize the Security and Performance of Transformer Protection

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This paper was presented at the 71st Annual Conference for Protective Relay Engineers and can be accessed at: https://doi.org/10.1109/CPRE.2018.8349831.

For the complete history of this paper, refer to the next page.

Presented at the
FISE IEEE/CIGRE Conference
Medellín, Colombia
December 4–6, 2019

Previously presented at the
45th Annual Western Protective Relay Conference, October 2018

Originally presented at the
71st Annual Conference for Protective Relay Engineers, March 2018

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***Abstract*—Transformers experience magnetizing inrush that creates an operating current in the transformer differential protection. Early transformer differential relays had to address the limits of analog technology. Analog filter circuits could extract the second- and fourth-harmonic components of the differential current, and these were used as a surrogate measure for determining if the operating current was due to inrush. Today, we can design algorithms that distinguish directly between inrush characteristics and fault current characteristics. By using the new time-domain algorithms, we can improve sensitivity and speed of transformer differential protection. We can also maintain protection security for transformers built using improved core steels.**

I. Introduction

Large power transformers are key assets in any power system. When damaged, they are expensive and difficult to replace, factoring in the cost, manufacturer lead time, and transportation. Transformers require high-speed protection to prevent catastrophic failures such as tank rupture and burning of core steel. Transformers also require high-sensitivity protection to detect low-grade turn-to-turn faults; otherwise, faults must evolve and grow to be detected, thus causing more damage.

In a typical zone of protection, we can take advantage of the complementary principles of high-set and fast elements combined with low-set and slow elements represented by the inverse-time overcurrent characteristic and various time-graded protection schemes. In contrast, transformer protection requires high-set and ultra-fast elements combined with low-set and as-fast-as-possible elements. Delay is simply not acceptable in short-circuit protection of large power transformers.

Differential protection is the protection principle that meets these difficult speed and sensitivity requirements. We will refer to the transformer differential element in general as 87T, the percentage restrained transformer differential element as 87R, and the unrestrained transformer differential element as 87U.

Unlike most differential zones that work on the principle of Kirchhoff's Current Law (KCL), the boundary currents of the zone of protection of a transformer are coupled magnetically, not galvanically, by the principle of ampere-turn balance (ATB) on the magnetic core of the transformer [1]. The transformer core draws a magnetizing current to facilitate the coupling. However, because it is not possible to measure the magnetizing current to include it in the 87T differential current, the magnetizing current upsets the current balance, and an operating current appears in the 87T element.

The B-H curve defines the relationship of the magnetic flux density, B, versus the magnetic field intensity, H. The transformer core saturates when the magnetic flux density of the core experiences excursions above the knee point of the B-H curve. The excitation curve is often substituted for the B-H curve where the voltage across the excitation branch is proportional to B and the current in the excitation branch is proportional to H. With the excitation characteristic that relates v and i, we can understand the slope of the excitation curve as an "instantaneous impedance." The slope of the portion of the curve going through the origin can be understood as the iron-core reactance. The high slope of the curve defines a high instantaneous impedance. The portions of the curve beyond the knee point can be understood as the air-core reactance lines. The low slope of these curves defines a low instantaneous impedance. See Fig. 1.

It is important to understand that the B-H curve is a time-domain plot and the v-i curve we are referring to is a time-domain plot of instantaneous values. The typical excitation characteristic is a plot of the rms values of v and i with the sinusoidal excitation voltage as the driving force and the distorted excitation current as the response.

During the portions of the power system cycle when the core is saturated, the instantaneous impedance of the coil plummets (the ratio of v/i is low), which allows magnetizing current to freely flow in the source winding of the transformer. It is impossible for the 87T elements to measure this current. All other currents around the zone are measured, and they balance to zero. Therefore, an 87T element sees the magnetizing current as an operating current and is prone to trip during magnetizing inrush.

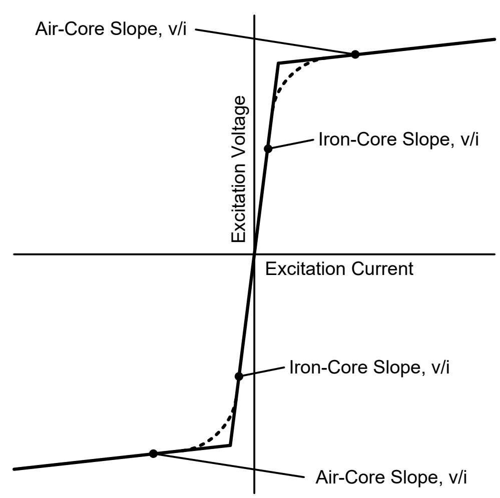

Fig. 1. Transformer time-domain excitation curve.

For a properly designed transformer, excursions of the B-H operating point above the knee point of the core's magnetic characteristic typically happen for only four conditions.

- When the transformer is energized, it draws an initial inrush current or a recovery inrush current that, when high, is typically asymmetrical.
- When a nearby transformer is energized, the transformer may experience a sympathetic inrush with current characteristics like those of the initial inrush.
- When the transformer is exposed to quasi-dc currents during a geomagnetic disturbance, it draws current similar to an inrush current but of typically lower magnitude and without the decay.
- When the transformer is overexcited due to overvoltage or underfrequency conditions, it draws an elevated symmetrical excitation current.

Because the excitation characteristic is not linear, the excitation current is rich in harmonics. During the initial, recovery, and sympathetic inrush and geomagnetic events, saturation occurs only during the positive or negative excitation voltage half cycles but not both, as shown in Fig. 2. Thus, the distorted magnetizing current is asymmetrical around the horizontal axis and therefore contains both even and odd harmonics.

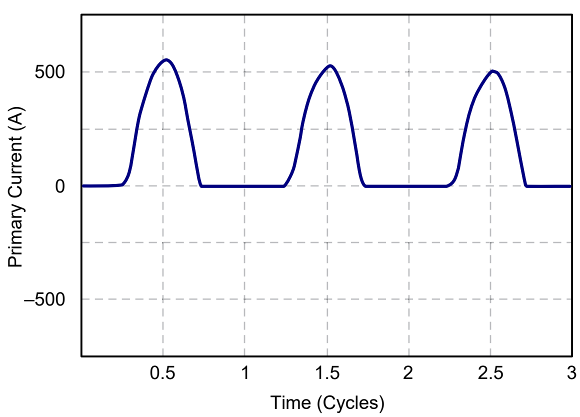

Fig. 2. Typical inrush current waveform.

Overexcitation results in saturation during both the positive and negative peaks of the excitation voltage as shown in Fig. 3. Thus, the distorted magnetizing current is symmetrical around the horizontal axis and therefore contains only odd harmonics.

Historically, we have used the presence of harmonics in the differential current to distinguish between a faulted transformer and one that is experiencing magnetic saturation effects. This method became prevalent because it was practical to construct harmonic filters in analog circuits. We use differential current harmonics to block or restrain 87T elements to maintain acceptable levels of security – at the expense of reduced dependability, speed, and sensitivity, as will be discussed in Section III.

The observation that inrush current is asymmetrical and therefore contains even harmonics lead to the use of second and/or fourth harmonics to identify inrush conditions. The observation that overexcitation current is symmetrical and therefore contains odd harmonics lead to the use of the fifth harmonic to identify overexcitation conditions. The third harmonic, if present in the terminal currents (wye or zigzag windings), is a triplin harmonic, which makes it a zero-sequence quantity that is removed from the 87T operating current by the vector group compensation. This paper focuses on the impact of inrush stability methods on transformer protection, and therefore, fifth-harmonic blocking for overexcitation will not be discussed further.

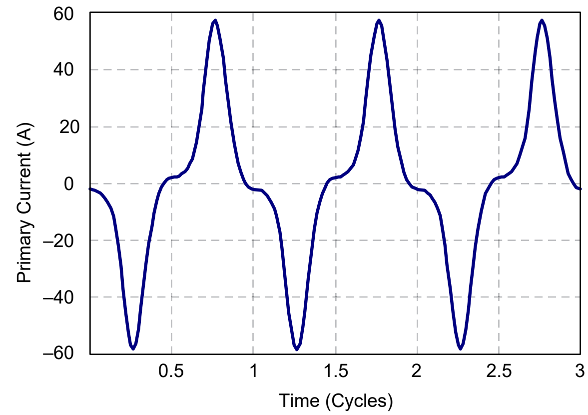

Fig. 3. Typical overexcitation current waveform.

Methods based on the level of even-harmonic content in the 87T operating current served us well for a long time. But, with the advent of modern high-permeability core steels, the industry began experiencing 87T security failures during transformer energization. The industry initially labeled the issue "a low-harmonic core steel problem." An in-depth analysis leads to the phenomenon of ultrasaturation. The remnant flux tends to remain at a high level with modern core steels and upon energization, the flux density can stay above the knee point for nearly the whole power system cycle. During ultrasaturation, the magnetizing branch impedance is not only low but also fairly constant. Given the magnetizing branch impedance is low and constant for a large portion of each power cycle, the core draws large and only slightly distorted magnetizing inrush currents with a low level of harmonics [2].

Modern numerical relays are not restricted by the limitations of analog circuit technology, so it is possible to design a new method of identifying inrush using waveshape recognition techniques applied directly to the 87T operating current samples [2]. Early implementations of the waveshape method concentrated on improving security for transformers with improved core steels. This approach used the waveshape recognition algorithm to further supervise the 87T elements that already included the harmonic methods, see Fig. 4. This figure shows two typical implementations of harmonic inrush methods: harmonic-blocked and harmonic-restrained 87R elements (see Section III for more details). Note that, for simplicity, the fifth-harmonic blocking logic is not shown in this and subsequent logic diagrams.

The extra supervision greatly improves the security of the 87T protection. However, the use of harmonic blocking or restraining prior to the extra supervision with the waveshape inrush method brings speed and sensitivity disadvantages to the scheme in Fig. 4. In this paper, we explain that it is possible to improve on the implementation in Fig. 4 and enhance all aspects of 87T protection.

In this paper, we characterize protection quality as:

- Reliability, as defined by high levels of both security and dependability.
- Performance, as defined by high levels of both speed and sensitivity.

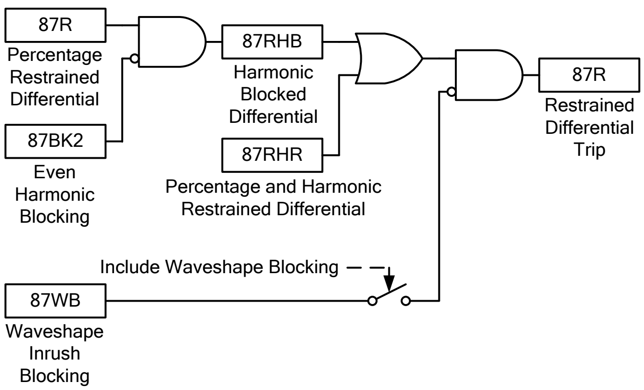

Fig. 4. Using additional waveshape inrush supervision to enhance security of the harmonic-blocked and harmonic-restrained differential elements.

This paper reviews fundamentals of transformer short-circuit protection to remind us of why we require both high performance and high reliability when protecting large transformers. Then it examines why harmonic methods for security during inrush can reduce dependability and performance of transformer protection. It reviews two new waveshape recognition algorithms: one for asserting a blocking bit on inrush and the other for removing the blocking bit when an internal fault is identified. The paper shows how the two algorithms can be used to improve all aspects of transformer short-circuit protection. The opportunity for lowering CT requirements when using the new method is also examined. Finally, the paper examines the benefits of the improved implementation of the waveshape inrush security method using field cases and simulated events.

II. Fundamentals of Transformer Protection

Differential protection is the preferred principle for transformer short-circuit protection. It excels in all measures of protection quality: security, dependability, speed, and sensitivity.

A. Requirements for Transformer Short-Circuit Protection

Speed of short-circuit protection is especially important for power transformers. The energy a short circuit can dissipate inside the tank of a transformer is often much higher than the energy any pressure-relief device can accommodate [3]. Fast protection is the best way to limit the energy and prevent tank rupture, which can result in costly cleanup in addition to the cost to replace or repair the transformer. When the tank ruptures, there is an increased danger of an oil fire leading to total destruction of the transformer and potential destruction of surrounding equipment. Additionally, an oil spill brings a danger of environmental damage if the oil containment system is not adequate or malfunctions.

High sensitivity is needed for power transformers to detect partial-winding faults. Partial-winding faults include turn-to-turn faults and turn-to-ground faults. When a few turns are shorted on a transformer winding, the winding acts as an autotransformer and a very high current may flow in the shorted turns, potentially burning the core steel. If an internal fault can be cleared before burning of the core occurs, the transformer can usually be economically rewound. Whereas, if the core requires restacking to replace damaged steel, the transformer is likely destined for scrap. However, the high current in the shorted turns is stepped down by the ratio of shorted turns to full-winding turns so that the fault current, seen at the terminals of the transformer, and thus the 87T operating current are small [1]. Determining the minimum fault levels for such faults is beyond the scope of this paper [4]. But, it is sufficient to say that the higher 87T sensitivity, the better.

Security of 87T protection is important not only because, in general, security failures remove assets from service and create contingencies, but because transformer analysis is also costly. After an unexpected 87T operation, it is often necessary to unbus the transformer and do extensive testing to determine the health of the transformer prior to returning it to service. In differential protection with only galvanically coupled zone currents (bus or line current differential), CT saturation is the prevailing security concern. In 87T protection, magnetic effects that upset the ATB are generally the biggest security challenge.

B. Speed

The speed of any protection element has two key components. If the protection element is inherently selective, no intentional delay is required to coordinate for faults external to the protected zone, and the element can operate without any intentional coordination delay. However, even if a protection element is not intentionally delayed, it cannot operate right at the fault instant. The element needs to “watch” the event for a certain minimum time to properly classify that event as an internal fault or a different event and operate or restrain, respectively.

In the case of 87T protection, ability to rule out inrush during internal faults is the key factor that impacts the speed of protection. In Section II, we shall discuss the challenge of quickly and correctly distinguishing between inrush and a fault.

C. Sensitivity

Differential protection is used with power transformers because it provides very good sensitivity compared with any other principle that is based on measuring terminal voltages and currents. Because a differential element responds to the sum of the currents entering the zone of protection, the load current entering and exiting the zone cancel each other. Thus, the element can be set to operate for current levels lower than the load current. 87T elements typically operate for differential currents as low as 0.2 to 0.3 of the transformer rated current.

The sensitivity of 87R elements to partial-winding faults can be diminished by through current. Through current during a fault happens when a low-grade fault does not depress the voltage enough to prevent load from flowing through the zone and adding restraint. Sensitive settings (low minimum pickup and low slope) can help detect a partial-winding fault and trip the transformer to limit damage. 87R sensitivity to partial-winding faults is a function of the transformer load. By using negative-sequence currents for restraining, the negative-sequence 87R element works with a much lower restraint during those faults because the load currents typically have a very small negative-sequence component. The negative-sequence 87R element needs to be supervised by external fault detection (EFD) logic for security because the negative-sequence restraint may not be sufficient during balanced or near-balanced external faults [5]. Sudden pressure and restricted earth fault protection also improve detection of partial-winding faults [6].

D. Dependability

Dependability has two aspects. A complete failure to trip is obviously a dependability failure. But, delayed tripping for an in-zone fault should also be considered a reduction in dependability. In the case of power transformer short-circuit protection, a trip delayed so much that a tank ruptures and oil ignites is no different than a failure to trip.

E. Security

Differential relays are inherently biased for dependability. It is important to properly balance this inherent dependability with security features. The main challenge to differential element security in general comes from CT saturation during external faults. False differential current caused by CT saturation is addressed by adaptively requiring higher operating current as the through current increases (a percentage slope characteristic). Single-slope relays must be set to accommodate all sources of error, including CT ratio error for low levels of through current, tap changer ratio mismatch errors, and finally, errors from CT saturation under larger levels of through current. Because of CT saturation concerns, this single-slope must be high, which reduces sensitivity, even for low currents when CT saturation is not likely. Dual slope or variable percentage slope characteristics provide a low slope for low current levels and a high slope for higher current levels, giving a better compromise between security and sensitivity [5].

87R elements include a percentage restraint (bias) to cope with CT saturation on external faults. Newer numerical 87R implementations incorporate EFD logic [1]. The 87T element uses EFD logic to force the differential protection characteristics into a high-security mode. The EFD can dynamically reduce sensitivity thresholds (raise slope) and/or add a small intentional delay or even block certain elements when an external fault is detected.

For 87T elements – as compared with differential elements in general – transformer inrush is another major security concern in addition to the challenge of CT saturation.

F. Adaptive Protection

In general, adaptive protection, such as dynamically changing the slope, is used instead of blocking to increase security only as high as necessary while maintaining some dependability. 87T elements that use adaptive techniques improve dependability and performance under normal conditions and increase security only when necessary, providing better overall protection.

III. 87R Elements With Harmonic Inrush Security

Measuring the harmonic content of the differential current is a surrogate means for distinguishing between short-circuit current and inrush current. Harmonics are also present in other situations when the differential relay should trip (CT saturation on heavy internal faults and internal faults during inrush).

Two methods of harmonic inrush detection came into common use. In harmonic-blocked 87R elements, a comparator determines the ratio of the even-harmonic component to the fundamental component of the differential current and blocks the 87R element if the ratio is high. In harmonic-restrained 87R elements, the magnitudes of the even harmonics are added to the restraining signal in the percentage restrained comparator to prevent the differential current from overcoming the percentage slope (bias) characteristic during inrush conditions.

Both these schemes face challenges. Harmonic blocking and harmonic restraining can be prone to security failures because some loops ("phases") of the 87T element may have low harmonics during core ultrasaturation and may fail to block or restrain, respectively. We use the term loops here because if delta or double-delta vector group compensation is applied in the 87T element, different phases from different windings are mixed together to form each of the three differential signals. We refer to these three differential signals and corresponding restraining signals and logic as loops because the ATB balance equations are written around the loops formed by pairs of core-legs. See [1] for an in-depth explanation of vector group compensation. Cross-blocking alleviates the low second harmonic problem in harmonic-blocked elements. However, cross-blocking can degrade dependability when energizing a faulted transformer because an 87T loop that uses only unfaulted phase currents can block the 87T loop on the faulted phase. Reference [7] provides more application recommendations for using 87R elements with harmonic blocking and restraining.

A. CT Saturation During Heavy Internal Faults

During heavy internal faults, CTs may saturate and produce harmonics in their secondary currents. These harmonics are not indicative of inrush but are an artifact of CT saturation. They may block or delay operation for internal faults of an 87R element that uses harmonics for inrush detection. This problem can be addressed by the requirement to select CTs that do not saturate for the time it takes the 87R element to operate (the CT time-to-saturation requirement) [8]. We shall discuss CT application in more detail in Section VI.

To offset the potential loss in dependability and speed of the 87R element, an unrestrained element (87U) can be applied in parallel with the 87R element. The 87U element operates without percentage restraint and regardless of the harmonic content if the differential current is above a threshold. Because harmonics do not block the 87U, it trips for heavy internal faults, even if CTs saturate and inadvertently block or delay the 87R element.

The 87U operating threshold must be set above the highest possible inrush current and the highest possible spurious differential current during external faults with CT saturation. The differential current is distorted in both these scenarios, and the setting needs to consider the amount of filtering a particular relay applies to its 87U element. Many 87T relays apply an EFD logic to add security for external faults. In relays that supervise the 87U element with EFD, the 87U element does not need to consider external faults but only the highest possible inrush current. Note that the EFD logic will not, and should not, trigger on magnetizing inrush.

Yet another solution to dependability challenges of the 87R element under CT saturation during internal faults is to use harmonic-restrained logic. This logic does not block from harmonics but increases the restraint with harmonics in the differential current. During heavy internal faults, the large differential current overcomes the restraint even if the latter is boosted with spurious harmonics caused by saturated CTs. Still, with the restraint elevated by the spurious harmonics, the harmonic-restrained 87R element may take longer to operate.

B. *CT Saturation During Inrush*

A typical inrush current, if large in magnitude, is asymmetrical (unipolar) and decays slowly to finally become a symmetrical excitation current. The unipolar nature of the inrush current drives the CT flux in one direction. This unipolar current can initially be as high as several times the transformer rated current and therefore several times the CT rated current. As a result, it is likely to eventually saturate the CTs. Even CTs that are properly sized to handle the maximum asymmetrical fault current without saturating may eventually saturate for this unipolar, long-lasting inrush current [9]. The effective X/R ratio during inrush is much higher than during faults because the magnetizing reactance controls the nature of the circuit rather than the system reactance.

C. *Low Harmonic Levels During Inrush*

Newer transformers with high-permeability core steel often experience ultrasaturation during inrush. In ultrasaturation, the flux density is above the knee point of the transformer magnetizing curve (B-H curve [10]) for large portions of each power system cycle, and therefore, the inrush current experiences much less distortion and lower harmonic content. A similar problem occurs with older transformers if they are de-energized with switches prone to restrike (during de-energization multiple restrikes drive the transformer flux to a very high level, resulting in ultrasaturation on a subsequent energization [2]). Lowering harmonic blocking thresholds or increasing harmonic restraint as well as enabling cross-phase blocking are sometimes used to address this problem. However, these solutions may hurt dependability and speed on heavy internal faults with CT saturation and for internal faults during inrush.

D. *Internal Faults During Inrush*

Moisture trapped inside the transformer migrates between the paper insulation and the oil, depending on temperature. A de-energized transformer may be cold, which leads to more moisture trapped in the paper insulation rather than dissolved in oil, degrading the insulation strength of the paper. In addition, the magnetizing inrush current during energization inflicts electromagnetic forces on the windings and may cause the coils to move. While the transformer is de-energized, dirt, animals, and debris may collect inside the transformer protection zone, outside the tank. It is therefore possible for a transformer to fail during energization.

A faulty transformer being energized will still draw an inrush current and produce harmonics in the 87T operating signal. Therefore, the dependability of the 87T element may be compromised when using harmonics to address security during inrush, especially if the cross-phase blocking logic is applied or the harmonic ratio thresholds are lowered.

E. *Operating Time for Internal Faults*

Another issue that is less readily apparent is that the rise of the differential current at the inception of an internal fault generates spurious transient output from the harmonic filters. These spuriously measured harmonics may slow down the 87R element. Fig. 5 illustrates the problem. Note that no harmonics are present in the current signal.

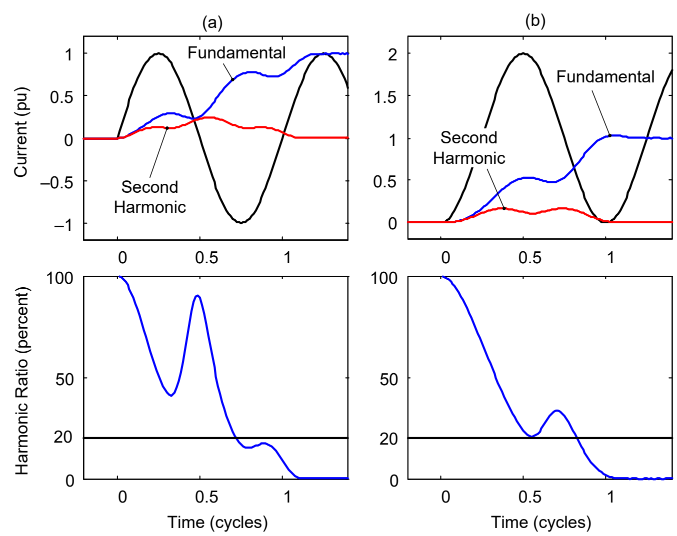

Fig. 5. A change in the differential current generates spurious output in the harmonic filters: symmetrical case (a), fully offset case with a decaying dc component (b).

Fig. 5 shows that the second-harmonic filter (red trace) is excited with the changing input signal. It takes approximately the length of the filter data window (typically one cycle) for the second-harmonic measurement to settle on a true value of zero. While the second-harmonic filter is excited with the change in the input signal, the second-harmonic ratio is large and the differential element may be blocked or restrained. These filter artifacts delay operation of the 87R element until the filters stabilize.

Fig. 6 illustrates the penalty we pay for a heavy internal fault when using harmonic methods for security on inrush. This plot is a field case associated with a failure of the C-phase bushing of a large autotransformer. A delta (IA – IC) vector group compensation is applied; therefore, two differential loops responded to this fault (the ones using IA – IC and IC – IB currents). We labeled these loops as A and C differential loops. The red traces, labeled I*n*M2, are the second-harmonic magnitudes, and the blue traces, labeled IOP*n*15, are the fundamental magnitudes multiplied by 15 percent to show the effective harmonic blocking levels (when the red trace is above the blue trace, the blocking condition is satisfied). The even-harmonic cross-blocking bit, 87XBK2, takes 1.5 cycles to deassert. The CTs performed well and the waveforms (not shown) were not visibly distorted other than they transitioned from pre-fault to fault levels.

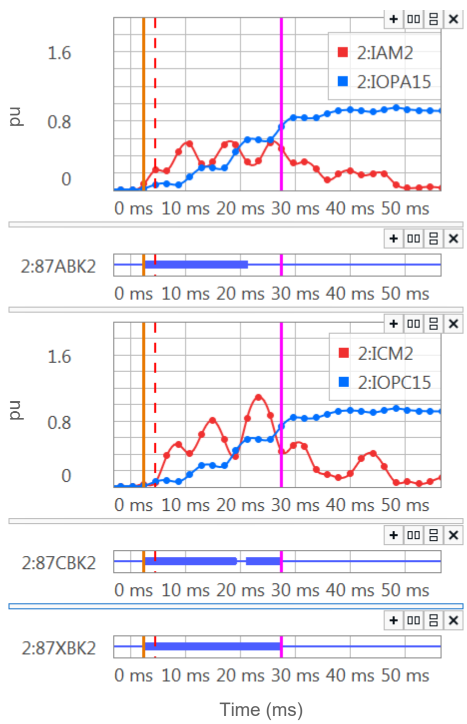

Fig. 6. 87R operation delayed due to spurious (filter-generated) harmonics (currents in per unit of tap).

This phenomenon is not limited to digital relays with digital filters. Any second-harmonic filter will show a similar behavior. A sudden change in the filter input (differential current) transiently contains a wide-frequency spectrum, and these transient frequency components excite the filter.

The phenomenon illustrated in Fig. 5 slows down operation of the 87R element for internal faults, but it is nonetheless desirable during inrush conditions. Fig. 7 shows the very first cycle of an inrush current, asymmetrical (fully offset) fault current, and symmetrical fault current, all with similar peak values. The inrush and the fully offset fault waveforms look similar during the first three-fourths of a cycle. The distinguishing features of inrush are visible in the waveform only toward the end of the first cycle. Therefore, a transformer differential relay must block or restrain during the first cycle for both an inrush and an internal fault, unless the fault current has a high magnitude that allows a clear distinction between a fault and an inrush. On the other hand, the inrush and symmetrical fault current waveforms are clearly different in as early as half a cycle. An 87T element can tell the difference between symmetrical internal fault current and inrush in half a cycle. We will use this observation later for accelerated tripping.

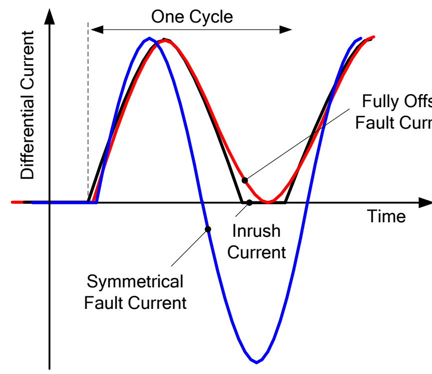

Fig. 7. Differential current during inrush and symmetrical and asymmetrical internal fault currents.

The spurious output from the harmonic filter due to the differential current rise provides the initial blocking required for security during inrush. While the harmonic filters are excited with the signal change rather than with the real harmonics (such as during the first cycle of an inrush current), the filter output may transiently decrease to a low value (see Fig. 5, Fig. 6, and Fig. 23). Practical implementations may include intentional dropout timers to ride through such "holes" in the harmonic blocking signal. These intentional dropout delays may further impair the 87T operating time for internal faults.

IV. 87R Elements With Waveshape Inrush Security

A general inrush security technique based on the waveshape of the differential current uses the repeating periods of small and flat differential current present in an inrush current but not in a fault current ("dwell-time" periods). References [2] and [10] describe a modern digital implementation of this general principle. We summarize this method below. The algorithm works in the time domain, processing individual current samples rather than phasors.

Referring to Fig. 8, we observe that when the transformer core briefly goes out of saturation, the inrush current exhibits periods when the current is low and its waveform is flat. In this example, these periods last about one-sixth of a power cycle and repeat every cycle. Moreover, for transformers with three-legged cores (i.e., without a low-reluctance magnetic path for a zero-sequence flux), these periods of low and flat current are aligned in time among all three 87T loops (phases).

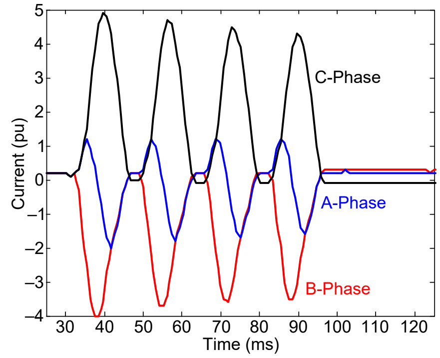

Fig. 8. Sample transformer currents during energization resulting in an undesired 87R operation.

We use the above observation for inrush detection and apply the logic shown in Fig. 9. Instantaneous values of the phase differential currents (87T IDIF A, B, and C) are the inputs to the logic, and the Boolean output, 87WB, is the output (when asserted, the differential element is blocked). The algorithm uses information from all three phases but asserts a single output that applies to all three phases of the 87R element.

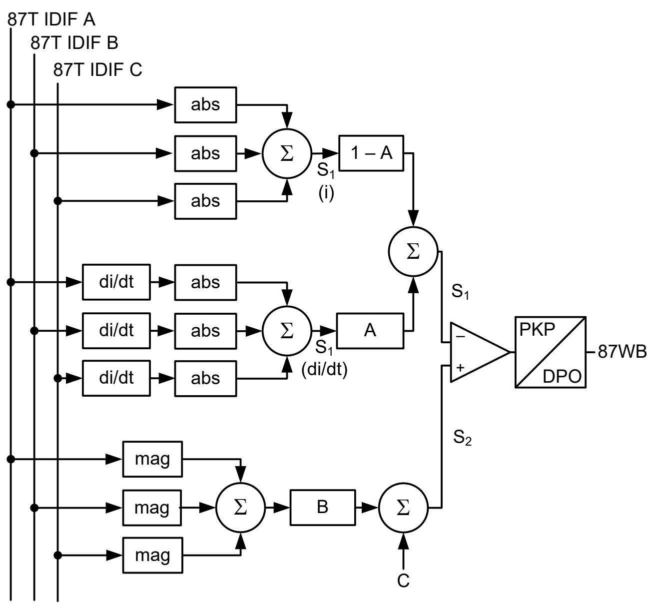

Fig. 9. Simplified block diagram of the waveshape inrush-detection algorithm.

The time-domain algorithm works as follows:

- We add the absolute values of the instantaneous differential currents in all three phases to form the S_1 (i) signal. During inrush conditions, this signal is very low for the duration of the dwell-time periods because all three differential currents exhibit their dwell times at the same time. During internal fault conditions, this signal is high and reflects the fault current. If CT saturation occurs during inrush, the differential currents during dwell-time periods start departing from zero and S_1 (i) starts to increase slightly with time.
- We calculate a time derivative of the instantaneous differential signals (di/dt). Because the inrush currents are flat during dwell-time periods, the derivative is ideally zero. We take the absolute values of the derivatives and sum them in all three phases to form the S_1 (di/dt) signal. Because all three inrush currents are flat at the same time during the dwell-time periods, the S_1 (di/dt) signal is very low during inrush conditions for the duration of the dwell-time periods. If CTs saturate during inrush, this signal may increase, but to a lesser degree than the S_1 (i) signal.
- Next, we add the S_1 (i) and S_1 (di/dt) signals using the weighting factor A (between 0 and 1, consider $A = 0.5$ for example). The resulting S_1 signal is low during the dwell-time periods of the inrush and high during internal faults. The S_1 signal is quite resilient to CT saturation during inrush. Increasing the value of A and biasing the operation toward using the derivative rather than the signal further increases the resilience of the algorithm to CT saturation during inrush.
- We measure and add together the fundamental frequency magnitudes of the phase differential currents to form an adaptive threshold for checking the value of S_1. S_2 is a portion of the sum of the magnitudes (multiplier B) plus a constant, C (consider $B = 0.1$ and $C = 0.1$ pu).
- During inrush, once every power cycle for the duration of the dwell-time period, the S_1 signal is very low compared with the S_2 signal. We use a comparator to check the level of S_1. If this signal is low for the duration of the pickup (PKP) time, then 87WB asserts and is maintained for the dropout (DPO) time (typically one power system cycle). The DPO timer is required to wait for the next dwell-time period to maintain reliable inrush detection.
- We apply the PKP time for the desired level of dependability of inrush detection. For example, we can set it to one-sixth (or even as low as one-eighth) of a power cycle, allowing it to cope with cases of the second harmonic as low as 10 percent [2] [10].

Fig. 10 and Fig. 11 illustrate operation of the algorithm using an inrush case recorded in the field with a simulated fault current superimposed on the blue-phase inrush waveform (in Fig. 10, the fault was “added” about 72 ms after transformer energization). We expect the algorithm to block for the first 72 ms of inrush (87T security) and unblock shortly afterward (87T dependability).

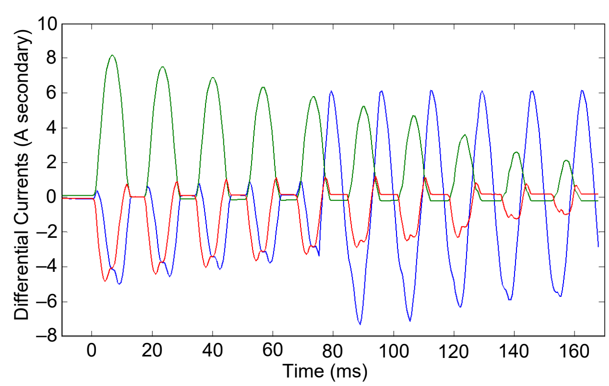

Fig. 10. Differential currents for an internal fault during inrush conditions.

Fig. 11 shows the key internal signals of the logic. As expected during inrush conditions, the S_1 (i), S_1 (di/dt), and S_1 signals are low for the duration of the dwell-time periods. After the internal fault develops in the blue phase, the dwell-time intervals have practically disappeared from the S_1 signal, though the other two phases continue to look like true inrush currents with clearly visible dwell-time periods.

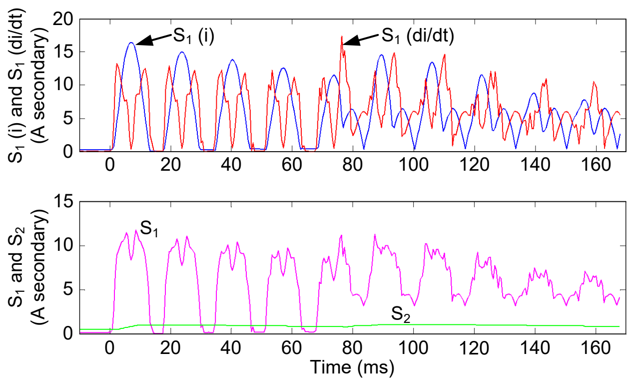

Fig. 11. S_1 (i) (blue), S_1 (di/dt) (red), S_1 (magenta), and S_2 (green) signals for the case shown in Fig. 10.

The S_1 signal drops repeatedly below the S_2 signal during inrush and stays consistently above the S_2 signal after the internal fault (Fig. 11). This means that during inrush conditions, the PKP timer picks up and maintains an 87WB assertion. The last dwell-time interval in the S_1 signal occurs at about 65 ms. If it was not for the internal fault, the next interval would occur at about 65 + 17 = 82 ms. The DPO timer expires after about one cycle (around 82 ms), and because there is no new dwell-time period present, 87WB deasserts at 82 ms, unblocking the 87R element and allowing it to operate.

While the even-harmonic methods may lose security when ultrasaturation occurs, the waveshape method is considerably more tolerant to ultrasaturation [2]. Of course, once the ultrasaturation is such that the differential current waveform appears sinusoidal, all methods based on the differential current will fail. Using both the harmonic and waveshape methods and allowing either method to block the 87R element (see Fig. 4) provides a very high level of security. Fig. 12 shows the new implementation. The user can add waveshape blocking to the harmonic-restrained 87R element, 87RHR, and add waveshape blocking in parallel with even-harmonic blocking for the harmonic-blocked 87R element, 87RHB. Note that the waveshape method of Fig. 9 is not inherently faster than the harmonic method. The DPO timer in Fig. 9 must maintain the 87WB output for about a cycle after the last dwell-time period.

We address the dependability and speed shortcomings of the logic in Fig. 12 in the next section.

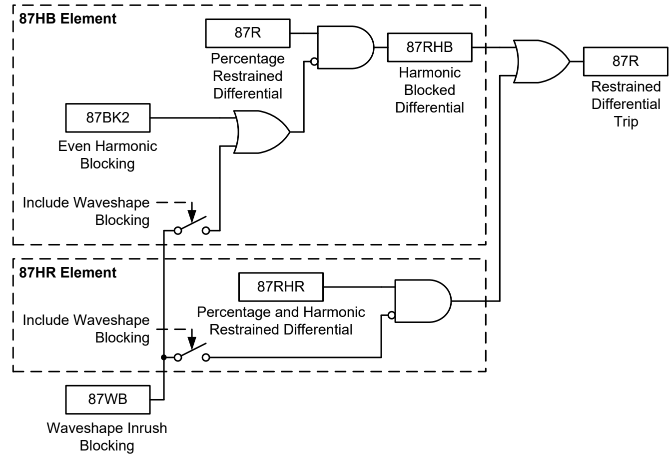

Fig. 12. New waveshape inrush supervision logic (compare with Fig. 4).

V. Enhancing Speed and Dependability

There is no inherent speed improvement using waveshape for inrush security (see Fig. 7). The waveshape method does not cause an extra delay for internal faults with CT saturation, but without CT saturation, the waveshape method is as fast as the harmonic method. Our solution to improve the 87R operating time is based on a bipolar differential overcurrent element. We first introduce this logic and follow with two applications: 1) unblocking the 87R element and 2) unrestrained tripping with the enhanced 87U element. This algorithm also works in the time domain, processing individual current samples rather than phasors.

A. Bipolar Differential Overcurrent Element

The inrush current, when high, is asymmetrical, i.e., unipolar. It becomes more symmetrical with the passing of time as the inrush current decays into a steady-state excitation current. Fig. 13 shows the B-loop differential current from Fig. 10 superimposed onto two levels: a positive threshold and a negative threshold, both placed symmetrically with respect to current zero. During inrush conditions (first 72 ms in this case), the differential current is negative and crosses the negative threshold (blue line in Fig. 13) but not the positive threshold (red line).

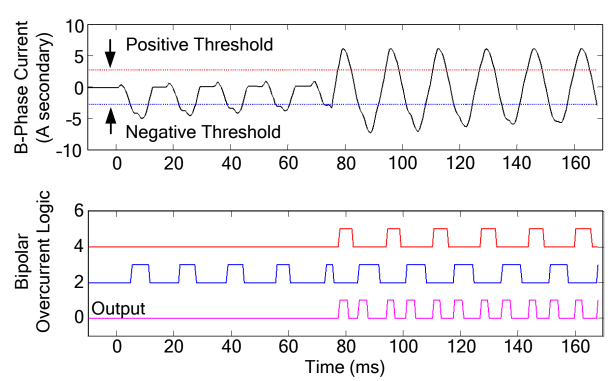

Fig. 13. B-loop differential current from Fig. 10 compared with positive (red) and negative (blue) thresholds.

When the internal fault develops at 72 ms, the differential current crosses the negative threshold; shortly afterward, it crosses the positive threshold and so on. We use this observation to devise the new protection element depicted in Fig. 14.

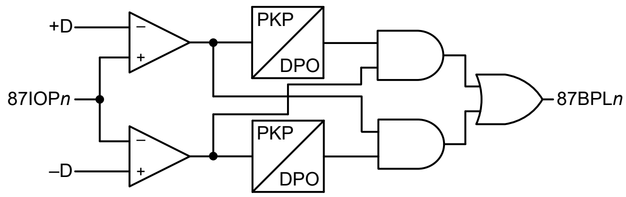

Fig. 14. Bipolar differential overcurrent element logic.

The bipolar differential overcurrent element, 87BPL*n*, compares the instantaneous differential current (87IOP*n*) with the positive (+D) and negative (–D) thresholds. If the differential current is above the positive threshold for a short duration of time (PKP timer), a window equal to the DPO timer opens to wait for the current to decrease below the negative threshold. If it does, the current must be symmetrical, and therefore, it is not an inrush current. Mirror logic is used for the negative polarity. The PKP timer in Fig. 14 is introduced for security (one-eighth of a cycle, for example). The DPO timer is set to about one-third to one-half of a cycle.

The magenta trace in Fig. 13 is the output of the bipolar differential overcurrent element. The element asserts at about 78 ms (the fault occurred at about 72 ms).

Owing to the positive- and negative-level checks, this element does not have to be set very high to differentiate between a fault current and an inrush current.

B. Inrush Unblocking Logic

Accelerating operation of the 87R element is our first application for the bipolar differential overcurrent element. We use a *low-set* bipolar differential overcurrent element to reset the inrush blocking bits, 87BK2 and 87WB, in the 87R logic. The low-set bipolar differential overcurrent element can be applied to improve speed of 87R elements that use both the time-domain waveshape method and the frequency-domain harmonic method for inrush security. If the differential current is relatively symmetrical, it cannot be an inrush current, and therefore, it is safe to reset the inrush blocking bits.

However, before we allow the bipolar differential overcurrent element to reset the inrush blocking bit, we need to determine that the symmetrical nature of the current is not caused by CT saturation during inrush. CT saturation during inrush makes the differential current appear more symmetrical, but it only does so gradually. In contrast, an internal short circuit results in a sudden change in the differential current. We check for a sudden change in the differential current before we allow the low-set bipolar differential overcurrent element to remove the inrush blocking action. Fig. 15 shows the inrush unblocking logic.

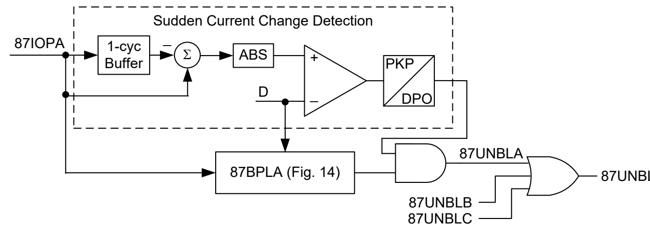

Fig. 15. Inrush unblocking logic using a low-set bipolar differential overcurrent element.

Fig. 16 explains how the inrush blocking action is removed in the 87RHB logic and in the 87RHR logic.

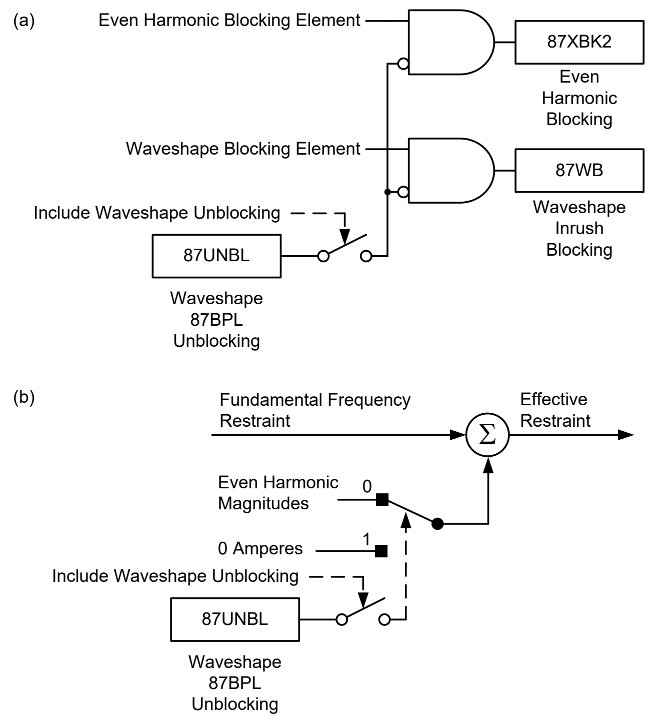

Fig. 16. Removing the inrush blocking action in the 87RHB (a) and 87RHR (b) elements.

We can expect the unblocking signal to assert as fast as one-half to three-fourths of a cycle – at least one-half-cycle improvement in the operating time of the 87R element (see Fig. 17 for an explanation and Fig. 6 and Fig. 22 for illustrations).

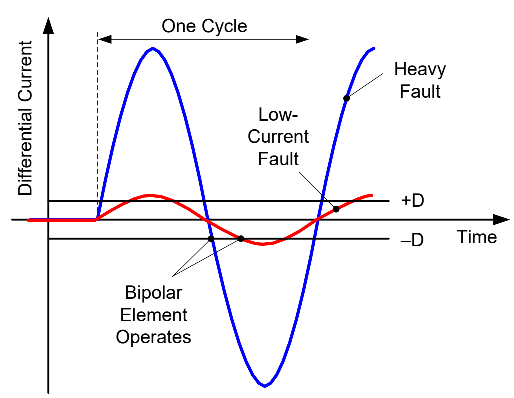

Fig. 17. Operating time for the low-set bipolar differential overcurrent element for a symmetrical differential current.

C. Unrestrained Differential Element

We also use a *high-set* bipolar differential overcurrent element to trip unconditionally, i.e., as an 87U element. The traditional 87U element must be set above maximum inrush and maximum spurious differential current for a through fault. The high-set bipolar differential overcurrent element, operating as a new 87U element, is effectively insensitive to differential current from inrush. However, spurious differential current from CT saturation during external faults must be examined further.

During asymmetrical CT saturation, the CT saturates on only the positive or negative portions of the cycle. The differential current from asymmetrical CT saturation is therefore unipolar. See Fig. 18 for illustration. But, when we consider the transformer vector group compensation, if a CT on more than one phase saturates, the resulting waveform of the differential current can be bipolar. See Fig. 19 for illustration (A- and B-phase CTs saturate in this three-winding transformer example: S, T, and W designate differential zone boundary currents). Because spurious differential current from CT saturation is an issue only during external faults, the EFD may be used to either dynamically raise the thresholds of the bipolar 87U element or to block the 87U element to allow it to ride through spurious differential current on external faults.

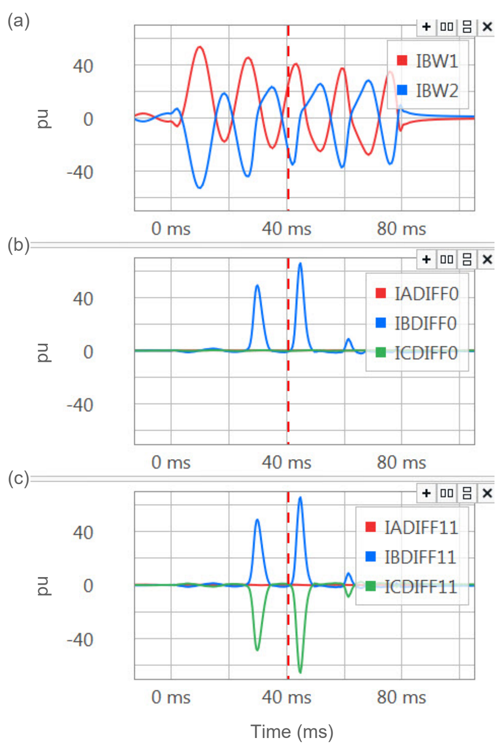

Fig. 18. Winding currents with B-phase CT saturation (a) and differential current with wye vector group compensation (b) and with delta vector group compensation (c), (currents in per unit of tap).

Examining the traces labeled I*n*DIFF0 in Fig. 19 shows that the spurious differential current is largely unipolar if wye-compensated (i.e., effectively not compensated). However, when the CT supplying the current labeled IBSPU pulls out of saturation and the CT supplying the current labeled IBTPU goes into saturation a cycle later, the B-loop differential current labeled IBDIFF0 switches polarities and appears bipolar for a cycle. Examining the traces labeled I*n*DIFF1 (after delta compensation), because both A-phase and B-phase have saturated CTs, the differential loop with IA – IB compensation shows a spurious bipolar differential current. The bipolar 87U element must be desensitized or blocked to remain secure in this case.

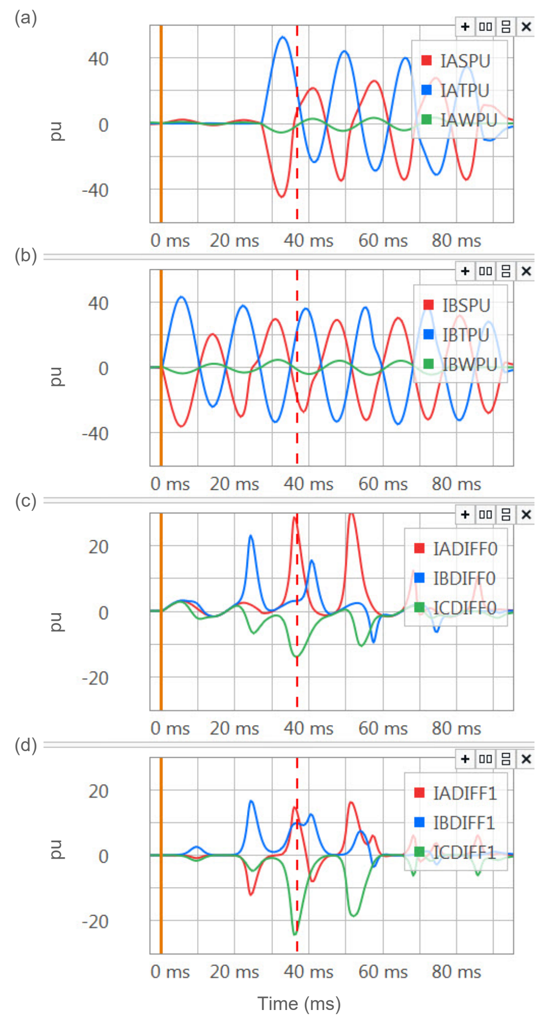

Fig. 19. A-phase currents (a) at transformer terminals S, T, and W; B-phase currents (b); and spurious differential current with wye vector group compensation (c) and with delta compensation (d), (currents in per unit of tap).

The bipolar nature of fault current allows fast 87U operation on heavy internal faults and takes advantage of the relatively low setting that is required for this 87U element compared with the setting for the traditional (filtered) 87U element. As shown in Fig. 17, we can expect this element to operate in half a cycle for heavy faults. For security, we use the change in current to supervise this bipolar 87U element and guard against operating on the dwell-time current that is shifted away from zero due to CT saturation on inrush. This supervision is similar to that used for the 87R unblocking application illustrated in Fig. 15.

D. Operating Time Benefits

Fig. 20 shows a comparison of the new 87T element implementation with a reference relay for a range of internal fault conditions. We simulated in-zone faults with a varying level of the fault current and plotted the operating times as a function of the fault current in per unit of tap. As expected for heavy faults, the inrush unblocking logic accelerates the 87R element by about half a cycle and the bipolar 87U element trips in as fast as half a cycle. This trip time reduction can make a difference between the tank rupturing or staying intact.

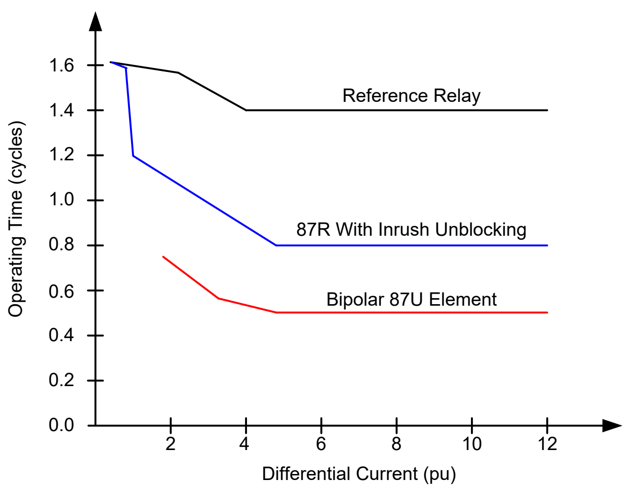

Fig. 20. 87T operating time as a function of the differential current.

E. Instantaneous Sample-Based Unrestrained Differential Element

To further improve speed for heavy internal faults, a third unrestrained element, 87UR, is included. The element asserts when the differential current instantaneous samples exceed a threshold. To remain secure, the threshold is the unrestrained differential element, 87UF, setpoint multiplied by $2 \cdot \sqrt{2}$. The factor of two accounts for a fully offset waveform and the $\sqrt{2}$ factor converts from rms to peak scaling. Here, we use the suffix R for raw as a shorthand for an instantaneous sample operating signal and the suffix F for a fundamental filtered operating signal. Because there is no filter delay, this element can operate in as little as a quarter cycle (on the first peak of the raw, unfiltered waveform).

VI. Current Transformer Considerations

Proper application of 87T protection requires adequately sized CTs, especially in terms of CT saturation under fault and magnetizing inrush conditions. This paper considers CT performance in the following three areas:

- 87T security for external faults,
- 87T dependability and speed for internal faults,
- Dependability of the 87T inrush-detection logic.

A. 87T Security on External Faults With CT Saturation

When considering current phasors (after band-pass filtering), a saturated CT reproduces the ratio current with magnitude and phase errors. The secondary current magnitude is lower than the true magnitude of the ratio current, and the secondary current phase leads the true phase of the ratio current. Because of both the magnitude and phase errors in one or more of the 87T zone currents, the 87T element measures a spurious differential signal even if it applies heavy filtering, i.e., works on phasors. The percentage restraint characteristic of the 87R element provides security if the spurious differential current does not exceed a set fraction (percentage) of the through current (the restraining signal of the 87R element). Setting the percentage restraint (slope) is not an easy task because it requires calculating the secondary current of a saturated CT. Such calculation involves the nonlinear nature of the CT, requires assuming a level of remanent flux, and requires reproducing the relay filters to reflect the actual differential and restraining signals as measured and used by any specific 87R element. In addition, several CTs may saturate for the same fault, making the analysis even more difficult (see Fig. 19). As a result, the slope selection is typically a judgement call. Instead of calculating the spurious differential current and selecting the slope, protection engineers place an emphasis on selecting CTs to avoid saturation during external faults.

Sizing CTs to avoid saturation for external faults is easier if using transformer bushing CTs or breaker CTs in a single-breaker termination for 87T protection (Fig. 21a). It is more difficult when using breaker CTs in a dual-breaker termination for 87T protection (Fig. 21b). In the former case, the external fault current (i_{F2}) is always limited by the transformer reactance, and therefore it cannot be higher than about ten times the rated transformer current, and therefore the rated CT current. In the latter case, the external fault current (i_{F1}) can be arbitrarily high compared with the CT rated current. This is especially true for small transformers connected to strong buses if the CT ratios are sized to the transformer MVA rating rather than the bus short-circuit rating. In this case, the CT performance can be poor resulting in poor 87T security for external faults. On the other hand, if the CTs are sized for the bus short-circuit level, 87R sensitivity may be reduced to an unacceptable level.

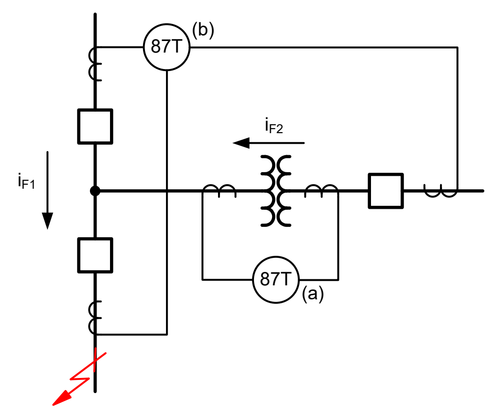

Fig. 21. Sizing CTs for external faults: 87T working with bushing CTs measures fault currents limited by the transformer impedance (a); 87T working with dual-breaker CTs can see very high current not limited by the transformer impedance (b).

Advanced 87R elements incorporate fast EFD logic and engage extra security – typically a second, higher percentage restraint – upon detecting a through-fault condition.

Practical 87T protection tolerates a degree of CT saturation. However, typical settings rules call for sizing CTs for the 87T protection to avoid saturation for external faults, typically assuming no residual flux in the CTs and a moderate system X/R ratio. The percentage restraint and external fault detectors provide an extra margin for neglecting the residual flux and high X/R ratios.

It is a misconception that the 87R inrush-detection logic based on harmonics can be relied on for security during external faults with CT saturation. The inrush-detection logic may sporadically assert due to the distorted waveshape of the differential signal; however, it must not be counted on, because the differential current shape may be complex and high harmonics are not necessarily guaranteed.

Another important consideration is the proper use of the 87T vector group compensation settings. An "excessive compensation" (defined here as unnecessary use of a delta compensation on delta-connected transformer windings and of double-delta compensation on wye-connected transformer windings) may lead to a spurious differential signal in healthy 87T loops during an external fault [11]. Healthy 87T loops do not produce a large restraining current, yet they may see a high differential current because they use the fault current from one or more phases in the differential current equation. Normally, these currents would cancel in the differential signal, but when reproduced with CT errors, they do not cancel and create a spurious differential signal without adequate restraint. Such a misapplication of the winding compensation settings may lead to the loss of 87T security on external faults with CT saturation, even with a very high slope setting and EFD logic [11].

B. 87T Dependability and Speed Under CT Saturation

A CT saturated for a heavy internal fault produces harmonics in its secondary current. These harmonics will appear in the differential signal, and the harmonic ratio will depend on the amount of fault current fed via the saturated CT versus the total current from all the other CTs. As explained earlier in this paper, the change in the differential current produces spurious harmonics for the first cycle of the fault as an artifact of the harmonic filter response. A subsequent CT saturation continues to produce spurious harmonics for as long as the CT remains saturated. As a result, CT saturation on internal faults may assert the harmonic inrush blocking bit and impair 87R dependability. The 87R element may fail to trip or trip slowly when the CT goes out of saturation.

Ideally, one would prefer CTs sized to ensure no CT saturation for internal faults, but this requirement may be difficult to meet, especially for smaller transformers connected to buses with high short-circuit levels. Typically, relay practitioners would select CTs to ensure that the CT time to saturation for internal faults is not shorter than the 87R element operating time plus a margin. This gives the 87R element time to operate on undistorted CT secondary currents before CT saturation occurs.

The 87U element can improve dependability if the internal fault current is above the pickup threshold of the 87U element. In a traditional 87U element, that threshold needs to be on the order of 5–7 times the rated current in order to ride through the inrush current.

The inrush-detection logic, based on waveshape recognition, is considerably more forgiving to CT saturation on internal faults. The logic tends to unblock the 87R elements because the "small and flat" periods do not occur in all three phases at the same time, even if the CTs are heavily saturated. Additionally, the improved 87U element, based on the bipolar differential overcurrent logic, operates for much smaller differential signals than the traditional 87U element with filtering. This gives the bipolar 87U element a good chance to clear internal faults, even with heavily saturated CTs.

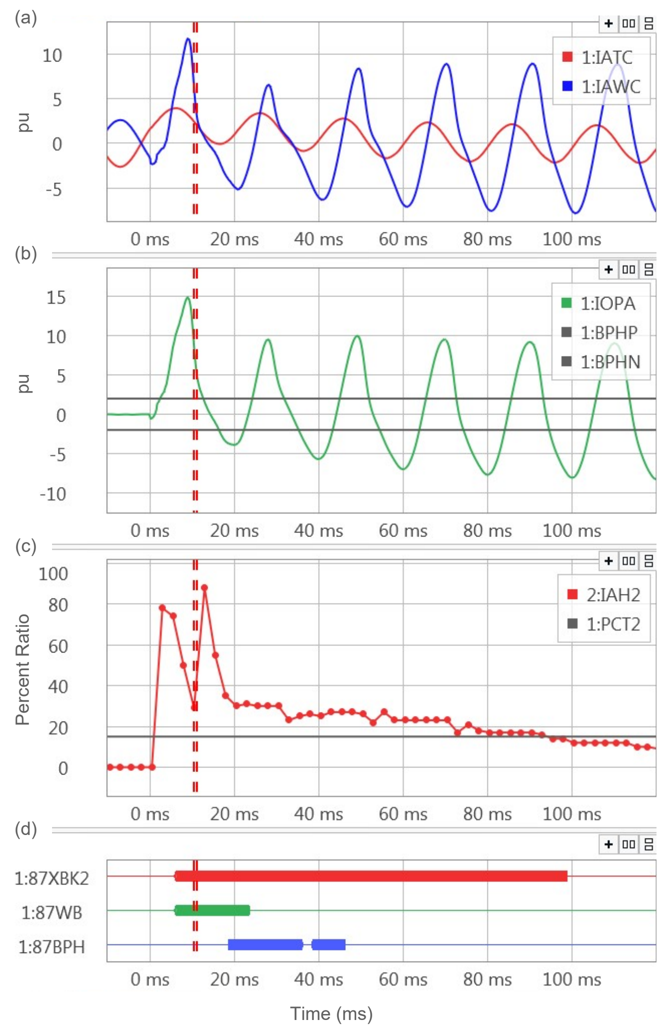

Fig. 22. Heavy internal fault with CT saturation (currents in per unit of tap).

Fig. 22 shows selected 87T signals for an internal fault causing CT saturation. Fig. 22a presents vector-group-compensated currents in the two windings of a transformer. One of the currents comes from a CT that saturates for this fault. Fig. 22b shows the differential signal superimposed on the positive and negative thresholds of the bipolar 87U element. Notice that after crossing the positive threshold, the signal crosses the negative threshold about 18 ms into the fault. The 87BPH bit in Fig. 22d signifies the operation of the bipolar 87U element. Fig. 22c plots the second-harmonic ratio for the differential signal. This ratio is above the 15 percent set point for almost 100 ms (87XBK2 bit), delaying operation of the harmonic-blocked 87R element for almost 100 ms. In contrast, the waveshape inrush blocking logic removes the 87WB bit in about 23 ms. In summary: the harmonic-blocked 87R element would take almost 100 ms to operate; the 87R element with waveshape inrush-detection logic, even without 87UNBL inrush unblocking, would operate in about 23 ms; the bipolar 87U element operates in about 18 ms.

C. Dependability of the 87R Inrush-Detection Logic Under CT Saturation

Magnetizing inrush current is a unipolar signal with a very slow rate of decay. The initial magnitude of an inrush current can be as high as 5–7 times the transformer rated current (and therefore, the CT rated current, typically). It may take 1–2 seconds for this current to decay and become a symmetrical steady-state excitation current at the level of 1–2 percent of the transformer rated current.

The long-lasting dc component in the magnetizing inrush current may cause CT saturation by slowly driving the CT flux into the saturation region. If CTs saturate during magnetizing inrush, the secondary waveform loses the dc offset and it becomes symmetrical. The ac component in the differential current can still be relatively high, such as 1–2 times the transformer rated current, when CT saturation occurs. The differential current, however, preserves the harmonic content, making the harmonic inrush-detection logic work adequately (block or restrain, respectively).

The waveshape inrush-detection logic will respond to the symmetrical nature of the differential waveform. The instantaneous current is no longer small during the dwell-time periods. The waveshape inrush blocking logic addresses this phenomenon by using the current derivative in addition to the current level (increasing the value of design constant *A* in Fig. 9 makes the logic more forgiving to CT saturation during inrush).

Fig. 23 illustrates CT saturation during inrush conditions. Fig. 23a shows the winding current during energization in primary amperes. Fig. 23b shows the differential signal in per unit of tap. The current values during the dwell-time periods depart from zero because of the A-phase CT saturation (see Fig. 23a). In this particular case, the second-harmonic ratio is temporarily low (see Fig. 23c at about 25 ms). Initially, the waveshape method blocks reliably, but later it may be affected by the substantial CT saturation (see the 87WB bit dropout in Fig. 23d). A combination of the harmonic and waveshape methods (87ABK2 OR 87WB) will perform well. This combined blocking action may be removed by the 87UNBL bit for speed on internal faults. As Fig. 23d shows, this bit does not assert during inrush, making the application dependable for detecting inrush and fast to trip should an internal fault happen during inrush.

Sizing or even evaluating the performance of CTs during inrush conditions is complicated and is not typically performed as a part of practical transformer protection application. One may consider blocking the 87R element with both the waveshape and harmonic inrush detectors to ensure 87T security during inrush conditions under CT saturation. In such applications, it is beneficial to apply the bipolar inrush unblocking logic. This logic is not affected by CT saturation during inrush, because it requires a sudden change in the differential current to unblock.

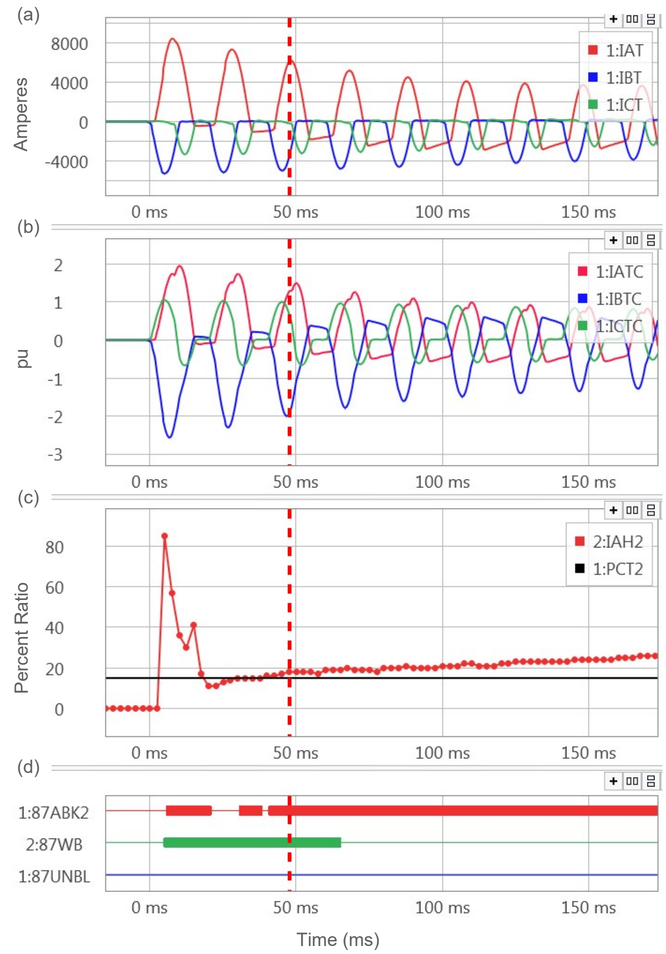

Fig. 23. CT saturation during magnetizing inrush (pu is per unit of tap).

VII. Performance Analysis of Traditional and Improved Protection

We use a field case of a C-phase bushing failure fault to illustrate the delay caused by harmonic methods. Fig. 24 shows the plots of the various C-loop differential elements. The analog and digital graphs in Fig. 24a focus on the bipolar differential overcurrent elements. The blue trace labeled IOPC shows the the instantaneous samples of the waveform with the low-set bipolar inrush unblocking element thresholds superimposed on the graph in black. The digital traces labeled 87BPLC and 87BPHC are the low-set bipolar inrush unblocking element and the bipolar 87U element, respectively. The trace labeled 87UNBL is the unblocking bit, which is limited to one cycle in duration by the logic described in Fig. 15.

The analog and digital graphs in Fig. 24b focus on the percentage restrained harmonic-blocked element, 87RHB. The red trace labeled ICM2 and the blue trace labeled IOPC15 show the magnitude of the second harmonic and the 15-percent threshold of the fundamental operate current. These traces are the same as the waveforms shown in Fig. 6. The even-harmonic blocking bit, 87CBK2, still asserts for approximately 1.5 cycles as in Fig. 6. This time, however, we can see that the C-loop tripping bit of the harmonic-blocked element, 87CHB, asserts as soon as the low-set bipolar differential overcurrent element identifies that this is not inrush and unblocks the 87R element.

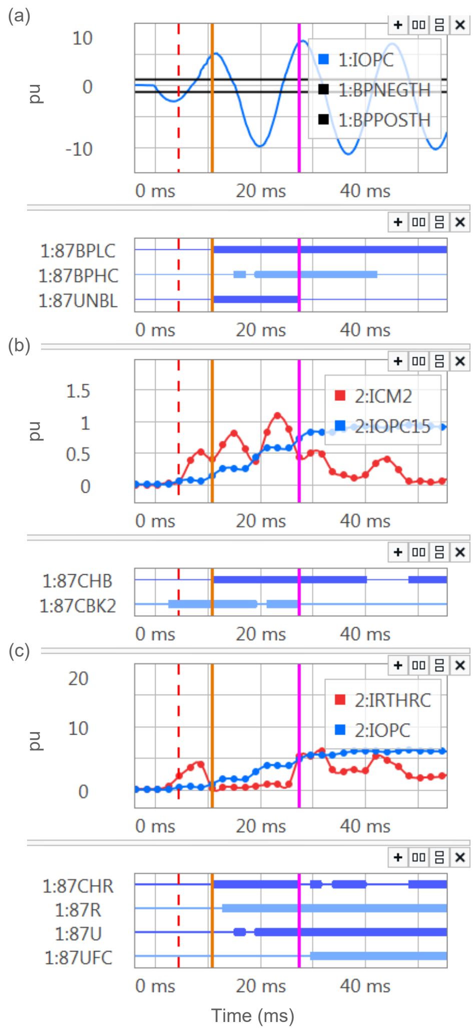

Fig. 24. Improved tripping time with new implementation (currents in per unit of tap).

The analog and digital graphs in Fig. 24c focus on the percentage restrained harmonic-restrained element, 87RHR. The red trace is the restraining signal, boosted by the magnitudes of the even harmonics. The blue trace is the operate current magnitude. It is easy to see the operation of the switch illustrated in Fig. 16b, which removes the harmonic signal from the summing junction, developing the restraining signal. While the 87UNBL bit is asserted, the restraining signal is instantly and considerably reduced. We can see that the C-loop tripping bit of the harmonic-restrained element asserts as soon as the operating current exceeds the restraint by the percentage slope amount.

The digital trace labeled 87R is the OR combination of the 87RHB*n* and 87RHR*n* bits from the restrained differential elements. The digital trace labeled 87U is the OR combination of the fundamental, 87UF*n*, and bipolar, 87BPH*n*, unrestrained differential elements. The 87UR*n* element was not included in this test case. We can see that the traditional fundamental component element (the trace labeled 87UFC) is much slower than the speed of the 87U protection enhanced by including the 87BPH*n* element.

VIII. Conclusion

Power transformers require secure, sensitive, and fast protection. Fast and sensitive protection can limit damage, reduce costs to respond to the failure, and speed restoration of critical facilities. Security failures are quite costly in both time of outage and expense to test the asset. Every effort must be made to avoid undesired protection operations.

Transformer differential protection relies on the principle of ampere-turn balance across the magnetic core of the transformer and for this reason is vulnerable to misoperation when the core becomes saturated during inrush, overexcitation, and geomagnetic events. Historically, the presence of even harmonics in the differential current has been used to ensure security for inrush and geomagnetic events, and fifth-harmonic blocking has been used to ensure security for overexcitation events.

Harmonics are only a surrogate measure of the magnetizing inrush and can be caused by events other than inrush. False harmonics reduce speed and sensitivity of transformer protection.

Harmonic inrush security methods may also face challenges in identifying 1) the inrush of transformers with modern core steels that can experience ultrasaturation and 2) inrush of older transformers if they develop high levels of remanence when being de-energized (restrikes in the switching device). Lack of dependable inrush detection leads to the loss of 87T security during inrush conditions.

The waveshape method that identifies the dwell-time period of the unipolar inrush current is better able to identify inrush and block the sensitive 87T elements. The initial implementation of this method only focused on improving security without fully exploiting the improvements in dependability and performance that were possible.

A bipolar differential overcurrent logic that looks at the bipolar versus unipolar characteristics of differential current can also be used to remove the harmonic security measures and therefore improve speed and sensitivity of 87R elements. Using unblocking when differential current is not caused by inrush allows us to gain speed and sensitivity without reducing security on inrush.

Two bipolar differential overcurrent elements are used in the new implementation. The low-set element unblocks the sensitive 87R elements, and the high-set element acts as an unrestrained 87U element and trips directly. Compared to the traditional 87U element, the bipolar 87U element provides faster and more sensitive protection. It inherently rejects unipolar inrush current, whereas the traditional element is equally responsive to the magnitude of the ac component in the unipolar inrush current and the bipolar internal fault current. A peak detector element, which operates on the instantaneous samples of the current waveform with a secure threshold, is also included to provide an even faster response for very heavy faults.

New developments in the field of transformer protection specifically target the challenges posed by inrush. Security during overexcitation is a different challenge that is properly handled by fifth-harmonic blocking, so no modification to this technique has been made.

Optimizing the integration of traditional frequency-domain protection concepts and time-domain protection concepts allows us to improve transformer protection reliability (by boosting security and dependability) and performance (by boosting speed and sensitivity). For optimal protection, we recommend enabling both harmonic-blocked and harmonic-restrained elements and supervising both with waveshape blocking to improve security. To improve speed and sensitivity, we recommend combining the inrush security methods with bipolar inrush unblocking logic and bipolar-unrestrained tripping.

IX. References

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X. Biographies

Bogdan Kasztenny has specialized and worked in power system protection and control since 1989. In his decade-long academic career, Dr. Kasztenny taught power system and signal processing courses at several universities and conducted applied research for several relay manufacturers. Since 1999, Bogdan has designed, applied, and supported protection, control, and fault locating products with their global installed base counted in thousands of installations. Since 2009, Bogdan has been with Schweitzer Engineering Laboratories, Inc. where he works on product research and development. Bogdan is an IEEE Fellow, a Senior Fulbright Fellow, a Canadian representative of the CIGRE Study Committee B5, and a registered professional engineer in the province of Ontario. Bogdan has served on the Western Protective Relay Conference Program Committee since 2011 and on the Developments in Power System Protection Conference Program Committee since 2015. Bogdan has authored over 200 technical papers and holds over 30 patents.

Michael J. Thompson received his BS, magna cum laude, from Bradley University in 1981 and an MBA from Eastern Illinois University in 1991. Upon graduating, he served nearly 15 years at a public utility, Central Illinois Public Service (now AMEREN). Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2001, he was involved in the development of several numerical protective relays while working at Basler Electric. He is presently a fellow engineer at SEL Engineering Services, Inc. He is a senior member of the IEEE, member of the IEEE PES Power System Relaying and Control Committee (PSRCC), past chairman of the Substation Protection Subcommittee of the PSRCC and recipient of the Standards Medallion from the IEEE Standards Association in 2016. Michael is a registered professional engineer in six jurisdictions, was a contributor to the reference book, *Modern Solutions for the Protection, Control, and Monitoring of Electric Power Systems*, has published numerous technical papers and magazine articles, and holds three patents.

Douglas Taylor received his BSEE and MSEE degrees from the University of Idaho in 2007 and 2009. Since 2009, he has worked at Schweitzer Engineering Laboratories, Inc., and currently he is a lead research engineer in the Research and Development division. Mr. Taylor is a registered professional engineer in the state of Washington and is a member of the IEEE. His main interests are power system protection and power system analysis.

Previously presented at the 2018 Texas A&M
Conference for Protective Relay Engineers.

20180813 • TP6854-01