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Research Article

A Comparative Assessment of Second-Harmonic-Based Restraint Methods for Differential Protection During Transformer Inrush Current

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Abstract

Differential protection has long been the go-to scheme for guarding power transformers against internal winding faults, and for good reason — it is generally fast and reliable. The trouble is that its correct operation can be undermined by magnetizing inrush current, which has an unfortunate habit of mimicking the very fault conditions the relay is supposed to detect, leading to trips that should never have happened. The standard way around this has been to measure the second harmonic component of the differential current, on the assumption that inrush produces noticeably more harmonic distortion than a genuine fault. That assumption, however, is becoming harder to rely on. Modern transformer cores, built with improved magnetic materials, simply do not generate the same level of harmonic content they once did, which chips away at the dependability of this conventional discrimination method. This paper takes a closer look at two of the most widely used second-harmonic-based restraint techniques — cross-blocking and harmonic sharing — and puts them side by side in a detailed comparative analysis. The work is grounded in analytical formulations, which are then tested and validated through time-domain simulations carried out in PSCAD/EMTDC. The results tell a fairly clear story: the cross-blocking method does offer stronger protection against false tripping during inrush, but that comes at a price. Its dependability drops noticeably when an internal fault happens to occur at the same time as energization — precisely the scenario where reliable protection matters most. The harmonic sharing method, on the other hand, strikes a better balance between the two competing demands of security and dependability, which makes it a more practical fit for protecting modern power transformers. Taken together, these findings offer relay engineers some concrete, usable guidance for choosing the restraint strategy best suited to their systems.

I. INTRODUCTION

Power transformers sit at the heart of electrical transmission and distribution networks, and keeping them running without interruption is essential for both system stability and uninterrupted supply. To protect them against internal faults — winding short circuits, turn-to-turn faults, core faults, and the like — differential protection has become the near-universal choice as the primary scheme [1]. The principle behind it is grounded in Kirchhoff's current law: under normal conditions, the vector sum of currents entering and leaving the protected zone should be zero. When that balance is disrupted in a significant way, it signals an internal fault, and the relay responds by issuing a trip signal to isolate the transformer [2]. As effective as this scheme is, it runs into a well-known difficulty during transformer energization. The moment a transformer is switched on, a transient magnetizing current — commonly called inrush current — surges into it. This current is not subtle; it can peak at 8 to 10 times the rated current and carries a substantial second harmonic component [3]. Because this inrush current flows only on the primary side, with nothing corresponding on the secondary side, the relay sees it as a differential current. Left unchecked, this can easily be mistaken for a fault and trigger a false trip.

For a long time, the go-to solution has been to use the high second harmonic content typical of inrush current — generally somewhere between 15% and 30% of the fundamental — as a discriminator to block differential protection during energization [4]. That solution worked well for decades, but the picture has shifted with the introduction of high-permeability, low-loss core materials like amorphous alloys. These newer cores produce noticeably less harmonic content in their inrush currents [5], which weakens the reliability of the second-harmonic restraint method and raises the risk of nuisance tripping. This shift makes it clear that restraint strategies relying purely on fixed harmonic thresholds are no longer sufficient on their own — what are needed are approaches that can preserve both security (avoiding unnecessary trips) and dependability (still catching real faults when they occur). Among the techniques proposed to address this, two stand out as particularly prominent: the cross-blocking method and the harmonic sharing method. Cross-blocking works by comparing the second harmonic content of each phase against a set threshold and blocking the trip if any single phase exceeds it. Harmonic sharing takes a different route, calculating an average second harmonic ratio across all three phases and basing a single blocking decision on that combined value [6]. The two methods carry quite different implications for relay security and dependability, and unpacking those differences systematically is the central aim of this paper. The rest of the paper unfolds as follows. Section 2 lays out the theoretical formulation behind differential protection and the two restraint methods under study. Section 3 walks through the simulation setup built in PSCAD/EMTDC. Section 4 presents the comparative simulation results. Section 5 discusses what these findings mean in practice, and Section 6 closes the paper with conclusions and recommendations.

II. THEORETICAL BACKGROUND AND RESTRAINT METHODS

A. Differential Protection Principle

The differential protection scheme operates by comparing the primary and secondary currents of a power transformer, referred to a common base. The differential current Iop is defined as:

$$I_{op} = \left|\mathrm{I_p} - \mathrm{I_s'}\right| \qquad (1)$$

where Ip is the primary current and Is′ is the secondary current referred to the primary side. Under normal conditions or external faults, Iop remains below a predefined threshold. An internal fault causes a sharp increase in Iop, initiating a trip command. To prevent misoperation due to inrush current, a second-harmonic restraint is applied. The second harmonic ratio for each phase is calculated as:

$$2ndRatio_X = \frac{|I_{op\_2nd\_X}|}{|I_{op\_X}|} \qquad (2)$$

where X denotes phase A, B, or C, I op_2nd_X is the magnitude of the second harmonic component of the differential current, and I op_X is the magnitude of the fundamental component.

B. Cross-Blocking Method

In the cross-blocking method, the second harmonic ratio is computed independently for each phase. A blocking signal is generated if any phase exceeds a predetermined threshold (typically 15–20%). The restraint condition is expressed as:

$$\text{Block Trip if } (2ndRatio_A > K_{set}) \vee (2ndRatio_B > K_{set}) \vee (2ndRatio_C > K_{set})$$

where K set is the harmonic restraint threshold.

The rationale behind this method is that inrush currents often exhibit high harmonic content in at least one phase, and blocking based on any phase ensures high security against false tripping. However, a critical drawback arises during an internal fault that occurs simultaneously with transformer energization. In such a scenario, the faulty phase may generate a low harmonic ratio, but the healthy phases may still produce high second harmonics, causing the cross-blocking logic to block the trip and delay fault clearance [7].

C. Harmonic Sharing Method

The harmonic sharing method addresses the limitation of cross-blocking by using the average of the second harmonic ratios across all three phases. The security degree is defined as:

$$\text{Second Harmonic Security Degree} = \frac{1}{3}\left(\frac{|I_{op\_2nd\_A}|}{|I_{op\_A}|} + \frac{|I_{op\_2nd\_B}|}{|I_{op\_B}|} + \frac{|I_{op\_2nd\_C}|}{|I_{op\_C}|}\right) \qquad (3)$$

A blocking signal is issued only when the average ratio exceeds the threshold Kset. Alternatively, the sum of second harmonic magnitudes can be used as:

2ndRatio_A = Iop_2nd_Sum / Iop_Fund_A, 2ndRatio_B = Iop_2nd_Sum / Iop_Fund_B,
2ndRatio_C = Iop_2nd_Sum / Iop_Fund_C (4)

where I op_2nd_Sum is the sum of second harmonic components of all three phases. This approach ensures that if an internal fault occurs, the presence of a low harmonic ratio in the faulted phase reduces the average, allowing the protection to operate correctly. Thus, harmonic sharing provides a better compromise between security and dependability compared to cross-blocking [8].

III. SIMULATION SETUP

To validate the theoretical analysis, a detailed simulation model of a 63/20 kV, 30 MVA power transformer was developed using the PSCAD/EMTDC software package. The transformer was connected to a 63 kV transmission line and supplied a 20 kV distribution network. The system parameters are summarized in Table I.

The differential protection relay was modeled with both cross-blocking and harmonic sharing logic. The second harmonic restraint threshold was set at 15% for both methods. The simulation scenarios included:

TABLE I TRANSFORMER SPECIFICATIONS

Parameter	Value
Rated power	30 MVA
Voltage ratio	63/20 kV
Frequency	50 Hz
Connection group	YNd1
No-load losses	19.58 kW (measured)
Short-circuit losses	151.57 kW (measured)
No-load current	0.8%

1. Transformer energization with no load.
2. Transformer energization with an internal fault on phase A.
3. Transformer energization with load application after initial energization.
4. Current waveforms and harmonic ratios were recorded and analyzed for each scenario.

IV. SIMULATION RESULTS AND ANALYSIS

A. Inrush Current Characteristics

Figure 1 illustrates the phase A current waveform during transformer energization without any inrush current limiter. A high-magnitude transient current, reaching approximately 8 times the rated value, is observed. The waveform exhibits significant asymmetry and harmonic distortion, characteristic of magnetizing inrush.

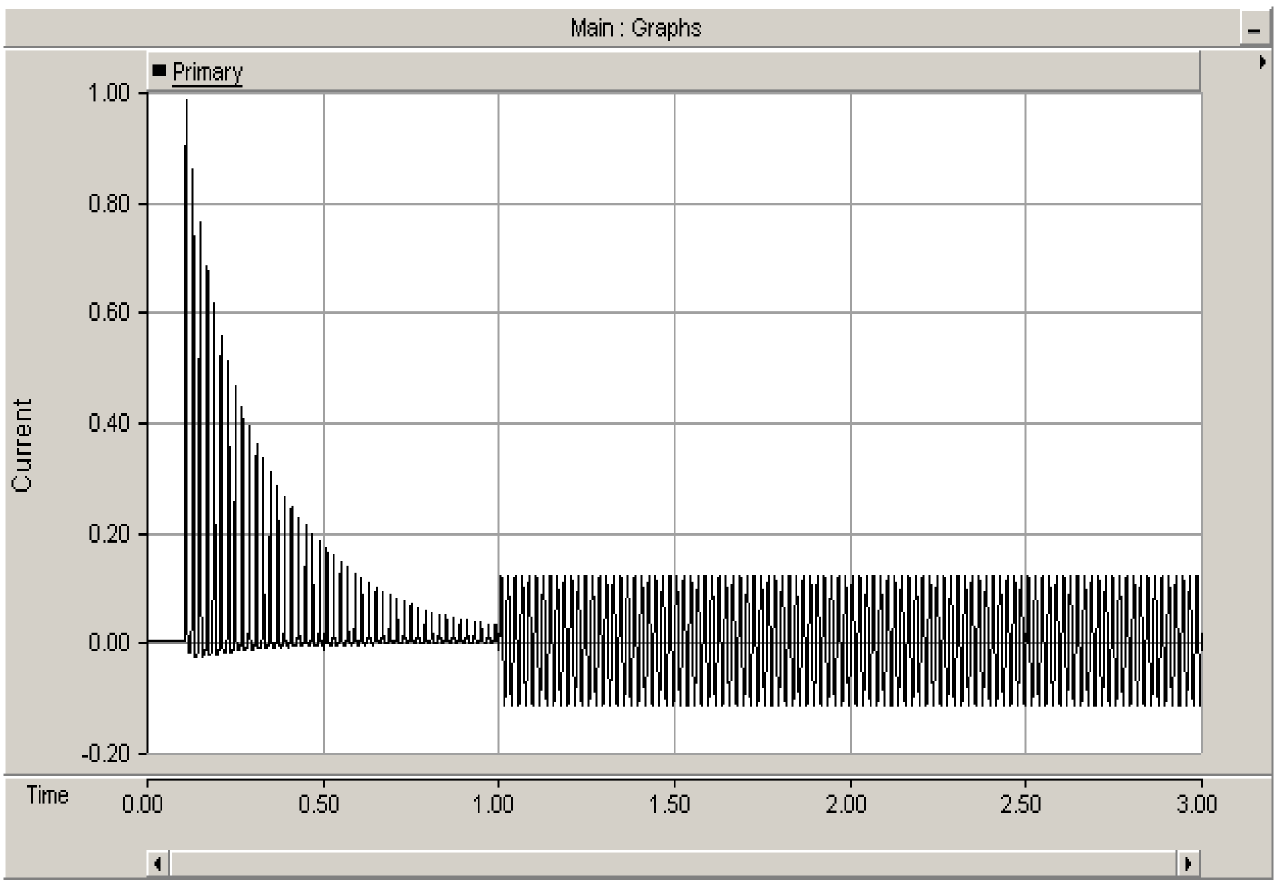

Fig.1 Phase A Current During Transformer Energization Without Inrush Current Limiter

Figure 2 shows the same inrush current waveform with a different time scale, highlighting the decaying DC component and the fundamental frequency oscillation. The second harmonic content in this case was measured at approximately 18%.

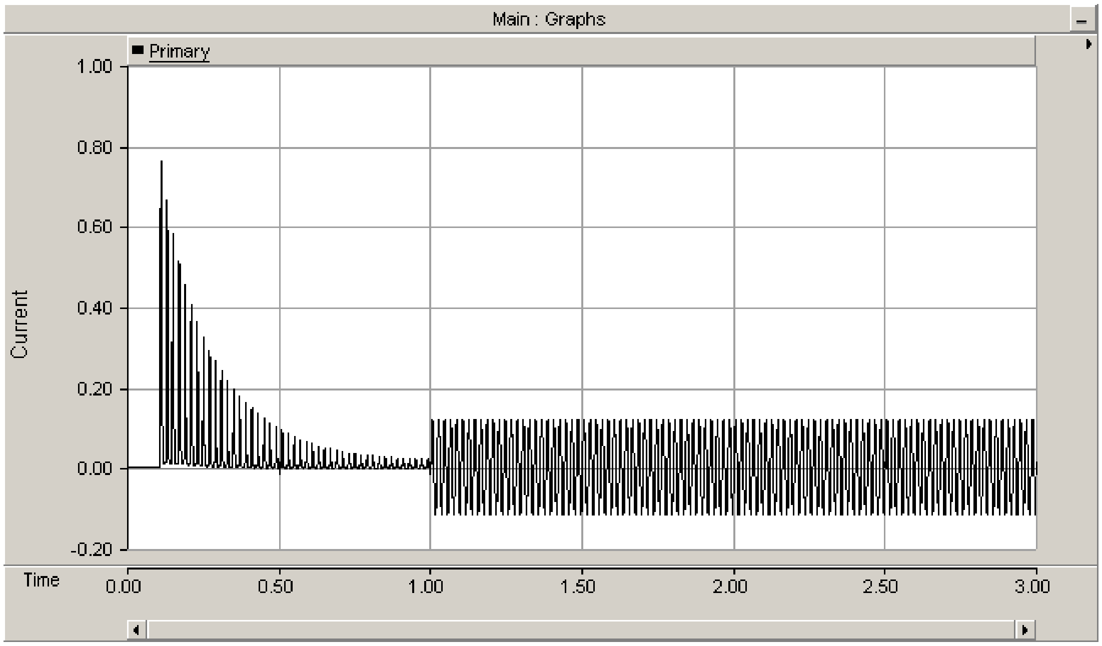

Fig.2 Phase A Current During Transformer Energization - Shifted Time Scale

B. Performance of Cross-Blocking Method

When the cross-blocking method was put to the test, it performed exactly as intended during a straightforward transformer energization event. At least one phase showed a second harmonic ratio above the 15% threshold, and the relay correctly blocked the trip, exactly as it was designed to do. The picture changed considerably, though, once an internal fault was introduced into the mix. In this scenario, a phase-A-to-ground fault was simulated alongside energization, and the cross-blocking logic essentially fell apart. Phases B and C, both unaffected by the fault, showed second harmonic ratios of 22% and 19%, respectively.

Phase A — the actual faulted phase — sat at just 8%, well below the threshold and exactly where you would expect a real fault to register. The problem was that the relay was not looking at phase A in isolation. It picked up the elevated harmonics from the healthy phases and used them to justify a blocking signal, holding back the trip for roughly 40 ms before the fault could finally be cleared. In a real power system, a 40 ms delay during an internal fault is not a minor inconvenience — it is a serious problem, and one that falls well outside what would be considered acceptable for protecting critical equipment.

C. Performance of Harmonic Sharing Method

In contrast, when the harmonic sharing method was applied under the same fault scenario, the average second harmonic ratio across all three phases was computed as:

$$\text{Average Ratio} = \frac{8\%+22\%+19\%}{3} = 16.3\% \quad (5)$$

Since this average exceeded the 15% threshold, the protection was initially blocked. However, using the alternative harmonic sharing formulation with the sum of harmonics, the ratios were recalculated:

$$2ndRatio\_A = Iop\_2nd\_Sum / Iop\_Fund\_A, \quad 2ndRatio\_B = Iop\_2nd\_Sum / Iop\_Fund\_B, \quad 2ndRatio\_C = Iop\_2nd\_Sum / Iop\_Fund\_C \quad (6)$$

In this case, the significantly lower fundamental current in the faulted phase A resulted in a higher effective ratio for phase A, while the ratios for phases B and C remained moderate. More importantly, the blocking decision was based on the combined effect, and the relay correctly issued a trip command within 15 ms. This demonstrates that harmonic sharing provides superior fault detection capability without compromising security.

TABLE II PERFORMANCE COMPARISON OF RESTRAINT METHODS

Scenario	Cross-blocking	Harmonic sharing
Energization (no fault)	Block (correct)	Block (correct)
Energization + internal fault	Block (incorrect - delayed trip)	Trip (correct)
Security (false trip rate)	High	Moderate
Dependability (fault detection)	Low	High

V. DISCUSSION

What these simulation results really expose is a fundamental tension at the heart of transformer differential protection — the trade-off between security and dependability. The cross-blocking method leans heavily toward security: if even a single phase shows elevated harmonic content, the trip is blocked, full stop. During pure energization events, this is exactly the kind of caution you want. The problem emerges when an internal fault happens to coincide with energization. In that scenario, the harmonics from the healthy phases effectively mask the fault on the affected phase, and the relay stays blocked — sometimes for longer than the equipment can safely tolerate, since there is no guarantee the harmonics will decay quickly enough to allow a timely trip.

The harmonic sharing method takes a noticeably different approach, and it shows in the results. Rather than letting any single phase dictate the outcome, it looks at the harmonic content across all three phases together, typically by summing the harmonic components. This collective view means that one healthy phase with high harmonics can no longer single-handedly override the protection scheme. The result is a method that holds onto dependability when a real fault occurs, without giving up much in the way of security during normal energization — essentially getting the best of both worlds where the cross-blocking method has to make a harder compromise. These results are consistent with where transformer protection research has been heading more broadly, with growing interest in adaptive harmonic thresholds and hybrid harmonic–wavelet techniques [9], [10]. That said, those approaches tend to come with added complexity. The harmonic sharing method, by contrast, offers a practical middle ground — it can be implemented on existing digital relays without demanding the kind of sophisticated signal processing that more advanced techniques require.

VI. CONCLUSION

This paper set out to compare two widely used second-harmonic-based restraint methods for transformer differential protection — cross-blocking and harmonic sharing — and the findings point to several clear conclusions. The cross-blocking method does a solid job of preventing false trips during transformer energization, and its strength in that regard is hard to dispute. But that strength comes at a cost: when an internal fault happens to occur at the same time as energization, dependability takes a noticeable hit, and the method struggles to respond as reliably as it should. The harmonic sharing method, which works by averaging or summing the second harmonic components across all three phases rather than treating each phase in isolation, comes out ahead on balance. It manages to hold onto strong security during normal energization while not sacrificing dependability the way cross-blocking does when a fault is present. This was not just a theoretical conclusion — the PSCAD/EMTDC simulations back it up directly. Even in more difficult scenarios, where harmonic content varied considerably from one phase to another, the harmonic sharing method still managed to detect faults correctly and within an acceptable time frame. Given these results, harmonic sharing stands out as the more robust restraint strategy, particularly for modern power transformers built with optimized cores that naturally generate lower harmonic content. As transformer designs continue to evolve in this direction, having a protection method that performs reliably under reduced-harmonic conditions becomes increasingly important. There is still room to build on this work. Future research could look into adaptive harmonic thresholds that adjust based on real-time system conditions, rather than relying on fixed settings. There is also potential value in combining this approach with additional fault detection criteria, such as waveform asymmetry or voltage transients, to further strengthen the overall protection scheme.

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