



Effective Detection of Incipient Faults in Dry-Type Transformers using only Negative Sequence: Practical Realization and Field Experience

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Abstract — Dry-type transformers are exposed to early failures in particular during testing, commissioning, and early operation, as observed in several railway projects. These failures are strongly associated with frequent switching operations involving vacuum circuit breakers and short cable lengths, which subject transformer insulation to repetitive high-frequency transients and cumulative stress. Over time, this stress leads to inter-turn insulation degradation and development of internal faults. Due to their small ratings, such transformers are often not equipped with differential protection, allowing faults to remain undetected until catastrophic failure. This paper presents a practical field-proven approach for early detection of incipient internal faults using negative sequence current (NSC) protection (ANSI 46) available in standard feeder protection relays with appropriate pickup and time-delay settings. The study is based on the analysis of more than 20 transformer failure events in railway projects, supported by relay records. Field-recorded disturbance data show that turn-to-turn faults are consistently characterized by sustained NSC lasting several minutes prior to failure, while normal operating conditions including load unbalance, traction operation, and magnetizing inrush produce significantly lower or shorter NSC levels. The proposed approach enables early fault detection and mitigation with minimal cost and complexity, making it particularly suitable for widely deployed MV/LV dry-type transformers in switching-intensive environments.

Keywords: *Dry-type transformers, Railway substations, Negative sequence protection, Switching transients, Incipient faults, Vacuum circuit breakers*

1. Introduction

Dry-type transformers (DTTs) are used in a wide range of applications (civil, industrial, transportation), with benefits of cost reduction, fire prevention, reduced maintenance, and suitability for indoor and underground installations. Focusing on railway power supply systems, DTTs are used for auxiliaries and for traction. In railway substations, auxiliary transformers typically supply station lighting, ventilation, signaling, communication, and control loads with ratings usually below 5 MVA. Traction supply transformers have in



general higher rating for both DC and AC applications, where rated power is in the tens of MVA.

Despite compliance with applicable design standards and successful factory and site acceptance tests, a significant number of premature failures of DTTs have occurred in several railway projects worldwide, although not disclosed to the public. Field experience indicates that these failures occur predominantly during testing, commissioning and early operation, rather than during long-term steady-state operation.

Commissioning activities are indeed characterized by frequent energisation and de-energisation of transformers due to system configuration changes, protection setting adjustments, temporary supplies, and construction-related loads. Unlike utility substations, where transformer switching is relatively infrequent, railway projects often subject transformers to a large number of switching operations within a short time frame. For traction transformers, insulation coordination and dielectric performance are governed by EN 50329 [1], which defines insulation levels specific to railway traction supply systems, while auxiliary DTTs are typically designed according to IEC 60076-11 [2]. The IEC 60076-11 states that DTTs are designed for a limited number of switching operations (reported as 24 operations per year in its sec. 4.2(i)). Exceeding this number requires consultation with the transformer manufacturer and, where necessary, the application of additional mitigation measures. In practice this design assumption is routinely violated during commissioning and trial phases.

A further distinguishing feature of railway substations is their compact indoor layout. Medium-voltage (MV) switchgear and DTTs are often installed within the same electrical room, resulting in very short cable lengths, typically 10–40 m between vacuum circuit breakers (VCBs) and transformer terminals. Similarly, short cable length occurs in many civil applications, with DTT located in a small technical room of the basement, as pointed out in [3] or even in the arc furnace case described in [4]. VCBs are well suited for frequent operation and their fast dielectric recovery characteristics make them prone to current chopping, prestrike, and restriking phenomena [4]–[6], and consequential overvoltages. When combined with short cable connections and inductive transformer loads, these characteristics give rise to high-frequency switching transients.

Extensive experimental and analytical work examined VCB switching of inductive loads, such as DTTs. Greenwood [5] demonstrated that rapid dielectric recovery of vacuum interrupters promotes current cutting and reignition, producing steep transient recovery voltages and voltage increase in lightly damped circuits. Shipp et al. [4] showed that VCB switching of lightly loaded transformers generates oscillatory overvoltages whose dominant frequency strongly depends on system surge impedance and cable length, with short connections producing higher-frequency, poorly damped transients.



McDermitt et al. [6] reported multiple MV transformer and instrument transformer failures attributed to such switching transients, emphasizing that internal winding stresses may exceed insulation limits even when terminal voltages remain within rated withstand levels. Rao and Gajjar [7] further demonstrated with statistical significance, through detailed electromagnetic transient modelling, that current chopping and reignition processes can lead to severe overvoltages under unfavourable network conditions. More recent studies, incorporating frequency-dependent cable and transformer models [8], [9], confirmed that compact installations with short connections promote transient frequencies from tens of kHz to some MHz, increasing the likelihood of exciting transformer internal resonance modes.

Furthermore, IEEE Std. C57.142 [10] has shown that the interaction of VCB, short cable length and DTT can produce oscillatory overvoltages with dominant frequencies ranging from tens of kHz to the MHz range, occurring for cable length reducing from some hundreds m to a tenth of m. Short cable length is particularly relevant in compact substations, such as those for metro and railway applications. When these frequencies approach the natural resonances of transformer windings, significant internal voltage magnification may occur [10]. Importantly, such internal overvoltages may develop even when terminal voltages remain within the transformer basic insulation level (BIL), leading to progressive inter-turn insulation degradation, rather than immediate failure.

To address switching-induced overvoltages, several mitigation measures are commonly applied, including increased insulation levels, surge arresters, distributed transient voltage suppressors within transformer windings, and RC snubber circuits [3], [4], [11]. When properly designed and implemented, these measures can significantly reduce the severity of switching transients. However, they are associated with increased equipment cost, additional engineering effort, and coordination with transformer manufacturers. In many projects, particularly during early stages, these measures are either only partially implemented or omitted, leaving transformers exposed to repetitive high-frequency voltage stress.

As a result, even in installations where mitigation measures are present, insulation degradation may develop progressively over time. This paper, therefore, focuses not on replacing established mitigation techniques, but on addressing the practical need for early detection of incipient internal faults in DTTs. By identifying incipient fault signatures (IFSs) that appear prior to the catastrophic failure, effective protection can be achieved even in installations where extensive mitigation is not feasible.

Diagnostic and early detection of IFSs for DTTs is associated to the appearance of unbalance components, namely negative sequence component (NSC), with a wide range of proposed algorithms. Use of advanced techniques, such as pattern recognition, machine learning and advanced transforms [12]–[15] is too expensive and not available in commercial products. Similarly, differential protections [14], [16], although effective, are also suitable for more



expensive applications, with higher voltage and power ratings. Differential protection can be anyway challenged by transformer magnetization inrush and other major transients [16], as for simpler NSC protection.

The directional methods discussed in [17], [18] make also use of the NSC at the primary and secondary sides, requiring additional current transformers (CTs) at the secondary side, as it occurs for HV/MV transformers. Since the LV switchgear is often installed at a distance from the MV switchgear for MV/LV DTTs, long CT secondary cable runs increase the burden and make CT sizing and cost a non-negligible issue. Secondary side CTs, in addition, cannot be connected directly to all protection relays, that need additional input hardware (e.g. expansion cards). The ratio [17] or difference [18] of primary and secondary side NSC can show if faults are internal (affecting only the primary side quantities) or external. It is noted, however, that the ratio function is not so common in commercial relays. In both studies the algorithms are tested by simulation and robustness with respect to various types of faults and imbalance, however, inrush was not demonstrated. Testing is more extended in [19], where a real and-time digital simulator, and not a physical transformer, is considered: the specific algorithm is custom made on a processor board and exploits voltages rather than currents (requiring specifically voltage transformers on both sides of the transformer).

The solution discussed and demonstrated here, instead, was conceived for the many low-cost DTTs of the MV/LV type in scenarios with a minimum number of basic protection relays, as it is exemplified in Section V by choosing devices from three different major manufacturers. It consists in a simpler NSC protection with enable/disable and delay signals available in all commercial protection relays.

2. Objectives

Detection of turn-to-turn insulation failures in transformers is important to prevent catastrophic failures of wider extent, avoiding extensive damages, fire and hazards to bystanders. DTTs are particularly exposed to this type of failures as explained in the Introduction and a wide range of algorithms has been proposed in the literature. Many of these algorithms require custom hardware or expensive protection relays and are suitable for high-end applications, e.g. using HV/MV transformers, where a large number of sensing elements and complex protection relays are justified.

There is, however, a large group of DTTs of small size (approximately less than 5 MVA) highly exposed to such failures due to the large number of manoeuvres (e.g. in railway applications), higher than what assumed in the relevant standards.

The objective of this work is to demonstrate a cheap protection method based on negative sequence monitoring that uses existing protection relays adding some simple settings. Such



additional settings are aimed at preventing unwanted tripping in case of some events that pose a challenge in general to all protection methods based on differential and negative sequence quantities, namely load imbalance and transformer magnetizing inrush. They are addressed by discussing the criteria and the details of the relay settings in Section 4.

All protection methods are challenged by insulation failures involving only one turn, especially between parallel conductors or windings. Our standpoint is that such failure at the very beginning may go undetected, but, when it propagates to only a few more turns, it can be detected preventing major general failures. There is no advantage in striving to detect it at the very beginning, because in any case the transformer must be put out of service and sent for repair, both for just a single damaged turn or a few turns. The objective is to prevent catastrophic failures and provide a monitoring capability that can be implemented easily during commissioning, even if not foreseen at the design stage.

Several recordings of incipient failures are shown and analysed in Section 4, showing then the sequence of operation of the various relay monitoring conditions in Fig. 6.

3. Methods

3.1. Overview of rapid transients, failure mechanisms and mitigations

3.1.1. Switching transients and transient recovery voltage

Owing to the extremely fast dielectric strength recovery of VCBs, the transient recovery voltage (TRV) can rise steeply immediately after current interruption. If the instantaneous TRV exceeds the withstand capability of the contact gap, reignitions or restrikes may occur, injecting additional energy into the circuit and generating oscillatory switching transients.

The TRV waveform is not solely a function of the breaker, but is determined by the interaction of source impedance, connecting cable, and transformer winding impedance. In railway substations, where cable sections are short, the resulting system exhibits low damping and high surge impedance. IEEE C57.142 [10] identifies such configurations as particularly susceptible to high-frequency oscillatory overvoltages during switching operations.

For no-load switching, current interruption may occur at low magnetizing current levels, leading anyway to current chopping of a few Amps. The associated transient overvoltage is not negligible and can be estimated by equating magnetic and electric energy as [7], [9].

$$\frac{1}{2}L_m I^2 = \frac{1}{2}C_g V^2 \quad (1)$$

where L_m is the transformer magnetizing inductance, C_g is the equivalent capacitance seen at the transformer terminals (including cable and winding-to-ground capacitance), I is the chopped current, and V is the resulting transient overvoltage.



The dominant oscillation frequency of switching transients and the corresponding surge impedance are governed by the total inductance and capacitance of the VCB+cable+transformer system and can be approximated as [9]:

$$f' = \frac{1}{2\pi\sqrt{L_m C_g}} \quad Z' = \sqrt{\frac{L_m}{C_g}} \quad (2)$$

Short cable connections reduce the effective capacitance C_g , thereby increasing both the surge impedance and transient oscillation frequency.

Importantly, whereas external surge arresters are effective in limiting terminal voltage magnitude, they do not significantly alter the transient frequency content and therefore cannot prevent internal resonance phenomena within transformer windings. Under resonance conditions, localized inter-turn voltages within the winding can significantly exceed the measured terminal voltage, even when the latter remains below the transformer BIL. Repeated excitation near resonance does not generally result in immediate breakdown; instead, it produces cumulative insulation stress manifested through partial discharges, localized heating, and progressive insulation degradation. Over time, this process may evolve into turn-to-turn faults (TTFs), most commonly initiating near the end sections of the winding where electrical stress is highest.

3.1.2. Mitigation measures and practical limitations

Various mitigation techniques were proposed and investigated:

- DTTs with increased BIL in combination with external surge arresters installed at transformer terminals, that does not suppress, however, high-frequency oscillations;
- surge arresters may be embedded across selected sections of the transformer winding, clamping local inter-turn voltages and mitigating voltage amplification at resonance; this solution does not provide anyway comprehensive protection, especially if arresters are provided only at accessible taps, and transformer complexity and cost are increased with a custom realization;
- RC snubbers connected at transformer terminals are probably the most popular and effective mitigation, that limits transient voltage magnitude and reduces surge impedance; cost and space remain a concern, especially if devised later when the design phase is concluded;
- controlled switching provides another mitigation option by synchronizing breaker operation with favourable points on voltage or current waveforms, minimizing current chopping and preventing restrikes; clearly, this approach requires precise timing control, additional sensors, and specialized breaker control hardware and software.



Although the mitigation techniques discussed above can significantly reduce switching-induced transformer stress, each involves trade-offs in terms of cost, space requirements, system complexity, or limited frequency effectiveness. As a result, comprehensive mitigation is not always implemented in practice, particularly during commissioning and early operation. This underscores the importance of complementary protection and monitoring approaches capable of detecting incipient internal transformer failures before a major catastrophic failure occurs.

3.2. Turn-to-turn faults and fault current

The purpose of this section is to clarify the problem and the relevant quantities with reference to published models and resulting currents for various amounts of shorted turns and their position. A MV transformer is considered with delta-star connection, where a TTF occurs shorting an arbitrary number of turns of one winding; as pointed out in [20], faults may occur also between windings. An additional fictitious winding simulating the fault is used in [20], with worst-case assumptions for the fault resistance (resulting in a minimal value in the middle of the winding and maximal at its ends), since the purpose is to estimate the smallest current associated with the fault.

The conclusion is that the fault impedance (prevalently resistive) in per-unit (p.u.) is almost equal to the internal short-circuit reactance of the transformer in the worst case of one turn shorted in only one of the parallel conductors forming a winding (all other cases lead to lower impedance values and thus higher fault current). For shorts between turns of different parallel conductors of the same winding or between different windings the fault impedance can increase up to values larger by two orders of magnitude leading to NSC amplitude of about 1 %. The considered scenario of MV/LV transformers prevalently limited to 5 MVA excludes the use of parallel conductors, being the winding current compatible with a single conductor. This excludes the extreme case leading to negligible NSC, allowing the detectability in all practical cases, as it will be demonstrated in Section 4.

Analysis of multiple transformer failures shows that internal winding failures do not initiate as solid short circuits, but develop progressively from a localized turn-to-turn insulation degradation to a major failure followed by a fault condition. The earliest observable manifestation is low-energy internal arcing, confined within a single phase winding, typically occurring in no-load or lightly loaded conditions. The proposed method addresses this scenario, preventing the major catastrophic transformer fault.

Fig. 1 illustrates such an event captured at 23:13:37.44, where the transformer was operating at no load. I_A remains negligible, while I_B and I_C have equal-magnitude flowing in opposite directions, indicating an internal circulating current path, rather than externally supplied load current. Over the first few cycles, the magnitude of these currents increases gradually, while the healthy phase remains essentially inactive, confirming that the fault is internal and does



not involve ground and for this reason is not detected by ground current protection, however sensitive.

The electrical asymmetry introduced by this condition produces a distinct electronic signature in the form of sustained NSC. NSC quantities are widely used in protection systems as indicators of phase imbalance and asymmetrical faults [21, 22]. The phase and sequence currents are related through the known symmetrical component transformation [23].

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}, \quad a = e^{j120^\circ} \quad (3)$$

For the observed condition where $I_A \approx 0$ and $I_B \approx -I_C$, both positive- and negative-sequence components exist with comparable magnitudes, while the zero-sequence component remains negligible. This explains why earth fault protection cannot detect such failures during their early stage.

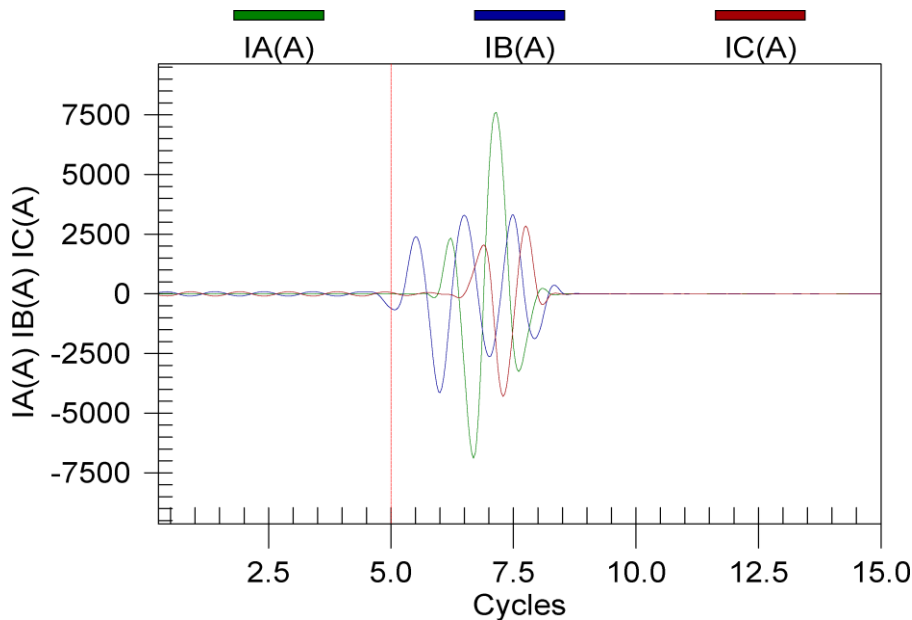


Fig. 1. Recorded phase currents by SEL 751A during an incipient turn-to-turn fault in the transformer (Tx1).

4. Results

4.1. Field evidence of internal faults and NSC

This section presents field-recorded disturbance data obtained from numerical feeder protection relays applied to auxiliary and traction transformers in railway substations. The objective is to identify and characterize the signature associated with incipient internal

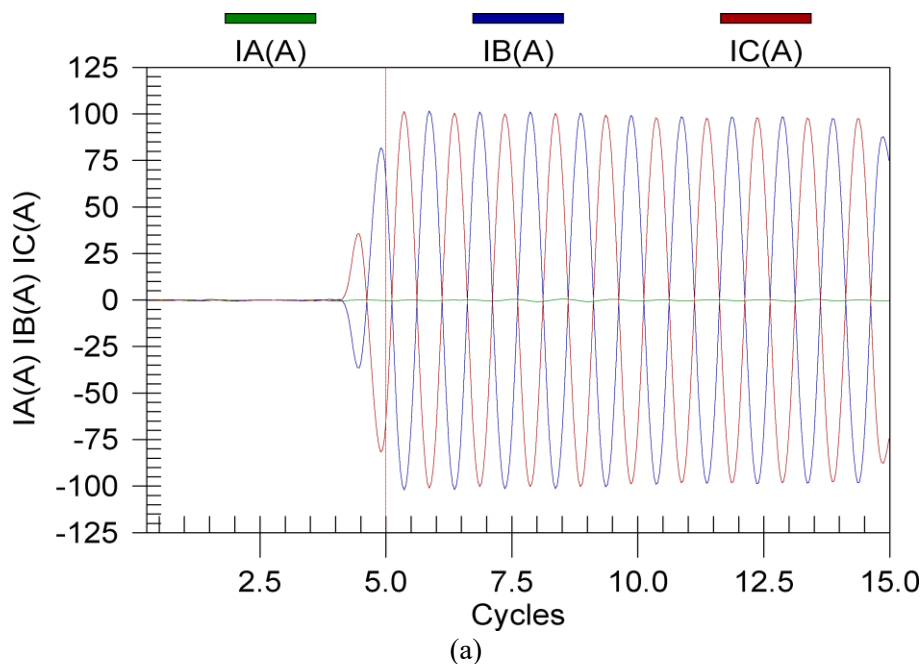


winding faults and to distinguish it from NSCs arising under normal operating conditions. In all current waveform figures discussed in this section, phase currents are plotted using the following convention: phase A current I_A is shown in green, phase B current I_B in blue, and phase C current I_C in red. Unless otherwise noted the same notation identifies the phasors at the fundamental frequency. The vertical axis represents current magnitude in amperes, while the horizontal axis represents time expressed in electrical cycles (for a 50-Hz system one cycle corresponds to 20 ms). Associated phasor and sequence components plots are derived from the same records.

4.1.1. Phasor and sequence evidence prior to catastrophic failure

Fig. 2 provides both the time-domain waveform and sequence element representation to cycle 7.5 of an event. The phasor plot shows $I_B \approx 102$ A at an angle of 9.2° , and $I_C \approx 101$ A at 189.6° , confirming near-perfect 180° opposition. The sequence plot shows that NSC magnitude is comparable to the positive sequence current, while the zero-sequence component remains minimal.

Important to note, this snapshot was recorded few minutes before the transformer underwent catastrophic failure. Relay records indicate that NSC was already present and sustained well before the high-energy event, confirming that internal arcing begins as a low-energy process and produces a measurable signature long before destructive failure occurs.



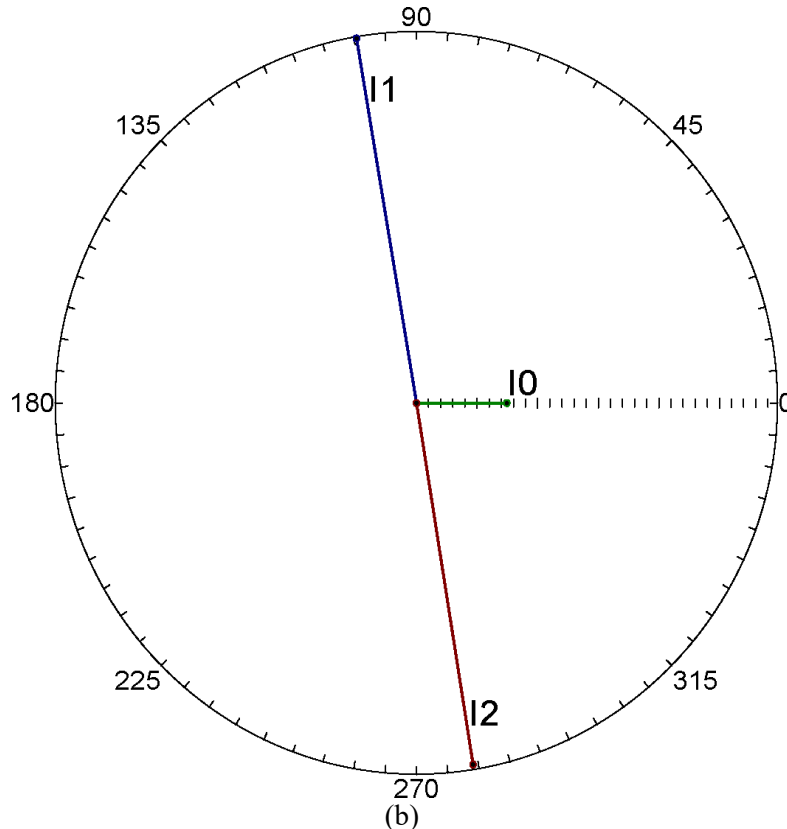


Fig. 2. Negative sequence recorded by SEL 751A before transformer failure: (a) phase current waveforms; (b) sequence phasor diagram at cycle 7.5.

4.1.2. Validation through repeated failure records

The same progression is observed in additional records, as shown in Fig. 3. In each case, an initial interval of several cycles is observed, where current flows predominantly in two phases with the third phase nearly unloaded, indicating a localized internal fault condition. This is followed then by a sudden increase in current magnitude across all three phases, corresponding to a transition from localized internal arcing to a severe internal fault with extensive winding damage.

Once this transition occurs, phase selectivity is lost and high current flows in all phases due to intense internal arcing. Field observations confirm that this stage is typically accompanied by transformer burning, smoke generation, and operation of fire detection and FM-200 gas suppression systems. The recurrence of the same electronic signature across multiple independent failure events provides strong validation that sustained NSC reliably precedes catastrophic transformer failure in both auxiliary and traction transformers.

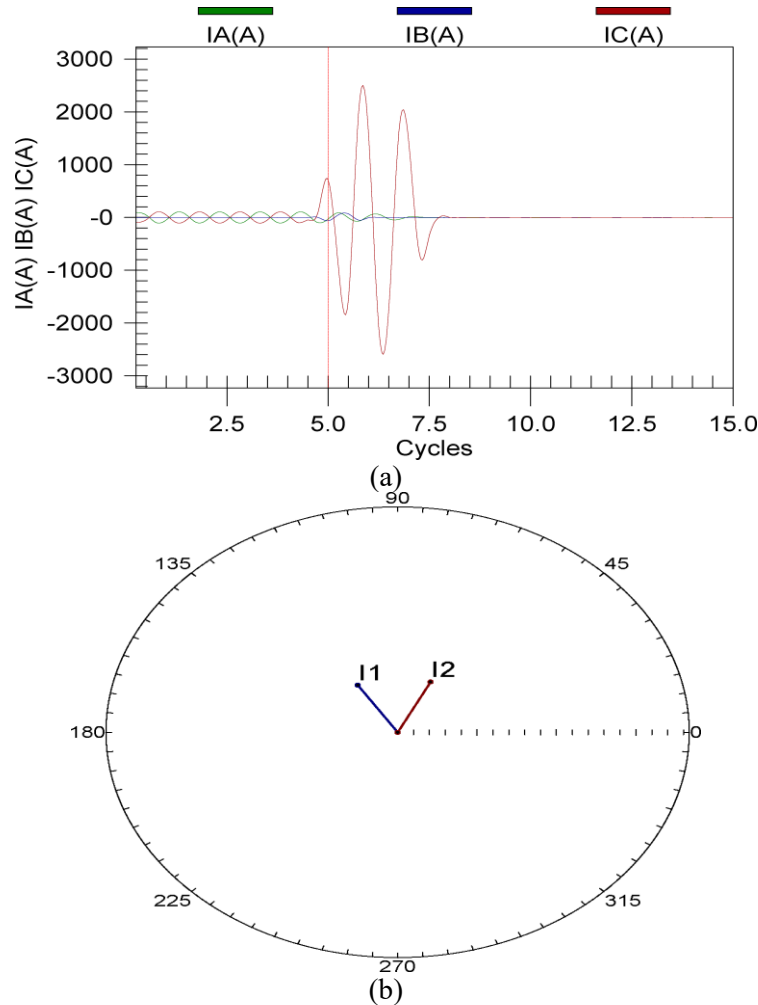


Fig. 3. Recorded phase currents by SEL 751A during an incipient turn-to-turn fault in the transformer (Tx2): (a) phase current waveforms; (b) sequence phasor diagram at cycle 1.00.

4.1.3. Negative sequence under normal traction loading

NSC is also produced under normal operating conditions and must be clearly distinguished from the fault-related electronic signature described above. Fig. 4 shows a representative traction loading event, where the transformer supplies a predominantly balanced three-phase load with continuously varying magnitude corresponding to train acceleration and braking. The phase currents vary smoothly and reach peak values of approximately 60-65 Apk. For the considered 2.23 MVA, 22 kV/0.59 kV transformer, the rated primary current $I_{p,r}$ is approximately 58.52 A (rms), indicating operation close to rated load.

The associated sequence and phasor plots show that the maximum NSC during this interval is approximately 3.8 A, corresponding to about 6.5 % of the rated current. This small negative sequence component arises from minor phase imbalance inherent in practical traction operation and remains low, stable, and directly correlated with load variation. Field



experience indicates that under normal auxiliary and traction loading, NSC typically remains below 10 % of the rated current and only rarely approaches 15-20 % under atypical single-load unbalanced conditions. This behaviour is fundamentally different from internal fault cases, where NSC becomes comparable to the positive sequence component and persists independently of load variation.

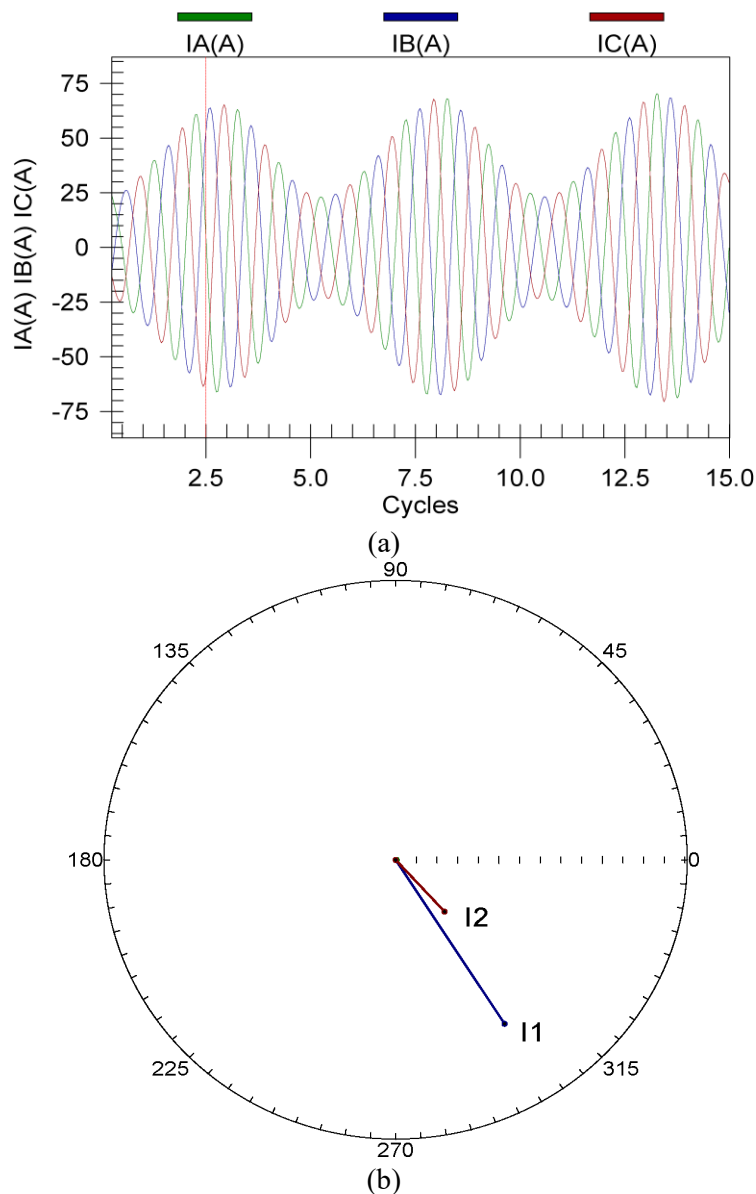


Fig. 4. Recorded traction loading current behaviour and corresponding NSC by SEL 751A: (a) phase current waveforms; (b) sequence phasor diagram at cycle 4.00.

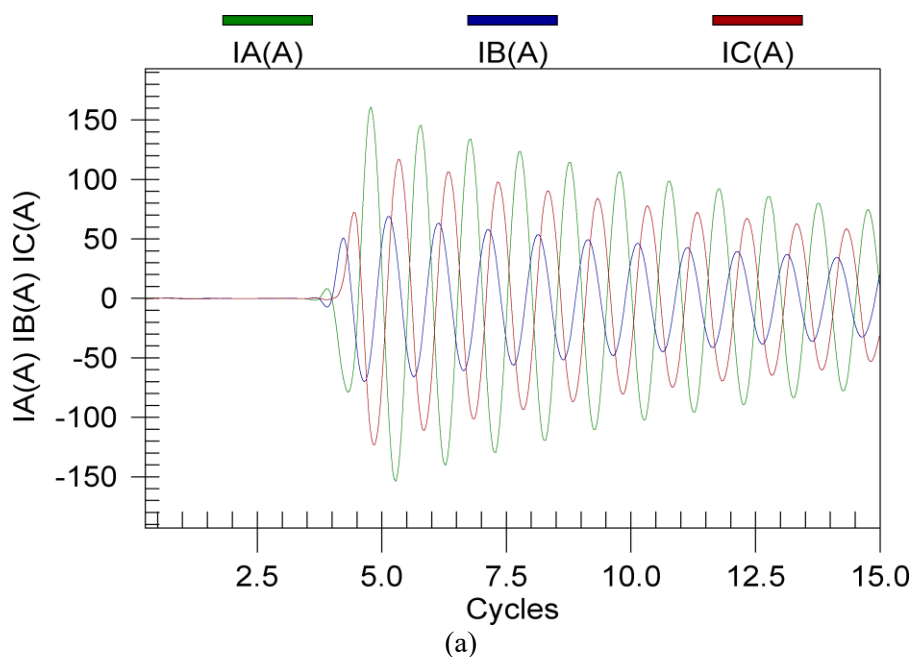


4.1.4. Negative sequence at transformer energisation (inrush)

Fig. 5 illustrates a transformer energisation event, where magnetizing inrush current produces a pronounced, but transient current asymmetry. During the initial energisation, unequal core saturation in the three phases results in significant imbalance, generating a large negative sequence component. The sequence element plot shows that the maximum NSC occurs at approximately 4.75 cycles and reaches about 54.2 A, which corresponds to nearly 93 % of the transformer rated current.

The selection of the detection threshold at 100 % alone avoids triggering and unnecessary tripping. This also addresses concerns for elements unrelated to internal transformer faults, such as grid unbalance (e.g. load unbalance) and current transformer saturation (although current transformers are already well sized for fault current levels), both causing amplitude errors of 10 to 20% at most.

The 5-cycle delay is also in this direction as, unlike fault-related cases, the NSC during inrush is short-lived and decays rapidly as the core flux stabilizes. All three phases remain involved, and the waveform symmetry improves within a few cycles. In relays equipped with transformer protection functions then, special inrush blocking or harmonic restraint prevents misoperation during this interval. Where feeder protection relays without inrush discrimination are used, secure operation can be achieved through the use of multiple protection setting groups, with NSP temporarily blocked during energisation and enabled after a short time delay once inrush has subsided.



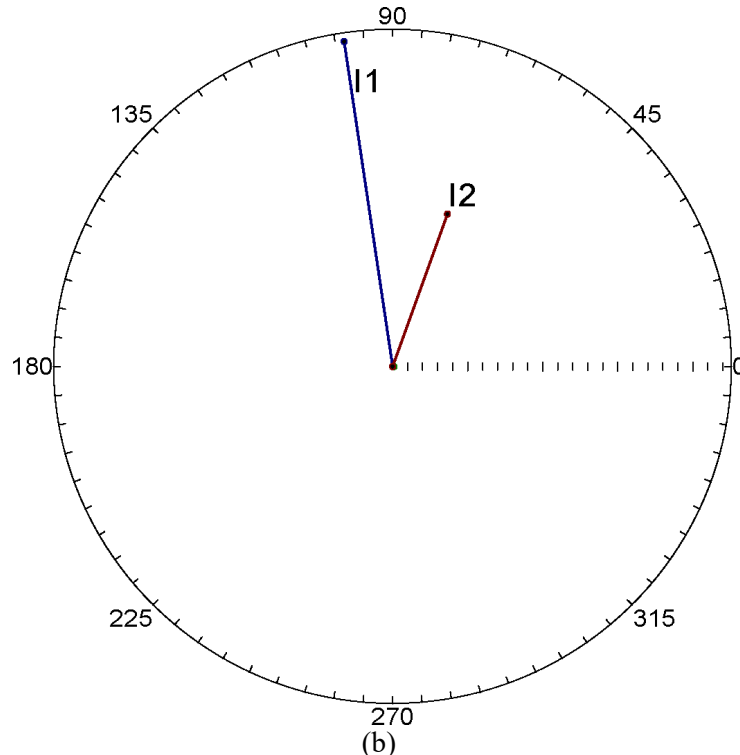


Fig. 5. Recorded transformer magnetizing inrush current and associated negative sequence behaviour by SEL 751A: (a) Time-domain phase current waveforms (b) Sequence phasor diagram at cycle 4.75.

The field data presented in this section demonstrate that incipient internal winding faults in auxiliary and traction transformers produce a characteristic signature of sustained NSC. This signature appears well before catastrophic failure and is clearly distinguishable from NSC due to normal loading or magnetizing inrush.

These observations that are graphically summarized in Fig. 6 form the basis for the protection approach developed in the following section. Fig. 6 shows that discrimination is achieved not only based on magnitude, but also on persistence of the negative-sequence component.

We may synthesize the overall criteria as:

- normal operating imbalance produces low NSC,
- magnetizing inrush produces high but short-duration NSC (and may be picked up by detecting 2nd harmonic), and
- incipient turn-to-turn faults produce sustained NSC exceeding the protection pickup threshold.

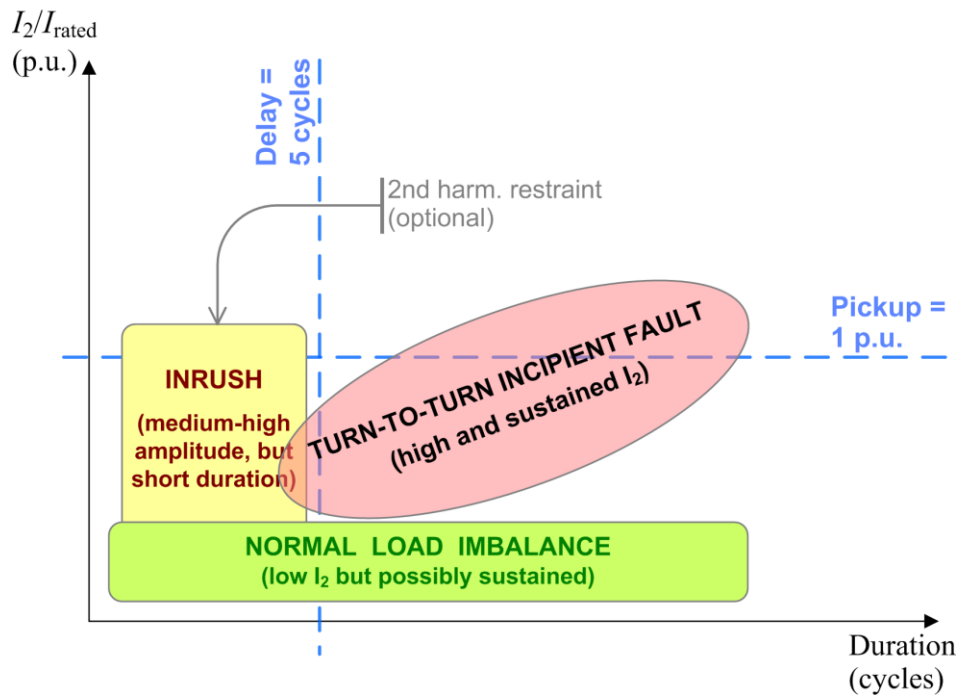


Fig. 6. Qualitative discrimination of operating conditions in the negative-sequence current magnitude–duration plane.

4.2. Negative sequence protection implementation

4.2.1. NSP on protection relays

Negative sequence overcurrent protection is widely available in numerical feeder protection relays and can be implemented without additional primary equipment. In the SEL 751A relay, NSP is implemented as a definite-time overcurrent element designated as 50Q, with independent pickup (50Q1P) and time-delay (50Q1T) settings. Equivalent functionality is available in most numerical relays under ANSI 46 ($I_{2>}$). For the installations investigated in this study, the pickup threshold was set to 100 % of $I_{p,r}$. Practically relay settings are done taking the CT ratio, that usually considers a larger full-scale current than $I_{p,r}$, such as 1.25 times larger. In one of the investigated cases (shown in Fig. 6) the ratio for the CT on the primary side was 75:1. The corresponding $I_{p,r}$ is 58.52 A that provides a ratio of 0.78 (if compared to the CT full scale), used as the pick-up threshold. This value was selected to ensure safe normal operation without unwanted tripping even during transients and abnormal loading, while maintaining sensitivity to internal winding faults. As demonstrated here in Section 4, NSC during normal auxiliary and traction loading remains below approximately 10 % of rated current and rarely exceeds 15– 20% under atypical unbalanced conditions, providing adequate margin from the selected pickup level.

A definite time delay of 100 ms was applied to the NSP element. This corresponds to five electrical cycles at 50 Hz and was verified to be sufficient to ride through short-duration



transient asymmetry, while remaining fast enough to interrupt developing internal faults before escalation.

4.2.2. Handling of magnetizing inrush using setting groups

Feeder protection relays applied to transformer breakers do not always provide dedicated transformer inrush discrimination (ANSI 68). In such cases, secure operation during energisation is achieved through the use of multiple protection setting groups, a standard feature of modern digital relays.

An elevated pickup group is enabled while the circuit breaker is in the open position, with NSP temporarily blocked. Upon breaker closure, group selection is automatically transferred to the normal protection group after a configurable delay, using a digital input derived from the VCB auxiliary contact. A delay of 0.5-1 s is typically sufficient to cover it. This approach ensures immunity to inrush-related asymmetry without compromising sensitivity to internal faults, once steady-state conditions are established. In addition, the NSP pick up threshold may be conveniently lowered well below 100% (setting it above the NSC level caused by normal load imbalance, so in the order of 30-40%), having removed the only relevant source of misoperation (namely temporary inrush transient).

4.2.3. Fault detection and clearing sequence

Fig. 7 illustrates a representative internal winding fault case successfully detected and cleared using NSP implemented in a SEL 751A relay. In this event, the transformer was operating under near no-load conditions when a turn-to-turn fault began, between phases A and C, resulting in a rapid NSC increase.

The negative sequence pickup element 50Q1P asserted at approximately 4.7 cycles from the beginning of the recording, coinciding with the moment when the NSC reached the configured pickup level of 100 % of $I_{p,r}$. Following pickup, the definite time delay element 50Q1T remained active for the configured 100 ms, corresponding to 5 cycles at 50 Hz. The time delay expired at approximately 10 cycles, at which point the NSP element issued a trip command since the NSC was still above the selected threshold.

Relay outputs OUT101 and OUT102, wired in series with the VCB trip coil, were energized and initiated breaker opening. Complete fault clearance occurred within approximately 2.5 cycles (50 ms) after time-delay expiry, including relay operating time and breaker mechanical opening time. The rapid isolation of the fault prevented escalation into sustained internal arcing, thermal damage or fire, thereby eliminating the risk of secondary hazards, such as smoke generation and fire-suppression system discharge.

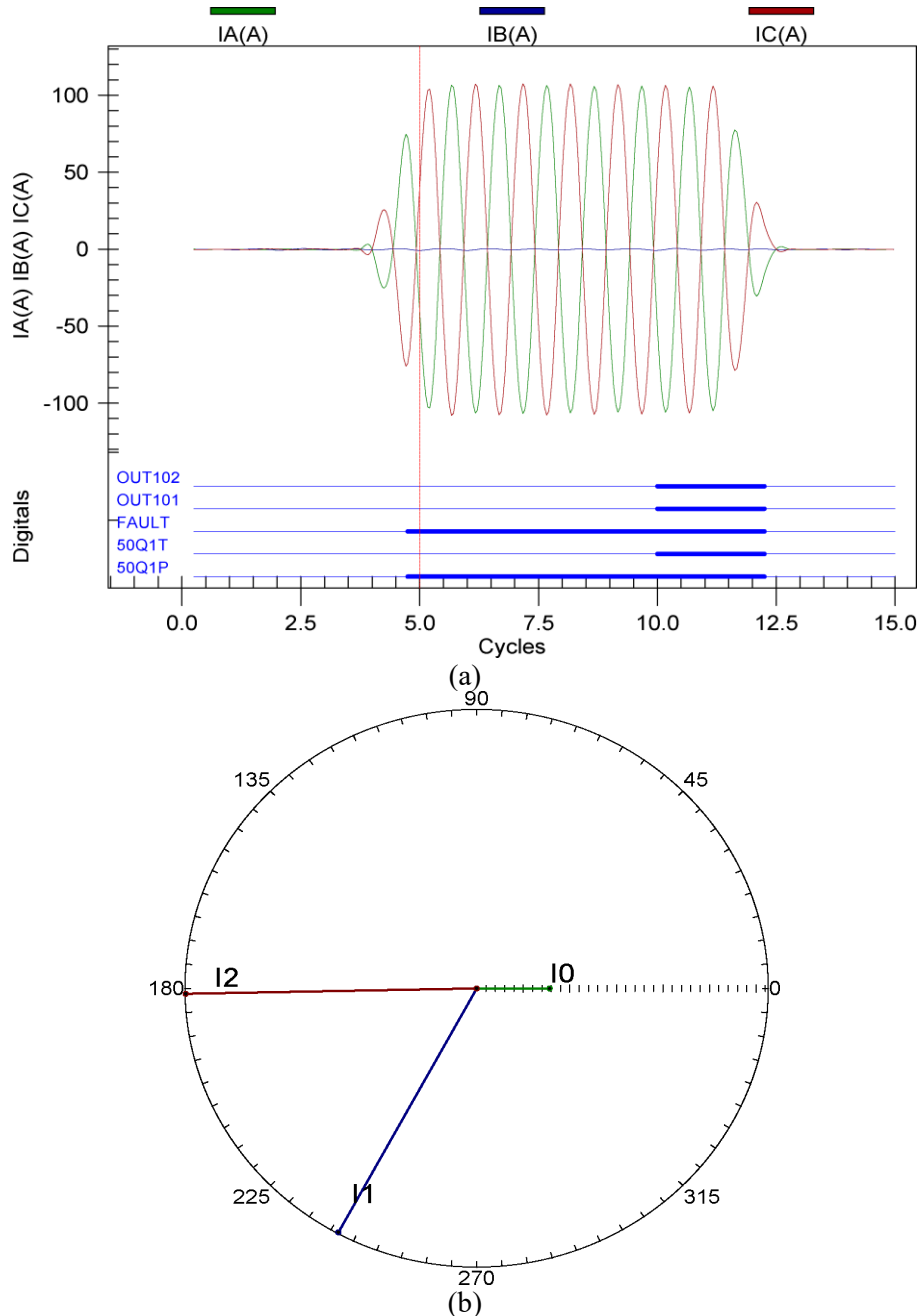


Fig. 6. NSP response to an internal transformer winding fault, showing pickup, time delay, and breaker tripping recorded by SEL 751A: (a) Time-domain phase current waveforms (b) Sequence phasor diagram at cycle 8.00.

4.2.4. Availability of NSP in feeder protection relays

NSP and multiple setting groups are widely available in commonly used feeder protection relays as summarized in Table 1 for representative protection relay products [24]-[27]. This demonstrates the wide applicability of the proposed protection sequence.



Table 1. NSP and inrush handling in common feeder relays

Manufacturer	Relay Model	Settings Groups	Neg. Seq. Element ($I_2 >$)	Inrush Handling Capability
SEL	751A	3	50Q	Not Available
Schneider Electric	P3U10/20/30	4	46	68F2 available
ABB	REF 615 (Cfg A-L)	4	NSPTOC	68 (3I2f>), INRPHAR
Schneider Electric	MiCOM P14x (P141,P142,P143,P145)	4	46	2nd harmonic blocking

5. Discussion

DTT failures associated with VCB switching are often treated as isolated events or attributed to manufacturing defects. The results presented in this paper show that, in many cases, these failures are instead the cumulative outcome of repeated high-frequency electrical stress imposed during commissioning and operational switching. The combination of short cable connections, low system damping, and the fast dielectric recovery of vacuum interrupters creates conditions under which internal winding resonances can be repeatedly excited, even when terminal voltages remain within specified insulation limits [4], [8].

A central outcome of this study is the recognition that incipient winding degradation produces a measurable and repeatable NSC long before catastrophic fault occurs. This NSC signature is fundamentally different from that produced by normal traction loading or magnetizing inrush and therefore provides a reliable indicator of developing internal failures. Field cases demonstrate that this signature evolves gradually, offering a practical window for detection and intervention.

This behaviour can be exploited using standard feeder protection relays, without the need for transformer differential protection or further processing of basic quantities (e.g. directional algorithms). By combining appropriately selected negative sequence pickup thresholds, definite-time delays, and pragmatic handling of inrush through setting groups or harmonic restraint, effective early fault detection is achieved with no additional hardware nor increasing system complexity. In summary, the proposed methodology transforms NSC from a secondary diagnostic quantity into a primary protection signal for dry-type transformers in applications where differential protection is not implemented, such as MV/LV units of limited rating.

From a system perspective, the findings highlight an important gap between transformer design assumptions and real-world railway commissioning practice, where the number of switching operations can far exceed those considered during insulation design. While mitigation measures such as RC snubbers, controlled switching, and enhanced insulation can reduce transient severity, they do not eliminate the need for sensitive and selective fault detection. NSP provides that complementary layer of defence that addresses this gap directly.



Field observations presented in this work show that insulation degradation leading to turn-to-turn faults produces a characteristic circulating current within the transformer winding long before catastrophic failure occurs. Although the resulting phase currents may remain relatively small, the electrical asymmetry introduces a sustained NSC that can persist for several minutes prior to failure. This behaviour makes NSC a particularly sensitive indicator of early-stage internal winding faults, enabling detection at a stage where conventional overcurrent protection would remain insensitive.

In summary, the proposed methodology transforms NSC from a secondary diagnostic quantity into a primary protection signal for DTTs. Its adoption enables earlier fault isolation, reduces the likelihood of fire and collateral damage, and delivers a cost-effective enhancement for transformer protection using equipment already deployed in modern substations. The approach is readily applicable to both auxiliary and traction transformers and offers a practical path toward improved reliability in switching-intensive railway environments. The present study is focused on MV/LV dry-type transformers, typically below 5–10 MVA, where differential protection is often not implemented due to cost and installation constraints.

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