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Review of differential protection schemes for power transformers in medium-voltage distribution networks

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Abstract

Power transformers are essential components of medium-voltage (MV) distribution networks, particularly in 33 kV substations, where they enable voltage transformation, maintain power quality, and ensure reliable electricity delivery. Due to their critical operational role, transformer failures can significantly affect system stability, service continuity, and equipment safety. However, transformers are highly vulnerable to both internal and external disturbances such as winding short circuits, insulation degradation, overloading, overexcitation, magnetizing inrush current, and current transformer (CT) saturation, all of which can compromise protection accuracy and operational reliability. Among transformer protection methods, differential protection remains the most widely used technique for internal fault detection because of its high sensitivity, fast response, and selective fault isolation capability. Over time, transformer protection systems have evolved from conventional electromechanical relays to numerical and intelligent relay-based systems, improving signal processing, fault discrimination, and communication performance. Despite these developments, challenges such as false tripping during low-harmonic inrush conditions, CT mismatch, saturation effects, harmonic distortion, and limited adaptability under fluctuating grid conditions still remain. This review critically examines transformer operating principles, fault behavior, protection hierarchy, differential protection schemes, relay technologies, and emerging intelligent methods involving adaptive algorithms, signal processing, and machine learning. Using a PRISMA-based systematic literature review, key trends, limitations, and research gaps were identified. The study emphasizes the urgent need for adaptive, robust, and cost-effective differential protection solutions specifically designed for 33 kV MV transformers, particularly in developing power systems with weak grid conditions and infrastructure limitations.

Nomenclature and units

AC	Alternating Current	MVA	Mega Volt Ampere
CB	Circuit Breaker	MV	Medium Voltage
CT	Current Transformer	OLTC	On-Load Tap Changer
DGA	Dissolved Gas Analysis	PT	Potential Transformer
DSP	Digital Signal Processing	PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
EMF	Electromotive Force	REF	Restricted Earth Fault
IEC	International Electrotechnical Commission	SCADA	Supervisory Control and Data Acquisition
IET	Institution of Engineering and Technology	SEL	Schweitzer Engineering Laboratories
ITD	Intrinsic Time-Scale Decomposition	SF_6	Sulfur Hexafluoride
KCL	Kirchhoff's Current Law		

1. Introduction

Power transformers are among the most critical assets in medium-voltage (MV) power systems because they ensure voltage regulation, energy transfer efficiency, and system stability across transmission and distribution networks. Their operational reliability directly affects grid continuity, equipment lifespan, and power quality. As MV systems become more complex with higher load demands and increased integration of renewable energy sources, transformer health and secure operation have become increasingly important in modern power networks (Han & Song, 2003; Meira et al., 2018; Okeke et al., 2024).

Reliable transformer protection is essential because transformer failures can result in severe operational disruptions, costly outages, insulation degradation, fire hazards, and long-term economic losses. Studies on transformer reliability and condition monitoring emphasize that early fault identification significantly improves maintenance planning and reduces catastrophic failures. Internal winding faults, insulation deterioration, and partial discharge events are particularly dangerous because they can rapidly escalate if not detected promptly (Tenbohlen et al., 2015; Kumar et al., 2008; Saponara et al., 2016; Okeke et al., 2024).

Among various transformer protection methods, differential protection remains the dominant and most widely adopted approach for detecting internal transformer faults. This protection scheme operates by comparing the currents entering and leaving the transformer and can quickly isolate internal abnormalities such as winding short circuits, turn-to-turn faults, and phase faults. Over time, traditional percentage differential relays have evolved with enhanced algorithms such as alpha-plane analysis, wavelet-based detection, and entropy-based protection techniques to improve sensitivity and dependability (Medeiros et al., 2015; Shah et al., 2018; Sayed & Abdelaziz, 2024; Huang et al., 2025).

Despite its widespread use, transformer differential protection still faces several technical challenges. One of the most significant issues is distinguishing internal faults from magnetizing inrush currents, overexcitation, current transformer (CT) saturation, and external disturbances, which may lead to relay maloperation or delayed tripping. Research has shown that transformer winding mechanical defects, electrical transients, and nonlinear current distortions can reduce protection accuracy and reliability under dynamic operating conditions (Bagheri et al., 2017; Mohammadpour et al., 2020; Khan et al., 2017; Moravej et al., 2023).

These limitations have motivated extensive research into intelligent and adaptive transformer protection methods. Signal-processing approaches such as wavelet transforms, variational mode decomposition, transfer function analysis, and machine learning-based classifiers have been proposed to improve discrimination between genuine internal faults and non-fault disturbances. Deep learning and hybrid artificial intelligence (AI) techniques are increasingly being integrated into relay systems to enhance speed, robustness, and predictive diagnostic capability (Bigdeli et al., 2012; Afsharisefat et al., 2024; Alenezi et al., 2024; Mishra & Singh, 2025).

Therefore, this review focuses on the evolution, performance, and emerging advancements in transformer differential protection for MV systems. It examines conventional protection principles, signal-processing-based improvements, AI-driven approaches, reliability considerations, and unresolved implementation challenges. The major contribution of this review is to synthesize recent developments in fault discrimination, adaptive relay intelligence, and transformer reliability enhancement, while identifying future research directions for more accurate and resilient transformer protection frameworks in modern smart grids (Atiyah et al., 2025; Kasztenny & Samineni, 2024; Yin et al., 2021; Tian et al., 2025).

2. Methodology

This review adopts the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to systematically identify, screen, evaluate, and synthesize literature related to transformer differential protection in medium-voltage (MV) power systems. PRISMA was selected because it provides a transparent, structured, and reproducible method for literature selection, reducing bias and improving scientific rigor. Transformer protection research covers multiple technical areas including relay engineering, transformer diagnostics, signal processing, artificial intelligence, and power system reliability. Therefore, PRISMA helps ensure only relevant and validated studies are included. The review followed four key stages: identification, screening, eligibility, and inclusion. This approach enabled systematic comparison of conventional and advanced transformer protection techniques while identifying technological progress, unresolved limitations, and research gaps.

2.1 Identification

The identification stage involved systematic literature collection from major engineering and scientific databases to capture both foundational and recent studies on transformer differential protection. The databases used were IEEE Xplore, ScienceDirect, SpringerLink, Google Scholar, and IET Digital Library because they provide strong coverage of relay protection, transformer diagnostics, fault analysis, and intelligent protection systems. Keyword-based searches were applied using terms such as transformer differential protection, power transformer fault detection, percentage differential relay, CT saturation, inrush current discrimination, and machine learning in power system protection.

2.2 Screening

After identification, retrieved studies were screened to remove duplicates and irrelevant publications. Titles, abstracts, and keywords were examined to ensure alignment with transformer differential protection objectives. The inclusion criteria covered peer-reviewed journal papers, conference proceedings, technical reports, and studies published between 2000 and 2025 focusing on transformer protection, internal fault diagnosis, inrush discrimination, CT saturation, and adaptive relay methods. The exclusion criteria removed non-peer-reviewed materials, unsupported reports, duplicate records, incomplete studies, and publications unrelated to transformer differential protection. Research centered only on smart grid communication, automation, or unrelated power applications was excluded. This screening process improved the quality, relevance, and reliability of the selected literature.

2.3 Eligibility Assessment

The shortlisted full-text studies were critically assessed for scientific validity, technical depth, and engineering relevance. Each paper was evaluated based on whether it clearly described a transformer fault detection or protection methodology, such as mathematical models, relay algorithms, signal processing techniques, or AI-based approaches. Studies also needed validation through simulation, laboratory testing, or practical implementation. Additional emphasis was placed on fault discrimination accuracy, especially the ability to distinguish internal faults from transient events such as inrush current or overexcitation. Research that lacked testing, practical significance, or engineering applicability was excluded. This eligibility stage ensured that only high-quality, technically sound, and practically useful studies contributed to the final review.

2.4 PRISMA Flow Diagram

The PRISMA flow diagram summarizes the systematic literature selection process. During the identification stage, 1,245 records were retrieved from major databases. After removing 215 duplicates, 1,030 studies remained for screening as shown in Figure 1. During title and abstract review, 690 studies were excluded because they were irrelevant or lacked direct focus on transformer differential protection. This left 340 full-text articles for eligibility assessment. After detailed technical evaluation, 198 studies were excluded due to weak validation, low engineering significance, or insufficient methodological depth. Finally, 142 studies were retained for qualitative and comparative synthesis. This PRISMA-based selection process enhanced transparency, reduced selection bias, and improved reproducibility of the review methodology.

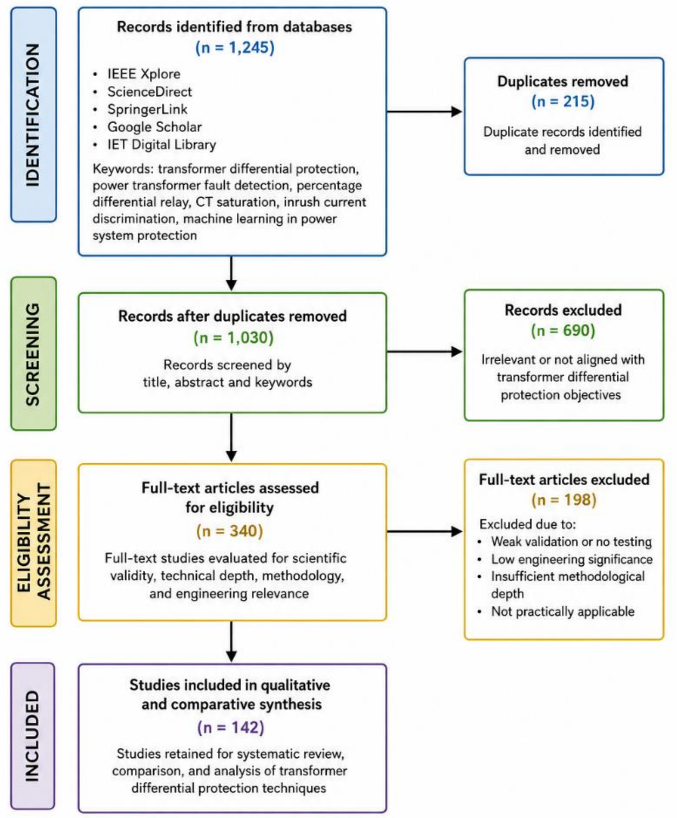

Figure 1. PRISMA Flow Diagram for this Review.

3. Fundamental Concepts of Power Transformers

The fundamental concepts underlying transformer operation and protection are essential for understanding the design of an effective differential protection scheme. Power transformers are key elements in electrical power systems, enabling efficient transmission and distribution of electrical energy by stepping voltage levels up or down. Their operation is governed by electromagnetic principles, and their performance is influenced by electrical, magnetic, and thermal characteristics. A detailed understanding of transformer construction, operation, and classification provides the necessary foundation for analyzing fault behavior and implementing reliable protection strategies.

3.1 Power Transformer

A power transformer is a static electromagnetic device that transfers electrical energy between two or more circuits through electromagnetic induction. It operates on the principle of mutual induction, where a time-varying current in the primary winding produces a magnetic flux in the core, which induces a voltage in the secondary winding. This process allows voltage levels to be changed without altering the system frequency (Chapman, 2012). Power transformers are widely used in generation, transmission, and distribution systems to improve efficiency by reducing transmission losses.

The basic construction of a transformer includes primary and secondary windings, a magnetic core, insulation systems, and cooling mechanisms. The magnetic core is typically made of laminated silicon steel to minimize eddy current losses, while the windings are made of copper or aluminum conductors. The efficiency of a transformer is generally high, often exceeding 95%, making it one of the most reliable components in power systems (Kothari & Nagrath, 2019).

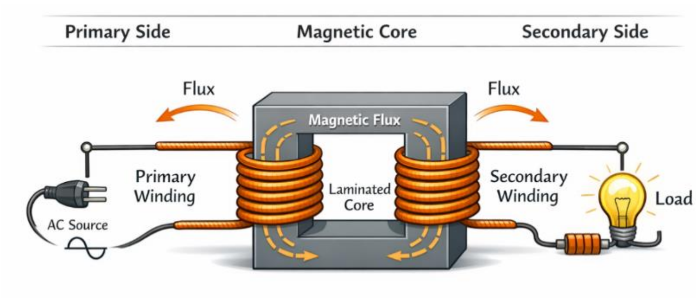

Figure 2. Basic Structure of a Power Transformer

Figure 2 illustrates the basic structure and operating principle of a power transformer. It shows the primary winding connected to an AC source, where alternating current generates a time-varying magnetic flux in the laminated core. This core, typically made of silicon steel, provides a low-reluctance path for the magnetic flux to link both windings efficiently. The changing flux induces a voltage in the secondary winding through electromagnetic induction, enabling energy transfer without direct electrical connection. The secondary side is connected to the load, where electrical power is delivered. This structure forms the basis for voltage transformation and is fundamental to understanding transformer operation and protection.

3.2 Operation of a Power Transformer

The operation of a power transformer is based on Faraday's law of electromagnetic induction. When an alternating voltage is applied to the primary winding, an alternating current flows, producing a time-varying magnetic flux in the core. This flux links both the primary and secondary windings, inducing an electromotive force (EMF) in the secondary winding. The induced voltage is proportional to the number of turns in the winding, as expressed by:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

where:
V_1, V_2= primary and secondary voltages
N_1, N_2= number of turns in primary and secondary windings

Under ideal conditions, the input power equals the output power:

$$V_1 I_1 = V_2 I_2$$

In practical transformers, losses such as copper losses (I^2R), core losses (hysteresis and eddy currents), and leakage flux reduce efficiency. During normal operation, the current entering and leaving the transformer remains balanced, which is a key assumption used in differential protection schemes (Grainger & Stevenson, 1994).

3.3 Classification of Power Transformers

Power transformers are classified based on several criteria, each reflecting their design purpose, operational environment, and application within the power system. Understanding these classifications is essential for selecting appropriate transformers and designing effective protection schemes.

(a) Based on Voltage Level
Transformers are categorized as step-up or step-down depending on their voltage transformation function. Step-up transformers are used at generation stations to increase voltage from low generator levels to high transmission levels, thereby reducing current and minimizing transmission losses over long distances. Conversely, step-down transformers are employed in distribution networks to reduce high transmission voltages to safer and usable levels for industrial, commercial, and residential consumers. This classification is critical in protection design because fault characteristics and current magnitudes differ significantly between high-voltage transmission and low-voltage distribution systems.

(b) Based on Construction
Based on physical design, transformers are classified into core-type and shell-type. In core-type transformers, the windings are placed around the core limbs, allowing easier insulation and cooling, which makes them suitable for high-voltage applications. In contrast, shell-type transformers have the core surrounding the windings, providing better mechanical strength and reduced leakage flux. This design improves short-circuit withstand capability and reduces electromagnetic interference. The construction type influences fault behavior, leakage reactance, and magnetic flux distribution, all of which are important factors in modeling transformer performance and designing differential protection schemes.

(c) Based on Phase
Transformers can be either single-phase or three-phase. Single-phase transformers are typically used in low-power applications such as residential loads and small equipment. Three-phase transformers, however, are widely used in power systems due to their ability to handle large power levels efficiently and provide balanced power delivery. They can be constructed as a single unit or as a bank of three single-phase transformers. Since most industrial and transmission systems operate on three-phase power,

differential protection schemes are primarily designed to monitor three-phase current relationships and detect phase-specific faults.

(d) Based on Cooling Method

Cooling methods are crucial for maintaining transformer performance and longevity. Dry-type transformers use air for cooling and are commonly installed indoors where fire safety is important. Oil-immersed transformers, on the other hand, use insulating oil to dissipate heat and provide electrical insulation. These are widely used in outdoor and high-power applications due to their superior cooling efficiency. The cooling method affects thermal limits, insulation life, and fault response, which are important considerations when setting protection parameters and evaluating transformer reliability under different loading conditions.

(e) Based on Application

Transformers are also classified according to their application in the power system. Power transformers are used in transmission networks and are designed for high efficiency at near-full load conditions. Distribution transformers operate at lower voltages and are optimized for varying load conditions throughout the day. Instrument transformers, including current transformers (CTs) and potential transformers (PTs), are used for measurement and protection purposes. In differential protection schemes, CTs play a critical role by providing scaled current signals to the relay, making this classification particularly relevant to the study.

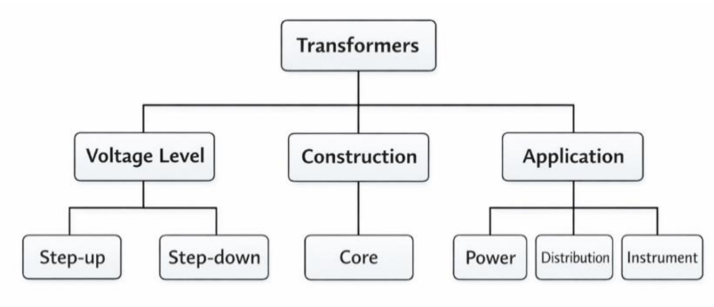

Figure 3. Classification of Transformers

Figure 3 presents a hierarchical classification of transformers based on three major criteria: voltage level, construction, and application. At the top, transformers are broadly grouped, then divided into categories that reflect their functional and structural characteristics. Under voltage level, transformers are classified as step-up or step-down depending on whether they increase or decrease voltage. The construction category distinguishes between core-type and shell-type designs, which differ in winding arrangement and magnetic flux paths. Finally, the application category identifies power, distribution, and instrument transformers, each serving specific roles in the power system. This classification helps in selecting appropriate transformers and designing suitable protection schemes.

3.4 Transformer Losses and Efficiency

1. Transformer Losses

Transformer losses are inevitable and directly impact efficiency and thermal performance. Core losses occur due to hysteresis and eddy currents in the magnetic core and remain relatively constant regardless of load. Copper losses arise from the resistance of transformer windings and vary with load current. Stray losses are caused by leakage flux inducing currents in surrounding metallic parts. These losses lead to heating, which can accelerate insulation degradation and increase the likelihood of faults. In protection design, understanding these losses is important for distinguishing between normal operating conditions and abnormal fault conditions.

2. Transformer Efficiency

Transformer efficiency is a measure of how effectively input electrical power is converted into output power. It is expressed as:

$$\eta = \frac{\text{Output Power}}{\text{Input Power}} \times 100\%$$

High efficiency is essential for reducing operational costs and ensuring reliable power delivery. Power transformers typically operate at efficiencies above 95%, especially near full load. Efficiency also influences thermal performance and loading limits, which must be considered when designing protection schemes to avoid unnecessary tripping during normal high-load conditions.

4. Overview of Power System Protection

Power system protection refers to the set of mechanisms and devices designed to detect abnormal electrical conditions (such as short circuits, overloads, or open circuits) caused by natural disturbances or operational faults, isolate the affected parts, and thus prevent damage and ensure system stability. The objectives include fast detection, selective isolation of faulty components, minimal disruption to service, and protection of equipment integrity (Alenezi, Anayi, Packianather, & Shouran, 2024; Tian et al., 2025). As systems become more complex (with more distributed generation, irregular loading, etc.), protection schemes must also evolve to handle uncertainty, measurement errors, and non-standard fault conditions (Alenezi et al., 2024; Atiyah, Karimi, & Moradi, 2025).

Effective protection systems are built on the interplay of sensing, decision-making, and actuation. Sensors (transducers such as CTs and PTs) monitor current and voltage; protective relays interpret sensor signals and decide if a fault exists; and circuit breakers or equivalent interrupting devices execute the disconnection as shown in Figure 4. Supplemental components such as communication links, backup power supplies, and hierarchical coordination across protection zones add reliability and robustness (Alenezi et al., 2024; Tian et al., 2025). The design must satisfy criteria like speed (to reduce damage and instability), sensitivity (to detect low magnitude or early faults), selectivity (to isolate only the faulty component), and reliability (accuracy, low false trips, fault tolerance).

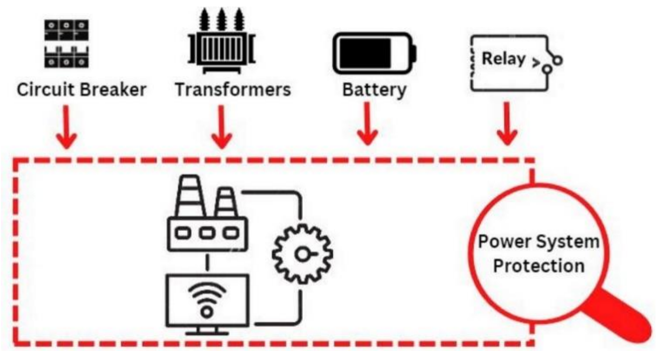

Figure 4. Typical Power System Protection Zones (Alenezi et al., 2024)

4.1 Hierarchy and Components of Power System Protection

The hierarchy of protection spans from the generation end through transmission and distribution. At generation stations, protection must deal with large machines, step-up transformers, excitation systems, and bus protection. Transmission level protections often deal with long distances, high fault currents, and need for rapid fault clearance to prevent propagation of instability. Distribution networks, often radial or lightly interconnected, deal with frequent, smaller faults and environmental disturbances. Each level demands different protection principles, settings, and devices (X. Yin et al., 2021). Table 1 present the summary of key power system protection components.

Key components in protection systems are:

i. Transducers: (Current Transformers, Potential Transformers) that scale high system currents/voltages to safe measurement levels;
ii. Protective Relays: that process signals and, based on pre-defined thresholds or algorithms (which may be traditional logic, fuzzy logic, or ML based), decide whether to issue a trip;
iii. Interrupting Devices: (Circuit Breakers or Disconnector+Breaker combinations) that physically isolate the faulty section.

Table 1. Summary of Key Power System Protection Components

Component	Primary Function	Example Device	Operating Principle
Transducers	Sense and scale current/voltage signals	CT, PT	Electromagnetic induction
Protective Relays	Process signals and issue trip/alarm	Electromechanical, Static, Numerical	Threshold and logic decision-making
Circuit Breakers	Execute physical isolation of faulted circuit	SF_6, Vacuum, Oil CB	Arc interruption via dielectric medium

Recent literature has also emphasized the integration of advanced protection elements, such as adaptive protection that adjusts settings dynamically (Alenezi et al., 2024), and protection schemes that incorporate communication and hierarchical coordination (X. Yin et al., 2021). These ensure that protection remains effective under changing system conditions, fault types, and renewable energy integration.

4.2 Importance of Transformer Protection in System Reliability

Transformers are core to power systems because they allow voltage level transformations which make efficient transmission and distribution possible. Because transformers are expensive, heavy, and often critical nodes (serving many loads), their failure can cause sizable outages, greatly increase repair costs, and degrade network reliability metrics. Internal faults (e.g., inter-turn faults, winding short circuits), as well as transient conditions (e.g., inrush, overexcitation), threaten their healthy operation (Okeke et al., 2024).

Modern research shows that improving transformer protection (for example through more accurate detection of internal faults, discrimination of inrush versus fault currents, using advanced algorithms/machine learning, accounting for CT saturation and measurement uncertainty) can significantly reduce false tripping, improve operational lifespan of transformers, and improve system reliability (Atiyah et al., 2025). Also, studies of transformer failure rates (from multiple feeders/systems) show that overloading, external short circuits, moisture, and thermal stress are common failure causes, reinforcing the need for robust protection and condition monitoring strategies (Okeke et al., 2024).

5. Transformer Faults and Protection Requirements

5.1 Categorization of Internal and External Transformer Faults

Power transformers are among the most vital components in electric power systems, as their performance directly affects system stability and reliability (Akbari, Werle, Borsi, & Gockenbach, 2002; Meira, Ruschetti, Álvarez, & Verucchi, 2018). A single transformer failure can result in significant financial losses and prolonged power outages (Abbasi, Mahmoudi, & Avazzadeh, 2018). Transformers are generally exposed to a combination of electrical, thermal, mechanical, and environmental stresses, all of which can deteriorate insulation over time the root cause of most internal faults (S. Li & Li, 2017; Meira et al., 2018). Transformer faults are broadly categorized as internal or external as illustrated in Figure 5. Internal faults occur within the transformer enclosure and include winding turn-to-turn, phase-to-phase, or phase-to-ground short circuits, insulation breakdown, core overheating, and winding displacement (Bagheri, Moravej, & Gharehpetian, 2017). These faults are highly destructive because they can lead to rapid energy release, arcing, and oil degradation. Studies indicate that nearly 70–80% of all transformer faults are internal, typically initiated by localized insulation discharge that develops into a complete dielectric failure (Bigdeli, Vakilian, & Rahimpour, 2012; R. Li et al., 2017). Internal defects may originate in the winding (axial displacement, shorted turns), tank (leakage), insulation oil (oxidation, water contamination), or core (shorted laminations and insulation failure) (Fu, Zhu, Mao, Zhang, & Chen, 2017; Hashemnia, Abu-Siada, & Islam, 2016).

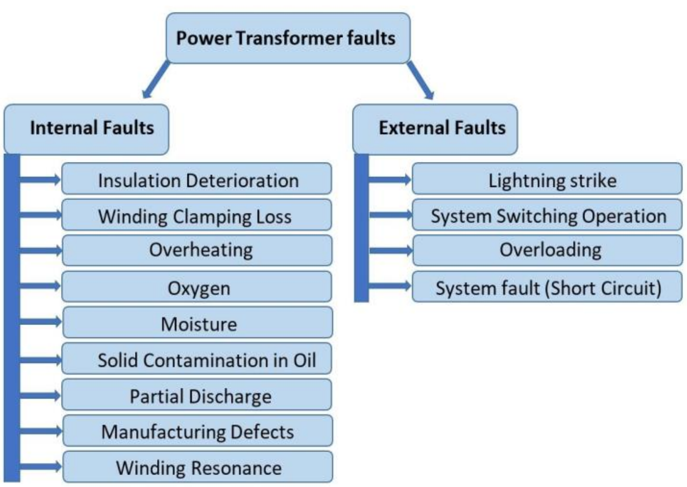

Figure 5. Classification of Transformer Faults (Bigdeli et al., 2012)

External faults, on the other hand, occur outside the transformer and include short circuits in feeders, overfluxing, switching surges, or system overloads (Mohammadpour, Dashti, & Shaker, 2020). Though not directly destructive, they impose severe thermal and mechanical stresses on transformer windings, accelerating insulation deterioration and increasing the likelihood of internal failure (Athamneh & Alqudah, 2024). Condition monitoring has therefore become essential to prevent disruptions by identifying early deterioration. Modern predictive maintenance strategies, such as vibration analysis, dissolved gas analysis (DGA), and frequency response analysis (FRA), enable early fault diagnosis and scheduling of preventive maintenance (Saponara, Fanucci, Bernardo, & Falciani, 2016). Online monitoring is increasingly preferred because it assesses the transformer under actual operating conditions, unlike offline methods which only detect manufacturing or dormant defects (Bhatt, Kumar, & Patel, 2018; Kumar, Gupta, Udayakumar, & Venkatasami, 2008). Table 2 shows the typical transformer faults and their detection techniques.

Table 2. Typical Transformer Faults and Their Detection Methods

Fault Type	Cause/Stress	Detection Method
Winding short circuits	Electrical stress/insulation	Differential protection, REF relay
Core overheating	Magnetic flux leakage	Temperature sensors, dissolved gas analysis (DGA)
Inrush current	Magnetization at energization	Harmonic restraint relay (2nd harmonic)
Overloading (thermal fault)	Excess load, cooling failure	Thermal relays, temperature monitoring
External feeder fault	Line-to-line/earth fault	Overcurrent and earth fault relays
Mechanical displacement	Short-circuit forces	Frequency response analysis (FRA), vibration monitoring
Overvoltage surge	Lightning, switching surges	Surge arresters, voltage relays
Incipient insulation fault	Partial discharge/gassing	Buchholz relay, dissolved gas analysis

5.2 Electrical, Thermal, and Mechanical Stress Causes

Transformers endure electrical, thermal, and mechanical stresses during normal and abnormal operating conditions. Electrical stress often results from overvoltages caused by lightning strikes, switching transients, or insulation deterioration, which may trigger partial discharges or arcing (Athamneh & Alqudah, 2024). Thermal stress emerges from sustained overloading, poor cooling, or circulating currents, leading to insulation aging and hotspots (Okeke et al., 2024). Mechanical stress, on the other hand, is produced by electromagnetic forces during short circuits or vibrations in windings, which can lead to deformation or displacement (Abbasi et al., 2018). Prolonged exposure to these stresses can significantly degrade the transformer's performance and reliability, underscore the importance of early detection and coordinate protection systems.

5.3 Protection Requirements at 33 kV Voltage Level

At the 33 kV voltage level, power transformers form the interface between sub-transmission and distribution systems, requiring rapid and selective protection to ensure both system stability and equipment safety. Protection at this level typically combines differential protection for detecting internal faults, overcurrent and earth fault relays for external faults, and Buchholz relays for gas generation or incipient faults (Alenezi et al., 2024). Complementary devices include restricted earth fault (REF) relays for sensitive winding faults, thermal relays for overloading, and surge arresters for transient overvoltage protection.

Modern protection schemes at 33 kV also integrate condition monitoring tools for real-time performance evaluation. Predictive diagnostic systems use electrical, thermal, and vibration data to enhance fault discrimination and minimize false trips (Saponara et al., 2016). This multi-layered approach ensures high dependability and security, balancing operational continuity with cost-effectiveness for medium-voltage networks (Han & Song, 2003; Tenbohlen et al., 2015).

6. Differential Protection Schemes for Power Transformers

6.1 Basic Principle of Differential Protection

Differential protection is one of the most widely applied methods for transformer protection due to its selectivity, sensitivity, and rapid response. The basic working principle is founded on Kirchhoff's Current Law (KCL), which states that under normal operating conditions, the sum of currents entering and leaving the transformer zone should be equal. Hence, the differential protection scheme compares the current entering and leaving the protected zone; any difference indicates a possible internal fault (Medeiros, Costa, & Silva, 2015).

Under normal load conditions or during external faults, the incoming current (I_1) and outgoing current (I_2) are equal in magnitude when referred to a common base. Therefore, the differential current (I_diff) is ideally zero. However, when an internal fault occurs within the protected zone, the balance is disturbed and the differential relay operates by tripping the associated circuit breakers on both sides of the transformer (Athamneh & Alqudah, 2024).

$$I_{\text{diff}} = | I_1 - I_2 |$$

Where:

I_1= current entering the transformer zone

I_2= current leaving the transformer zone

In practice, a restraining current (I_rest) is introduced to stabilize the relay operation against through-fault and magnetizing inrush conditions. It is typically defined as the average of the magnitudes of the two CT currents (Alenezi et al., 2024):

$$I_{\text{rest}} = \frac{| I_1 | + | I_2 |}{2}$$

The differential relay is designed to operate only when the differential current exceeds a set threshold that is proportional to the restraining current. This ensures stability during external faults or minor CT errors while maintaining sensitivity to internal faults (Bagheri et al., 2017).

6.2 Percentage Differential and Restraining Current Concept

To enhance selectivity, percentage differential protection is widely adopted. It introduces a percentage bias that prevents false tripping during conditions such as CT saturation, load unbalance, and magnetizing inrush current. The relay characteristic is defined by a slope that determines how much restraining current is required for a given differential current to operate. This principle is known as the percentage bias method, mathematically expressed as (R. Li et al., 2017):

$$I_{\text{diff}} \geq K \times I_{\text{rest}}$$

Where *K* is the bias or slope setting (typically between 20–50%).

During normal operation, the currents on both sides are balanced, and the relay remains inactive. However, when an internal fault occurs within the transformer windings, an imbalance arises, generating a significant differential current that exceeds the bias setting. Consequently, the operating coil is energized, and the relay initiates a trip signal to disconnect the transformer (Han & Song, 2003).

In a 33 kV transformer, differential protection schemes are typically applied to units rated 2 MVA and above, following the Merz–Price circulating current principle, which compares secondary currents from current transformers (CTs) installed on both sides of the transformer (Medeiros et al., 2015). For star–delta connected transformers, the CTs on the star side are delta-connected, and those on the delta side are star-connected to maintain phase compensation (Alenezi et al., 2024). The restraining coil is connected between the CT secondaries to limit unnecessary relay operation. The operating coil detects imbalance and trips when the difference exceeds a set threshold. Under healthy conditions, the restraining coil maintains stability by offsetting minor measurement discrepancies or transient effects (Bagheri et al., 2017).

6.3 Challenges and Mitigation in Differential Protection

Despite its advantages, differential protection faces operational challenges such as magnetizing inrush current, which can reach up to 10 times the full-load current during transformer energization (Akbari et al., 2002). This transient current may falsely appear as a differential current, leading to incorrect relay operation as presented in Figure 6. To prevent this, modern relays employ second-harmonic restraint or time-inverse characteristics that distinguish between inrush and internal fault currents (Saponara et al., 2016). Earlier systems used kick fuses across relay coils to delay operation during inrush events, but current digital relays use harmonic analysis to identify non-fault conditions (Abbasi et al., 2018). By combining percentage bias, harmonic restraint, and adaptive thresholding, modern differential schemes provide dependable protection with minimal false tripping in 33 kV distribution networks (Okeke et al., 2024).

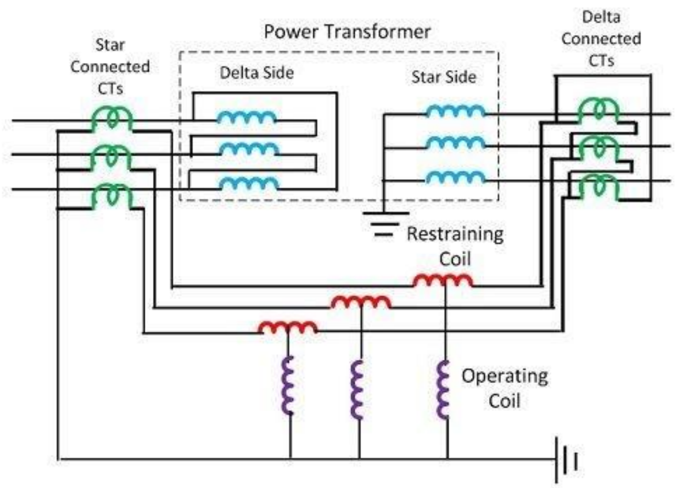

Figure 6. Basic Principle of Transformer Differential Protection

6.4 Design Considerations for Differential Protection

Designing an effective transformer differential protection system requires careful attention to current transformer (CT) selection, ratio matching, polarity, and magnetization characteristics, since these directly affect the relay's accuracy and stability as presented in Table 3. In a differential scheme, CTs installed on both sides of the transformer must have identical ratio and polarity orientation to ensure balanced secondary currents under normal conditions. Any mismatch can introduce false differential currents, potentially leading to unwanted relay operation (Tenbohlen et al., 2015). Additionally, the magnetization characteristics of CTs determine their ability to accurately reproduce primary currents during faults; CTs with high saturation flux densities are preferred for maintaining accuracy under high fault currents (Khan, Voloh, & Robinson, 2017). CT errors can arise from ratio mismatch, saturation, and phase angle displacement. When one CT saturates earlier than the other during external faults, spurious differential currents may appear, causing maloperation of the relay (Okeke et al., 2024). To mitigate this, modern relays use percentage bias characteristics that introduce a restraining torque proportional to the average through current. This ensures that for high external fault currents, the relay remains stable, while still maintaining sensitivity to genuine internal faults (Bagheri et al., 2017).

Furthermore, additional stabilizing components such as stabilizing resistors and harmonic restraint filters are incorporated to improve system dependability. A stabilizing resistor is connected in series with the operating coil to limit relay current during CT saturation or external faults (Han & Song, 2003). Meanwhile, harmonic restraint utilizes second-harmonic detection to distinguish magnetizing inrush currents from internal fault currents, preventing false tripping during transformer energization (R. Li et al., 2017). The percentage bias method combines both restraint and sensitivity by defining operating zones in a biased differential characteristic curve, which determines the tripping threshold as a function of restraining current (Medeiros et al., 2015).

Table 3. Design Parameters for Transformer Differential Protection

Parameter	Description	Typical Value
CT Ratio	Matches line current	600/5 A
Bias Setting	To avoid false trips	20–40%
Harmonic Restraint	To block inrush currents	2nd Harmonic

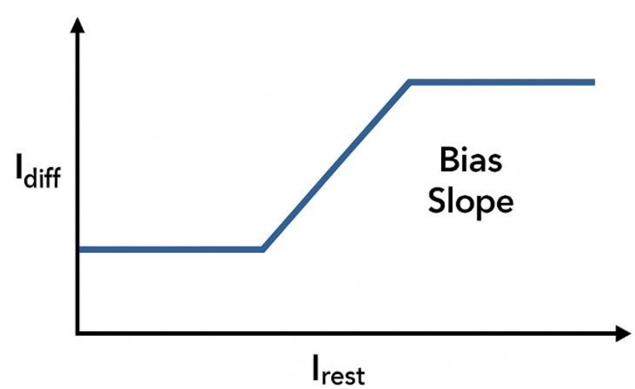

Figure 7. Biased Differential Characteristic Curve(Medeiros et al., 2015)

Figure 7 shows how relay sensitivity increases with fault current while remaining stable for external disturbances and CT errors. The slope represents the bias setting, which adjusts relay stability during through-fault conditions (Saponara et al., 2016).

6.5 Challenges in Differential Protection of Power Transformers

Although differential protection is one of the most effective protection schemes for transformers, its performance can be affected by several practical challenges. A major issue is magnetizing inrush current, which occurs during transformer energization and can reach up to 10 times the rated current. This current is rich in second-harmonic content and may falsely appear as a differential current if not properly restrained (Athamneh & Alqudah, 2024). Similarly, CT saturation during heavy external faults can cause unbalanced secondary currents that mimic internal faults, leading to maloperation (Bagheri et al., 2017).

Through-fault conditions, where heavy current flows through the transformer without originating within it, also pose a challenge. Such faults cause CT saturation asymmetrically, producing false differential components. Moreover, on-load tap changer (OLTC) operations introduce ratio changes that result in small differential currents even under normal conditions, requiring careful bias adjustment and dynamic restraint (Medeiros et al., 2015; X. Yin et al., 2021).

In addition to these technical challenges, power quality issues such as voltage sags, harmonic distortion, and frequency variations can further complicate protection system performance, particularly in developing regions with unstable grids (X. Yin et al., 2021). In countries such as Uganda, fluctuating supply conditions and frequent feeder switching increase transformer stress and cause nuisance relay operations. Hence, adaptive relaying schemes that incorporate digital signal processing (DSP) and harmonic restraint algorithms are increasingly recommended to enhance protection reliability in medium-voltage (33 kV) systems (Okeke et al., 2024).

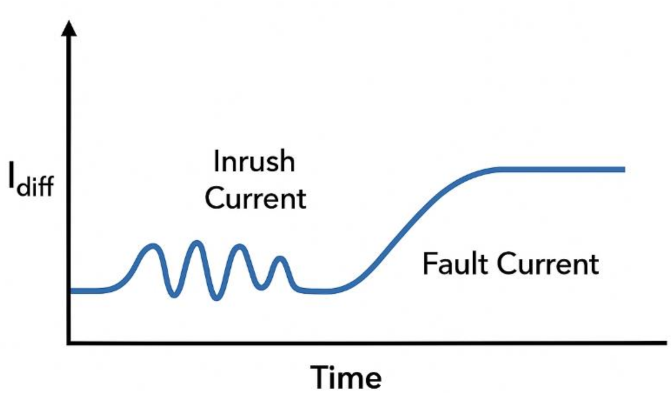

Figure 8. Inrush Current vs Fault Current Comparison (X. Yin et al., 2021)

Figure 8 illustrates the transient nature of inrush current compared to fault current. While fault current is steady and high, inrush current decays rapidly and exhibits harmonic components that can be filtered to prevent misoperation.

7. Review of Differential Relay Technologies

Differential relays are critical devices for protecting high-value electrical equipment such as transformers and generators against internal faults and short circuits. These relays operate by comparing currents entering and leaving the protected equipment; when the difference exceeds a predetermined threshold, the relay immediately trips the circuit breaker to isolate the equipment, preventing extensive damage (Bagheri et al., 2017). Importantly, differential relays do not respond to external faults, which allows them to provide fast and selective protection while avoiding unnecessary trips.

7.1 Evolution of Relay Technologies

The earliest differential relays were electromechanical, relying on magnetic torque to operate contacts when the current imbalance exceeded the set limit. They are simple and robust but have slow response times and limited logic capabilities (Tenbohlen et al., 2015). With the advancement of solid-state electronics, static relays replaced mechanical components with semiconductor circuits, offering improved accuracy and faster response, though their logic and programmability were limited.

In recent decades, numerical (microprocessor-based) relays have become the standard, especially for medium-voltage transformers (33 kV). These relays use digital signal processing (DSP) techniques to calculate differential currents and implement complex protection algorithms, including percentage bias, harmonic restraint, and adaptive trip settings (Alenezi et al., 2024). Microprocessor relays provide high reliability, remote monitoring, event recording, and integration with modern SCADA systems. Leading manufacturers for the African context include Siemens, ABB, and Schweitzer Engineering Laboratories (SEL), whose models are widely deployed in substations and distribution networks.

7.2 Working Principle and Types of Differential Relays

Differential relays operate by detecting the difference between two or more electrical quantities, typically currents or voltages, across the protected zone. There are three main types:

i. Current Differential Relays: Compare currents entering and leaving equipment; operate when internal fault currents are detected.

ii. Voltage Balance Differential Relays: Compare voltages on either side of the protected equipment; fault-induced voltage differences generate operating currents that trip the relay.

iii. Percentage/Biased Differential Relays: Incorporate a restraint coil to prevent tripping during external faults or transformer inrush conditions; the operating coil trips the relay only when the differential current exceeds the restraining force (R. Li et al., 2017).

All differential relay types aim to provide fast, sensitive, and selective protection as indicated in Table 4. While current differential relays are straightforward, voltage balance relays require precise CT matching, and percentage relays use biasing to enhance stability and minimize false tripping.

7.3 Advantages and Limitations

Differential relays provide critical protection for power transformers and generators, particularly for internal winding faults. Advantages include:

i. High accuracy due to precise analog-to-digital conversion in microprocessor relays.

ii. Fast response times, minimizing equipment damage.

iii. Compatibility with modern digital substation systems for monitoring and diagnostics.

Limitations:

i. CT mismatches, saturation, and cable capacitance can affect accuracy.

ii. Voltage balance relays are complex to construct.

iii. Protection is mostly limited to the defined protected zone (Bagheri et al., 2017; Saponara, Fanucci, Bernardo, & Falciani, 2016).

Differential relays are widely used to protect transformers, generators, busbars, and feeders. For example, Merz–Price relays are frequently applied to generator stator windings, while percentage-biased relays safeguard medium-voltage transformers against internal faults (Medeiros et al., 2015).

Table 4. Comparison of Relay Technologies

Relay Type	**Principle**	**Advantages**	**Limitations**
Electromechanical	Magnetic torque	Simple, robust	Slow response
Static	Solid-state circuits	More accurate	Limited logic
Numerical	DSP-based	Flexible, fast, programmable	Requires training, digital complexity

8. Review of Similar Works

Transformer differential protection has been extensively studied to enhance the reliability and sensitivity of protection schemes. Early research focused on traditional methods, while recent studies have introduced advanced techniques, including signal processing, machine learning, and hybrid models.

(Ali et al., 2018) proposed an improved transformer differential protection scheme based on the ratio of absolute current differences. The methodology involved developing a mathematical model that enhances sensitivity by comparing normalized current magnitudes rather than relying solely on conventional differential calculations. Simulation results demonstrated faster detection of internal faults with improved discrimination between fault and non-fault conditions. The study concluded that the method significantly enhances relay responsiveness and accuracy. However, it identified gaps related to performance under CT saturation and limited validation under complex real-world disturbances such as inrush currents and high-resistance faults.

(Yin, Lian, Buckheit, & Fan, 2021) applied convolutional neural networks (CNNs) for power system protection, focusing on improving fault classification accuracy. The methodology involved training deep learning models using fault data under various operating conditions. The findings showed that CNNs could effectively identify complex fault patterns and improve detection accuracy compared to traditional methods. The study concluded that machine learning offers a promising approach for modern protection systems. However, it highlighted challenges such as the need for large datasets, computational complexity, and limited real-time implementation in practical transformer protection systems.

(Simões et al., 2021) conducted a comprehensive review of transformer differential protection techniques. The methodology involved analyzing existing protection schemes, including conventional and advanced methods, to identify their strengths and weaknesses. The findings revealed that while modern techniques improve accuracy and speed, issues such as CT saturation, inrush current misinterpretation, and lack of adaptability persist. The study concluded that future research should focus on hybrid and adaptive protection systems. A key gap identified was the lack of practical implementation and validation in real power system environments.

(Moosavi, Damchi, & Assili, 2022) developed a differential protection method based on discrete energy separation algorithms. The methodology focused on signal processing techniques to separate fault-related energy components from inrush and noise signals. Simulation results showed improved sensitivity and better discrimination between internal faults and magnetizing inrush currents. The study concluded that the approach enhances protection reliability. However, it identified gaps in handling highly distorted signals and the need for validation under varying system conditions, including CT nonlinearities and network disturbances.

(Moravej, Ebrahimi, Pazoki, & Barati, 2023) introduced a time-domain differential protection scheme using Intrinsic Time-Scale Decomposition combined with an Ensemble of Bagged Trees algorithm. The methodology integrated signal decomposition with machine learning classification to improve fault detection accuracy. The findings demonstrated high reliability and adaptability under different fault scenarios. The study concluded that hybrid intelligent approaches significantly improve protection performance. However, it highlighted gaps related to computational complexity, implementation cost, and limited testing in real-time or hardware-based systems.

(Sayed & Abdelaziz, 2024) proposed the application of the Alpha Plane concept, traditionally used in transmission line protection, to transformer differential protection. The methodology involved adapting the alpha-plane characteristic to analyze current ratios and improve fault discrimination. Results showed enhanced accuracy in distinguishing internal faults from external disturbances. The study concluded that the method improves selectivity and stability. However, it identified gaps in integration with existing relay systems and the need for validation under varying transformer configurations and operating conditions.

(Kasztenny & Samineni, 2024) focused on improving the security of differential protection schemes against second-order harmonic distortion. The methodology examined harmonic restraint techniques and their effectiveness in preventing false tripping during magnetizing inrush conditions. The findings showed that enhanced harmonic filtering improves relay stability. The study concluded that harmonic-based methods remain essential in protection design. However, it identified limitations in cases where harmonic content is low or distorted, indicating the need for complementary detection techniques.

(Sayed, 2025) developed an artificial neural network (ANN)-based differential protection scheme for transformers. The methodology involved training the ANN to distinguish between internal faults and inrush currents using extracted signal features. Simulation results indicated high classification accuracy and reduced false tripping. The study concluded that ANN-based protection significantly improves reliability and adaptability. However, it highlighted gaps related to data dependency, training complexity, and challenges in real-time deployment in protection relays.

(Huang, Fang, Hsu, Yang, & Zhou, 2025) proposed an integrated protection approach combining percentage differential protection with scale-dependent intrinsic entropy for online fault diagnosis. The methodology utilized entropy-based signal analysis to enhance real-time monitoring and fault detection. The findings showed improved sensitivity and faster detection of faults under dynamic conditions. The study concluded that combining traditional and advanced analytical methods enhances protection performance. However, it identified gaps in computational efficiency and the need for validation in practical medium-voltage systems such as 33 kV networks.

(Obiora *et al.*, 2025) investigated transformer failure rates and reliability in medium-voltage networks. The methodology involved statistical analysis of transformer performance data to identify common failure causes. The findings revealed that internal faults, insulation failure, and protection system limitations significantly affect transformer reliability. The study concluded that improved protection schemes are essential for enhancing system performance. A key gap identified was the lack of advanced, adaptive protection systems specifically designed for medium-voltage transformers, particularly in developing regions.

These studies demonstrate a transition from conventional differential protection methods to advanced techniques incorporating signal processing and artificial intelligence. While improvements in sensitivity, accuracy, and fault discrimination have been achieved, persistent gaps remain in handling CT saturation, detecting low-level faults, managing inrush current variability, and validating methods in real-world 33 kV systems. Table 5 present the Summary of Reviewed Previous Related Literature

Table 5. The Summary of Reviewed Previous Related Literature

Authors	Title	Observations/Gaps
(Ali et al., 2018)	Power Transformer Differential Protection Using Current and Voltage Ratios	Proposed a ratios-based scheme for improved sensitivity. Lacked extensive field testing and consideration of CT saturation effects.
(Shah, Bhalja, & Patel, 2018)	A Novel Approach to Transformer Differential Protection Using Superimposed Differential Current	Proposed a method using superimposed differential current. Limited exploration of effectiveness in diverse fault scenarios.
(T. Yin et al., 2021)	Bridging Power System Protection Gaps	Applied convolutional neural networks. Limited focus on

	with Data-Driven Approaches	transformer-specific protection challenges.
(Simões et al., 2021)	Power Transformer Differential Protection Based on Support Vector Machines Combined with High-Frequency Features	Proposed a scheme using SVM and high-frequency features. Limited real-time application and testing.
(Moosavi et al., 2022)	A New Fast Method for Improvement of Power Transformer Differential Protection Based on Discrete Energy Separation Algorithm	Developed a method using discrete energy separation. Limited exploration of performance in diverse fault conditions.
(Moravej et al., 2023)	Time Domain Differential Protection Scheme Applied to Power Transformers	Introduced ITD and Ensemble of Bagged Trees. Lacked practical implementation and validation in operational settings.
(Liu & Jing, 2023)	Power System Relay Protection Based on Faster R-CNN Algorithm	Applied Faster R-CNN for relay protection. Limited focus on transformer-specific protection needs.
(Kasztenny & Samineni, 2024)	Differential Protection Enhancement for Power Transformer	Examined enhancement against second-order harmonics. Limited focus on practical implementation challenges.
(Sayed & Abdelaziz, 2024)	Transformer Differential Protection Using the Alpha Plane Concept	Enhanced transformer protection using Alpha Plane. Limited exploration of integration with existing protection schemes.
(Afsharisefat, Jannati, & Shams, 2024)	A Power Transformer Differential Protection Method Based on Signal Processing Methods	Introduced a signal processing-based method. Limited practical validation and consideration of system dynamics.
(Huang et al., 2025)	Improving the Protection of Step-Down Transformers by Utilizing Percentage Differential Protection and Scale-Dependent Intrinsic Entropy	Integrated percentage differential protection with scale-dependent intrinsic entropy. Limited consideration of CT saturation and fault resistance.
(Mishra & Singh, 2025)	A Review of Machine Learning Applications in Power System Protection	Reviewed ML applications in protection. Limited focus on transformer-specific protection challenges.

9. Research Gaps Identified

Although transformer differential protection has significantly advanced from conventional electromechanical relays to intelligent digital protection systems, several important research gaps remain unresolved. One major challenge is the poor handling of CT saturation under severe through-fault conditions. During external high-current faults, current transformers may saturate and distort secondary current waveforms, causing false differential current measurements. This can reduce relay stability and increase the risk of unnecessary tripping or delayed protection response. Existing compensation methods such as filtering and saturation correction algorithms still struggle under highly dynamic transient conditions.

Another critical gap is inrush current misclassification, particularly in low-harmonic cases. Conventional harmonic restraint techniques rely heavily on second harmonic detection to differentiate magnetizing inrush from internal faults. However, modern transformer core materials, residual flux effects, and switching conditions can produce inrush currents with reduced harmonic content, weakening the effectiveness of traditional discrimination methods. This increases the probability of relay misoperation.

Protection adaptability in weak and fluctuating medium-voltage grids also remains limited. In developing MV systems, renewable energy penetration, unstable loading, voltage fluctuations, and changing network impedance can alter transformer fault characteristics. Most conventional differential relays use fixed settings that cannot dynamically respond to such operating uncertainties.

Furthermore, AI-based protection methods face high computational complexity, requiring large datasets, significant memory, and processing capability. This limits practical implementation in embedded numerical relays. Many proposed intelligent schemes are also validated only through simulation, creating a lack of real-time, hardware-in-loop (HIL), FPGA, or field-level validation. Additional research is also limited for 33 kV distribution transformers in developing regions, despite their critical role in sub-transmission systems. Finally, there is weak integration between transformer condition monitoring and relay logic, preventing predictive and adaptive fault protection.

10. Future Research Directions

Future research in transformer differential protection should focus on creating faster, adaptive, and more intelligent systems capable of operating reliably in modern MV networks. One promising direction is the development of hybrid DSP (Digital Signal Processing) and Machine Learning-based relays. DSP techniques provide fast deterministic signal extraction, filtering, and harmonic analysis, while ML models can improve fault classification and transient discrimination. Combining both approaches can improve accuracy while maintaining practical relay speed.

Another important area is online adaptive percentage bias control. Traditional percentage differential relays operate with fixed restraint characteristics, which may not remain optimal under varying load conditions, CT behavior, or network disturbances. Adaptive bias adjustment can improve relay sensitivity while reducing false trips during abnormal but non-fault operating conditions.

The use of digital twin-based transformer protection is also emerging as a major research opportunity. A digital twin can create a virtual real-time model of transformer behavior, enabling fault prediction, performance monitoring, and proactive relay decision-making. This can significantly improve reliability and reduce unexpected failures.

In smart substations, IEC 61850-enabled communication systems can enhance interoperability between relays, sensors, breakers, and monitoring devices, enabling coordinated intelligent protection. Additionally, FPGA-based real-time relay implementation offers high-speed parallel processing suitable for AI and signal-processing algorithms. Future work should also examine wide-area coordinated transformer protection, especially in interconnected MV grids. Finally, designing low-cost intelligent relays for developing regions is essential to improve reliability in resource-limited 33 kV systems.

11. Conclusion

Transformer differential protection remains the most dominant and widely adopted protection method for detecting internal transformer faults due to its speed, selectivity, and reliability. By comparing currents entering and leaving transformer windings, differential protection can effectively identify internal abnormalities such as winding short circuits, phase-to-phase faults, insulation breakdown, and turn-to-turn failures. Its importance is particularly high in medium-voltage substations where transformer reliability directly affects power continuity and system stability.

Traditional protection methods such as electromechanical and static relays provided the foundation for transformer fault protection, but they often lacked flexibility, accuracy, and advanced transient analysis capability. The evolution toward numerical relays has significantly improved performance through digital signal processing, programmable settings, self-diagnostics, communication capability, and improved fault sensitivity. Numerical relays have demonstrated superior operation under varying load and fault conditions compared with conventional systems.

In recent years, AI-based methods, wavelet transforms, entropy analysis, and hybrid intelligent protection schemes have shown strong potential for improving discrimination between internal faults, CT saturation, magnetizing inrush current, overexcitation, and non-fault disturbances. These methods can improve protection accuracy and reduce false tripping. However, challenges such as computational burden, weak-grid adaptability, implementation cost, and limited field validation still restrict widespread adoption.

Overall, there is a strong need for adaptive, real-time, and cost-effective transformer differential protection systems specifically optimized for 33 kV medium-voltage transformers, particularly in smart grids and developing power networks where operating uncertainties, infrastructure limitations, and changing grid behavior require more intelligent and resilient protection solutions.

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