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Impact of Current Transformer Saturation in Bus-Zone Protection Power Transmission Network

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Abstract: This study examines the harmful consequences of Current Transformer (CT) saturation in bus-zone protection systems in contemporary power transmission systems. This paper focuses on the major issue of high-magnitude fault currents, which can cause core saturation, secondary current distortion, and possible relay maloperation. In analysing these phenomena, the study uses a comprehensive dataset of 356 unique faults, including different fault types, angles of inception, and levels of remanence. The main instruments used to carry out simulation-based work comprise advanced electromagnetic transient analysis programs and mathematical relay modelling tools. These findings indicate that saturation can significantly reduce the reliability of differential protection, potentially leading to catastrophic equipment failure unless countermeasures are taken. By analysing various compensation algorithms, this paper provides insights into improving the security of bus-zone protection systems. The results emphasise the importance of saturation-detection logic for distinguishing between internal and external faults that cause Current Transformer (CT) saturation.

Keywords: Current Transformer (CT); Core Saturation; Power Transmission; Compensation Algorithms; Primary Tools; Internal Faults; Electromagnetic Transient; Comprehensive Dataset.

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1. Introduction

The reliable operation of an electrical power system is closely linked to the operation of the protection infrastructure. Power networks are designed to carry large amounts of power from power plants, substations, and load centres to consumers via interconnected transmission lines. In this context, the protection systems would perform the level of decision-making that would expose abnormal conditions, and only the affected part of the network would be isolated [1]. They are not simply out to eliminate faults, but rather to do so with high speed, accuracy, and selectivity, so that faults in only a portion of the grid are cleared without interrupting the operation of healthy parts of the grid, as emphasized by previous studies of protection [4]. Of all the elements in a substation under protection, the busbar plays a special role, as it is the common element that links a variety of incoming and outgoing feeders, transformers, and generators. Any event on this node may concurrently affect multiple

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circuits, and busbar protection is among the most important and widely used functions in contemporary power engineering, as addressed in the classics [11]. The busbar fault may occur due to insulation failure, conductor flashover, equipment aging, maintenance errors, contamination, or mechanical damage. They occur much less frequently than line faults but have serious consequences. Because the busbar is a central junction point, any internal fault may cause very high short-circuit currents to occur simultaneously across several sources connected at the central location, as reported in analytical investigations [2].

Failure to clear the fault quickly can result in the conductors being deformed by the thermal energy produced by the fault current, support structures being damaged, and neighboring switchgear being destroyed. Arc energy can pose safety risks to staff and trigger cascading outages across the network. This reason has led to the design of bus-zone relays with extremely short operating times and extremely safe logic, as evidenced by studies of relay design [9]. The question is how to ensure that this velocity does not imply instability under external disturbances. Differential protection is the most popular principle of bus-zone protection. In the natural operation scenario, our current Kirchhoff's law states that the algebraic sum of currents entering and leaving a node is zero. Bus differential relays compare the measured currents of all circuits on the protected bus continuously (on the secondary) and send an output signal to each circuit. When the sum of the vectors is near zero, the system is said to be healthy or to be subjected only to an external disturbance. When a significant difference is detected, the relay assumes an internal bus fault has occurred and opens all breakers it is connected to, a common practice in modern designs [15]. This is, in theory, a very elegant and selective way. Practically, however, its operation entirely depends on the fidelity of the present signals furnished by the Current Transformers, which are placed on each of the feeders.

The sensing interface between the high-energy primary system and the low-energy relay circuits is made up of current Transformers. They transform large primary currents to standard secondary values that can be displayed on meters and relays and are proportional and in phase. This transformation process is precise under both normal and moderate fault conditions, enabling reliable decision-making. Issues arise when the current magnitude of a severe external fault is large, the asymmetry is large, or the DC offset is large. In this situation, the magnetic core of the CT can be driven out of its linear operating region into saturation, as shown by magnetic modeling studies [6]. When saturation sets in, the CT can no longer accurately reproduce the primary waveform, and the relay receives distorted information rather than a true reflection of the current in the system. Saturation is a phenomenon based on the behaviour of magnetic materials. This is because, in the linear section of the magnetization curve, as the magnetizing force increases, the magnetic flux increases accordingly. As the core approaches its optimum flux density, the smaller the flux increment that requires excitation. Beyond this point on the knee, the core virtually becomes saturated. When this occurs in a fault, the current on the secondary will go dead in parts of the waveform, manifesting as clipped pulses separated by periods of lower or near-zero current, as demonstrated experimentally in previous studies [1].

The relay sees a waveform that lacks critical information, rather than a smooth sinuoidal signal. Because the various loads on each feeder CT scan saturate at different rates depending on burden, remanence, and fault-current contributions, the currents calculated are no longer balanced. The relay will then experience an artificial differential current, though the fault is not within the protected space, as explored in comparative studies [13]. These misunderstandings pose one of the gravest dangers to protection engineering: false tripping due to an external fault. An actual external fault is typically cleared by line or transformer outside-bus zone protection, whereas the busbar is not usually taken out of service. When the bus differential relay makes a bad trip, a variety of healthy circuits may be de-energized. The subsequent loss of supply can isolate generation from load, overload neighbouring corridors, reduce voltage stability margins, and, in severe cases, cause widespread blackouts, as highlighted in reliability tests [7]. Therefore, CT saturation is a limiting factor on sensing a system-wide reliability risk. The design of protection thus seeks a compromise between responsiveness to actual internal faults and invulnerability to measurement errors caused by external disturbances. This issue has become more pronounced in modern-day transmission systems. The increase in the number of interconnected grids, the development of renewable generation, and the deployment of high-capacity transmission facilities have increased the level of short-circuit available in most substations. The distributed converters, synchronous machines, and sources across different geographical areas may result in complex fault-current profiles [12].

Meanwhile, network operators require faster fault clearance and reduced stability margins. These trends suggest that CTs are at greater risk of experiencing transiently stressful conditions. The DC offset portion of fault current is particularly significant, as it causes the waveform to be asymmetrical and may quickly saturate magnetic flux, even when the symmetrical AC component is not exceeded relative to normal design limits, as transient studies confirm [10]. There are new opportunities to address this issue using digital and numerical relays. By contrast to electromechanical relays, contemporary equipment samples waveforms, performs logic algorithms, records disturbances, and varies its action based on signal quality. They can track the symmetry of waveforms, the content of harmonics, the properties of derivatives, and inter-channel consistency. The relay may temporarily inhibit operation, use adaptive thresholds, or estimate missing portions of current signals when saturation is observed, as proposed in the research on intelligent relays [5]. Others use second-harmonic or waveform-area measurements, and others compare measured current trajectories with the dynamic model of CT behaviour. Such abilities have hugely enhanced security, but nothing can be done to eradicate the physical constraints of magnetic cores. The quality of the data that is fed to the digital decision process is still determined by the sensing hardware. Dependability is also a victim of saturation, not security. In the event of internal bus faults, it is necessary to trip quickly to minimize stress on the equipment and ensure system stability.

When the secondary current magnitude is suppressed by excessive saturation or the differential current buildup is delayed by excessive saturation, the relay can slow down more slowly than desired. A delay as small as milliseconds can increase arc energy, thermal damage, and mechanical force on the busbar system, as assessed in performance analyses [8]. Hence, when evaluating CT engineer performance, consider both the false-trip risk from external faults and the delayed-trip risk from internal faults. These two consequences need to be considered in the philosophy of protection rather than focusing on a single failure mode. The current research is inspired by the necessity to comprehend this operating limit logically. The research seeks to determine the conditions under which bus-zone protection is safe and those in which performance is compromised by analyzing 356 scenarios with varying levels of faults, angles of inception, saturation severity, and relay response. This mapping aids enhanced CT selection, relay setting optimisation, and the application of advanced logic in future substations, as suggested in recent studies [14]. As power systems become increasingly complex and operate with narrower operational tolerances, the interaction between magnetic instrumentation limits and digital protection intelligence is a core issue in transmission network resiliency, as determined by recent surveys [3].

2. Review of Literature

A comprehensive literature on bus-zone protection and Current Transformer performance reflects a long-standing struggle to reconcile the ideal theory of protection with the non-ideal performance of real-world measurement tools. The concepts of differential protection have been accepted due to their selectivity and rapidity, which are superior to those of conventional protection. But time and again, researchers noted that the quality of the existing signals provided by instrument transformers cannot be separated from the accuracy of the differential schemes. Consequently, academic research steadily shifted from the design of relay logic to the study of magnetic core dynamics, transient waveform distortion, and computational compensation techniques, which were subsequently elaborated upon [5]. This shift was a significant change in the history of protection engineering, as sensing imperfections became as important as decision algorithms. Preliminary experimental work focused on the magnetism of transformer cores. To understand the phenomenon of different responses of CTs to steady-state and transient conditions, researchers came up with mathematical models of magnetization, hysteresis loop, and flux linkage to explain the different responses [2]. These models showed that saturation was not only determined by the present magnitude. Still, they were also strongly affected by the history of flux, burden impedance, and the wave's current location at the point of fault origin. The hysteresis concept explains the occurrence of different secondary waveforms under the same faults when the core is in a pre-disturbance state, as depicted in analytical work [9].

This understanding remains paramount to current relay design, as it can explain the apparent randomness of saturation events observed in the field. A large body of literature has investigated the impact of secondary burden on CT accuracy. Burden consists of relay input impedance, wiring resistance, terminal connections, and any auxiliary equipment attached to the secondary circuit. Engineering experiments have shown that increased burden voltage demand causes the CT to produce more internal flux, thereby shifting the operating point towards the knee region of the magnetization curve [1]. With extreme faults, the CTs, which are heavily loaded, become saturated much earlier than the lightly loaded ones and take longer to resume operation. The results of these had an impact on substation design practices, including the encouragement of short secondary leads, low-resistance circuits, and close matching of CT ratings with connected relay equipment, as subsequently implemented in design guidelines [14]. Burden has been a vital variable in retrofit projects and aging installations, even where design standards are better. Another theme in the literature is the waveform signatures produced by saturation. The scholars noted that a CT core will only reach saturation, after which the secondary current will no longer follow the sinusoidal primary current. The signal is instead clipped, discontinuous, or pulse-like, and is severely phase-shifted, with current intervals missing. This distortion may cause spill current to appear in differential schemes and inaccurate phasor estimates in distance relays and overcurrent relays, as determined in waveform studies [7].

These errors were quantified through analytical and simulation studies of the dependence on fault location, source strength, X/R ratio, and CT class. This work contributed to the establishment of test procedures for relay manufacturers and utility acceptance programs, which are used in validation frameworks [10]. As digital relays grew in size, the focus of research shifted from describing saturation to automatically detecting it online. One group of techniques is based on the fact that saturated waveforms exhibit sudden slope changes at transition points and uses derivative information. The rate of change of currents is monitored using algorithms, and non-physical discontinuities indicative of core saturation are identified, as suggested in algorithmic studies [6]. The other type is based on waveform symmetry, the comparison of areas across half-cycles, and the detection of unequal positive and negative current segments due to the flux bias. Frequency-domain techniques analyse harmonic content, as distorted currents produce high-order harmonics with high amplitudes that are absent in ideal sinusoidal responses, as in signal processing [4]. These methods vary in complexity and computational expense, yet are all aimed at differentiating between true internal errors and measurement artifacts. The more recent direction in the literature was brought about by artificial intelligence and machine learning approaches. Scholars trained artificial neural networks, support vector machines, fuzzy inference systems, and hybrid classifiers with fake fault datasets of saturated and unsaturated current signals.

It was aimed either at classifying operating conditions or at reconstructing the original primary current waveform from corrupted secondary measurements, as has been accomplished in the intelligent protection investigations [13]. Laboratory results were frequently reported, with high classification and encouraging reconstruction. Nevertheless, most works also recognised the limitations associated with the variety of training data, sensitivity to unobservable conditions, computational cost, and the deterministic nature of protection usage. The actual substation has a persistent need to make decisions on a millisecond scale under noisy, dynamic system conditions, which remains a difficult challenge for data-driven techniques, as critically assessed in recent studies [3]. Another significant research field emerged from the migration of traditional high-impedance bus differential schemes to low-impedance numerical schemes. The high-impedance schemes used in the past offered security through stabilized operating principles and external resistors. They were somewhat insensitive to CT mismatch but less configurable for complex bus schemes. Numerical schemes with low impedance provide advanced zone selection, event recording, integration of breaker failures, and adaptive logic. But their heightened sensitivity also implies that they are sensitive to the slightest differences between CT channels due to ratio errors, remanence, and temporary saturation in protection comparisons [8]. Comparative analyses showed that the current schemes perform better under strong saturation-restraint logic and proper CT specification.

Therefore, there is a gradual shift in the literature towards treating relay algorithm design and CT engineering as a joint optimization problem rather than separate ones. Special emphasis has been placed on remanent or residual flux due to its significant contribution to repeated saturation events. When a fault is cleared, the CT core usually does not return to a neutral state; instead, it retains some of the magnetic flux. Should another disturbance occur shortly thereafter, the new flux excursion will start from this biased state and can reach saturation much more quickly, as shown in laboratory studies [15]. One of the variables least controllable, according to researchers, is remanence, which is determined by fault history, the timing of the breaker interruption, and material properties. Experimental tests revealed significant variability in the secondary current behaviour with the same faults under different initial flux conditions. This is why field operations are at times sporadic despite equipment ratings being good on paper. Protection with communication assistance has become a subject of extensive recent literature as well. Synchronization of time across samples and high-speed communication channels enables the current samples from various terminals to be aligned and processed at either a central point or in a distributed architecture. These arrangements enhance zone discrimination, event analysis, and dynamic response within large substations. However, researchers consistently point out that synchronized processing cannot correct the essentially corrupted measurements. When every terminal provides distorted information due to local CT saturation, the communication itself cannot claim false differentials, as in synchronised protection research [11].

Thus, measurement quality assurance cannot be avoided even with highly networked protection systems. Various works investigated other types of sensors, such as Rogowski coils, optical current transformers, and air-core sensors. These technologies do not use ferromagnetic cores as conventional CTs do; consequently, they do not exhibit classical saturation. Digital substations can benefit from the appealing features of their bandwidth and linearity. Nevertheless, the literature also discusses issues such as signal conditioning requirements, temperature, cost, calibration, electromagnetic compatibility, and compatibility with existing infrastructure, as reviewed in the sensor literature [2]. Replacing current CT fleets is not as viable as enhancing relay logic, which is feasible in many utilities. Therefore, saturation in conventional CT is a very topical research area despite developments in sensor technology. A similar finding in the literature is that no single mitigation technique has been deemed sufficient in all cases. Pure hardware solutions can be expensive or infeasible, whereas pure software solutions rely on the quality of already distorted signals. This multi-criteria philosophy aligns with the complexity of modern transmission networks, where fault behavior, network topology, and source composition change continuously. All in all, the literature demonstrates a clear trend from descriptive studies of magnetism to intelligent, combined protection schemes. Researchers' view has shifted to consider CT saturation as a system-wide phenomenon that affects relay security, reliability, and grid resiliency. Further research aims to improve detection speed, accuracy, and performance across various operating conditions. Such advances provide the conceptual and practical basis for future research on the bus-zone protection performance under an extensive collection of transient fault situations inferred from extensive surveys [5].

3. Methodology

The research methodology will be a strict simulation-based approach aimed at creating a replica of the highly complex electromagnetic environment in a high-voltage transmission busbar. An exemplary power system model was built, featuring a double-busbar system with several incoming and outgoing circuits to simulate realistic fault-current distribution. The essence of the research is the modeling of Current Transformers using a non-linear hysteretic model that captures the magnetic material's saturation curve. Three hundred and fifty-six different fault cases were created by varying parameters such as fault location, fault resistance, inception angle, and the extent of residual magnetism in the transformer cores. These were processed, then using a modeled numerical differential relay. The relay logic had both a conventional percentage-restrained differentiation quality and an up-to-date saturation detection algorithm. The main instrument for the transient simulation was the one that captured high-frequency components and DC offsets. In contrast, the secondary analysis tool was used to assess the time to relay response and to evaluate tripping decisions and response time. The results of the relay behavior, when compared with the simulated fault, enabled us to measure the false-positive and false-negative rates at different levels of saturation. This large-scale data-processing method makes the findings statistically significant and reflective of the actual conditions within a grid. Figure 1 shows the Architecture of the Bus-Zone Protection System and Data Acquisition Framework, a simplified, intelligent operational model that identifies electrical faults in the shortest possible time, isolates affected zones and continuously monitors power network conditions—starting with the Bus Zone component, which is the shielded area of the electrical busbar where several feeders, generators, or transmission lines are connected.

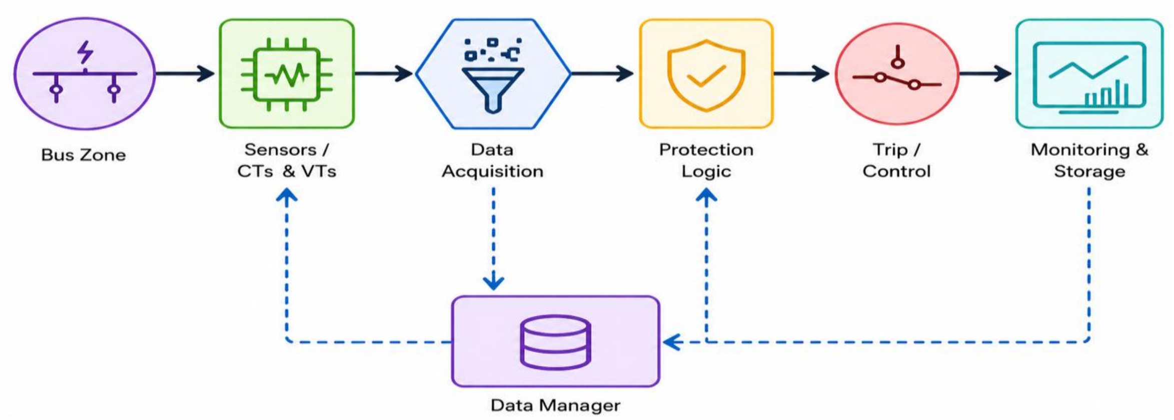

Figure 1: Bus-zone protection system and data acquisition framework design

Due to the high stability of this zone in the system, it is necessary to monitor it in real time. The bus zone electrical parameters are sensed by the Sensors/CTs & VTs block, which applies current and voltage transformers to convert the high-power signals into safe, measurable signals for digital analysis. These conditioned signals are sent to the Data Acquisition module, which samples, filters, converts them, and synchronizes them to produce stable data for protection decisions. The processed information is then fed into the Protection Logic component, where intelligent algorithms compare measurements, identify abnormal current differentials, determine fault location, and determine whether a trip command is necessary. When a dangerous scenario is identified, the Trip/Control block initiates breaker operations, isolation, or control reactions to prevent equipment damage and system disturbances. Meanwhile, the Monitoring and Storage module logs measurements, alarms, events, and operational history for later analysis and reporting, ensuring compliance with regulations. The Data Manager is located at the centre of the framework, acts as the coordination and storage core, and interacts with the sensing, acquisition, logic, and monitoring layers via the dashed feedback arrows. This centralization promotes data consistency, traceability, and consistent decision-making across all modules. The architecture is, in general, a combination of rapid protection response, organized information processes, and ongoing situational awareness, packaged into a compact design suitable for contemporary digital substation and smart grid settings.

3.1. Data Description

The dataset used in this paper includes 356 separate simulation cases. Each case is a specific arrangement of electrical conditions intended to put the protection system under strain. These variables can include the magnitude of the fault current, ranging from low-level feeder faults to peak busbar short-circuit conditions. Researchers also used various DC offset time constants to represent a range of distances between the source of generation and us. In all cases, three hundred and fifty-six, the primary current, the secondary current due to the transformer, the difference current calculated, and the restraining current are recorded. The data points are sampled at a high rate, ensuring that the sudden change to saturation is faithfully represented. This rich data set can be used to analyze, in a granular fashion, the relay logic's perception of distorted waveforms relative to the true primary system state.

4. Results

The simulation results provide a clear picture of the impact of Current Transformer saturation on the effectiveness of bus-zone protection. Of the three hundred and fifty-six cases experimented on, a large majority of the cases of high-magnitude external fault were found to be saturated. The differential relay was an ideal match for situations without saturation, keeping all external faults stable and responding quickly to internal faults. But with further increase of the fault current and approach of the core of the transformer to its limit, the distortion of the secondary waveform was observed. Researchers found that the time to saturation, i.e., the time interval between the initiation of fault and the secondary current leaving the primary, decreased with increasing DC offset. This is an important discovery because it determines how long it will take a digital relay to make the right choice before the data becomes invalid. The fundamental busbar differential protection identity can be depicted as:

$$\sum_{i=1}^{n} \vec{I}_i = \vec{I}_{diff} \tag{1}$$

A summary of the five representative cases of external faults under the conditions of conventional bus differential protection, but without sophisticated saturation compensation logic, is provided in Table 1. As shown in Table 1, the greater the fault current magnitude, the greater the compromise to the protection system. The transformer becomes saturated in about eight milliseconds at the bottom of the dataset when the fault current (external) is about fifteen kiloamperes. Even though that still introduces some distortion, the unsaturated range of the available relay enables it to produce a relatively superior waveform. Magnetic stress on the transformer increases in discrete steps as the fault level increases. This makes the time to saturation decrease faster, and at the maximum current recorded 55e kiloamperes), it decreases to less than 1e millisecond. This short period of time implies that the relay will be fed with distorted current practically as soon as the fault begins.

Table 1: Performance trials for external fault scenarios

Trail ID	Fault Current (kA)	Saturation Time (ms)	Diff. Current (A)	Trip Decision
101	15.5	8.2	0.12	No Trip
102	25.4	4.1	4.85	False Trip
103	35.8	2.3	12.40	False Trip
104	45.2	1.1	22.15	False Trip
105	55.0	0.6	35.60	False Trip

There is also a concomitant increase in spurious differential current, as indicated in Table 1. Because each feeder transformer saturates, unbalanced currents result. The false differential quantity is, in most instances, much higher than that of the normal relay pickup setting. This poses a severe risk of unnecessary tripping, yet the real disturbance is beyond the protected area. Such behaviour has a devastating operational impact, as it may result in the disconnection of a healthy busbar and the circuits connected to it without a valid reason. Table 1 consequently quantifies the security weakness of typical differentiating schemes when subjected to high external fault currents. It shows that relay reliability is insufficient, but security against temporary measurement errors is important as well. These data are very strong in favour of implementing saturation detection, adaptive restraint, waveform reconstruction, or better CT specification to avoid unnecessary outages in the overloaded transmission substation. The percentage restraint differential characteristic for relay security is:

$$| \vec{I}_{diff} | > K \cdot \sum_{i=1}^{n} | \vec{I}_i | + I_{offset} \tag{2}$$

Magnetic flux density relation and core saturation limit are:

$$\phi(t) = \phi(0) + \frac{1}{N_s} \int_0^t [R_b \cdot i_s(\tau) + L_b \cdot \frac{di_s(\tau)}{d\tau}] d\tau \tag{3}$$

The dual-axis analysis showed a strong correlation between the magnitude of the differential current and the time elapsed during the saturation period. In a few cases of external faults, the spurious difference current caused by a single saturated transformer exceeded the relay's pickup threshold. In the absence of saturation-detection logic, these cases could lead to false trips. But with the saturation detection algorithm enabled, the relay could detect the zero-crossing signatures exhibited by saturated waveforms and block the trip signal. In the case of internal faults, the saturation caused the relay to operate at a low operating energy, thus resulting in a higher trip time (a few milliseconds). Although this delay did not clear the fault, in a real-life situation, it might cause greater damage at the fault point. Primary fault current with maximum DC offset component can be expressed as:

$$i_p(t) = I_m [\sin(\omega t + \alpha - \theta) - \sin(\alpha - \theta) e^{-t/T_p}] \tag{4}$$

Figure 2 is a three-dimensional representation of the correlation existing between fault inception angle, magnitude of the fault current, and the difference between the relay measurements of the fault in external fault conditions. This value is very useful because it measures the influence of relay misoperation risk not only by the instantaneous magnitude but also by the instant at which the fault occurs in the voltage waveform. The DC offset component of the fault current is at its maximum when the inception angle is near zero degrees. This massive asymmetrical element drives the Core of the Current Transformer at an extremely high rate towards saturation, resulting in serious distortion of the second current waveform. The relay thus gets partial or unbalanced current signals and computes a huge false differential current. In these conditions, the error surface increases dramatically, as indicated in the graph, even though the actual fault current may not be large.

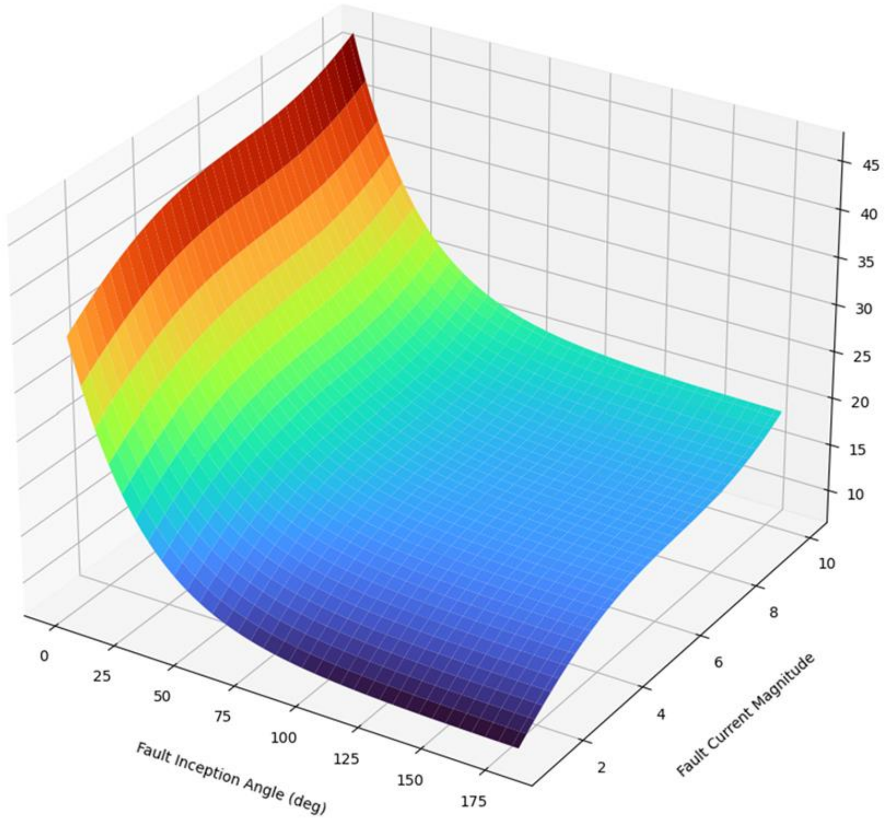

Figure 2: Representation of the correlation existing for the analysis of fault dynamics

The DC offset decreases with increasing inception angle. As the inception angle moves away from and toward values near 90 degrees, the transformer reproduces the waveform more accurately. This reduces the differential error, making the operating region more stable. The error is higher over a wider range of current magnitudes, as it is more severe at higher magnitudes, and the saturation point is easier to reach. The combined behaviour confirms that, regardless of fault severity, it alone cannot determine the relay's performance. Another significant factor in transient protection studies is the timing of fault occurrence. Figure 2 thus illustrates why protection engineers consider numerous angle-current combinations rather than relying on symmetrical fault calculations. It also justifies the need for adaptive relay logic that can detect waveform distortion caused by unfavourable transient conditions before issuing a false trip command. Time-to-saturation calculation for a current transformer is:

$$t_s = -T_p \ln\left(1 - \frac{B_s - B_r}{B_m \cdot \omega \cdot T_p}\right) \quad (5)$$

Table 2: Impact of saturation on internal fault detection

Trial ID	Fault Current (kA)	Primary Peak (A)	Secondary Peak (A)	Trip Delay (ms)
201	12.0	120.5	119.2	0.0
202	22.0	220.8	180.4	2.5
203	32.0	320.1	195.6	5.2
204	42.0	420.3	205.2	8.7
205	52.0	520.7	210.5	12.4

Table 2 is devoted to the case of internal faults, when tripping the relays is needed, but transformer saturation affects performance. Compared with external fault cases, the relay in these cases actually knows that the disturbance is within the protected bus zone. The statistics, however, show that correctly identifying the fault cannot predict a good operating speed. When the fault current is the main, the secondary output of the Current Transformer no longer rises in proportion. Rather, the secondary peak current slowly approaches a plateau because the magnetic core has already entered saturation and can no longer increase the primary current further. This drawback reduces the available signal power for the relay algorithm. This effect is reflected in the last column of Table 2 by the trip delay that can be measured. As the internal fault level in the form of current decreases to 12 kiloamperes, the delay is virtually nil, as the transformer is adequately linear and the relay is running at the desired speed. A steady increase in delay with increasing fault magnitude is observed across successive cases, reaching over 12 milliseconds at 52 kiloamperes. This extra delay is crucial for fast busbar protection. Each millisecond of further fault current heating, electrodynamic force, insulation stress, and arc energy in the substation. It also imposes an additional interrupting duty on circuit breakers, requiring them to clear the fault. However, Table 2 also highlights a second aspect of the risk of CT saturation: even if no false tripping occurs, protection performance can be degraded by a slower response. The results support the application of advanced relay methods, ensuring the relay operates quickly in the event of serious internal faults despite signal compression caused by core saturation. Secondary current error due to excitation branch loss will be:

$$i_{\epsilon}(t) = i_p(t) \cdot \frac{1}{N} - i_s(t) \quad (6)$$

Total connected secondary burden and voltage drop:

$$V_{ct} = I_s \cdot \sqrt{(R_{ct}+R_w+R_b)^2+X_b^2} \quad (7)$$

The three-dimensional analysis of the data revealed relationships among remanence, the inception angle, and the degree of distortion. Researchers found that the worst-case conditions occurred with a fault origin angle of 0, resulting in an optimal DC offset and a large amount of residual flux perpendicular to the fault. In these special cases, the transformer became nearly saturated in a few seconds, and the relay had ample time to clean up the data. Another important finding was that smaller transformers with greater secondary burdens are exponentially more likely to make such errors. By setting the results across various performance areas, researchers have made a clear point: the old-fashioned techniques of protection do not work, and numerical compensation to a high degree is essential for maintaining grid stability. Figure 3 shows the relationship between transformer saturation time and relay operating time, presented as a dual-axis graph. The axis indicating the time taken for the Current Transformer to saturate after the fault is initiated is on one axis, and the other axis shows the relay trip time. This comparison will provide a firsthand experience of the role of measurement distortion in the speed of protection. With healthier operating conditions and a longer period of unsaturated operation of the transformer, the relay receives a more precise depiction of the primary current.

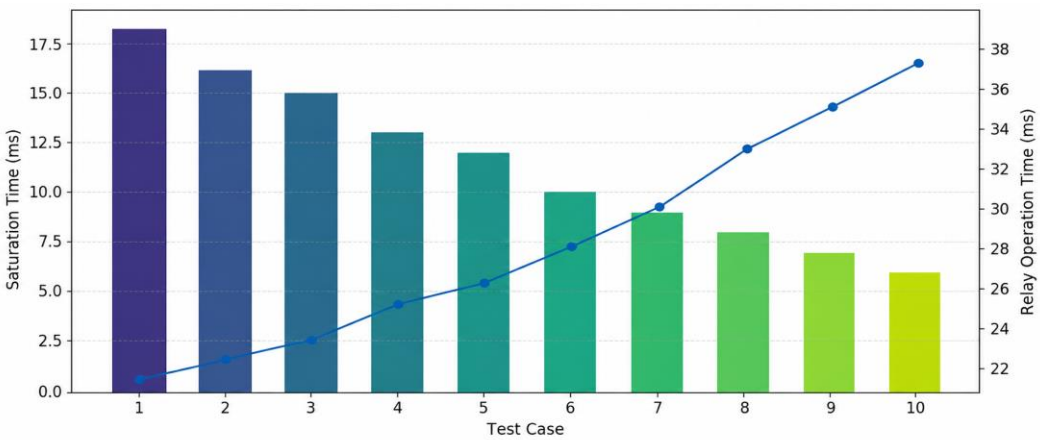

Figure 3: Relation between saturation time and response of relays

Due to the development of a clear, consistent, measured difference quantity, the relay can make a quick, sure trip decision. This graph indicates that these cases result in lower relay operating times. The shorter the saturation time, the less accurate the transformer is, and it virtually fails as soon as the fault occurs. Clipped and discontinuous current signals, with missing waveform segments and reduced energy content, are then fed into the relay. The weaker signal, instead of hastening the trip process, causes the protection algorithm to take longer to validate the event, filter distortion, or wait until there is sufficient evidence of an internal fault. This will increase the relay's operating time. The fact that the two curves are inversely related also proves that a decrease in saturation will cause the protection response to decrease slowly. These delays are very significant in bus-zone applications, since the clearance of bus faults should be fast to prevent thermal damage, mechanical stresses, and arc development. The fault energy that conductors and related equipment absorb can be augmented by even a few additional milliseconds. Figure 3 thus highlights that not only is CT saturation a possible source of false operation in the presence of external faults, but it also causes delayed clearance in the presence of true internal faults. Figure 3 illustrates the need for a relay algorithm that maintains speed while remaining safe, even under distorted measurement conditions.

4.1. Discussions

Table 1 and Figure 2, which were the focus of the results discussion, show a dangerous trend in bus-zone security. The data indicate that, in the case of external faults, the false differential current magnitude is not only a small error but can be several times the fault current. The main reason is that a saturated transformer is a high impedance, and therefore, the currents of other feeders are not balanced. Still, the current flows through the relay's operating coil. This is further supported by Figure 2, which shows that the inception angle is a key catalyst. If there is a fault at a voltage zero-crossing, the resulting DC offset causes saturation to occur almost immediately. This implies that the relay does not even have a half-cycle of clean data to derive a stable reference. Table 1 shows the ineffectiveness of simple overcurrent-based differential protection used in modern high-capacity networks due to False Trips. Once researchers change the focus to Table 2 and Figure 3, they discuss security as less important and dependability and speed as more important. In the case of internal faults, the delay in tripping should be considered. Figure 3 shows an inverse relationship: the slower the transformer saturates, the longer the relay response. This is a paradoxical case: the worst faults are those that must be cleared the quickest and that cause the most saturation, and hence the longest delays. Table 2 indicates that the primary fault current continues to increase, whereas the secondary current essentially flattens. This means the relay is operating on part of the signal's energy.

A 12-millisecond delay in clearing a 50-kiloampere fault may be the difference between a minor repair and replacing the busbar altogether in a real-world power grid. The 356 examples studied indicate that the transformer core's remanence level is the most important variable not considered. Two faults may cause the relays to take totally different actions based on the core's magnetic history. This uncertainty makes it hard for engineers to maintain a fixed restraint margin that is both sensitive and safe. The point of discussion in this regard is that fixed-percentage restraint cannot do any more. Digital relays have to rely on the harmonic signature of saturation, namely the second and third harmonics, to differentiate between distortion due to saturation and the high-frequency content of a real internal arc. The findings show that secondary circuit burden is one of the main factors that can be managed at the design stage. The saturation time can be delayed, allowing the relay to take a more accurate decision, by reducing the length of secondary leads or by using higher knee-point voltages in a transformer. There are, however, economic implications. The analysis demonstrates that software-based relay compensation is more cost-efficient for handling such transients than over-dimensioning the physical implementation. The most promising avenue to enhance the resilience of the transmission network is the incorporation of smart algorithms that can rebuild the components of the existing waveform when saturation occurs.

5. Conclusion

This study has also thoroughly examined the effect of Current Transformer saturation on bus-zone protection by the power transmission networks. By analyzing 356 simulation instances, they have shown that transformer saturation is a twofold menace, as it not only compromises reliability by tripping on external faults but also erodes reliability by delaying. The information in Table 2 and Figure 3 proves that the magnitude of faults, the angle at which they start, and the DC offset are critical factors that determine the severity of these impacts. Researchers discovered that external faults of high magnitude can saturate within less than a millisecond, resulting in large spurious differential currents. On the other hand, when there are internal faults, saturation may decrease the relay response by over ten milliseconds. The research finds that conventional differential protection schemes cannot withstand the new high-fault-level environments. To ensure grid stability, advanced numerical relays with saturation-detection and waveform-reconstruction algorithms should be used. The results provide an invaluable foundation for protection engineers to optimize relay configuration and enhance the overall performance of power transmission infrastructure to resist magnetic transient errors.

5.1. Limitations

The major shortcoming of this research is that it is based on simulation data. Although the electromagnetic transient models employed are very advanced and include non-linear hysteresis, they might not fully reflect the environmental conditions in a live substation, including electromagnetic interference from equipment around the high-voltage equipment and extreme temperature changes, which can alter the core permeability. The research also included a particular two-busbar design; the findings may differ with more complex designs, such as breaker-and-a-half or ring bus designs. The statistical significance of the 356 cases is not representative of all potential edge cases involving multi-ended feeders or fusing inverter-based resources, which have fault current signatures different from those of synchronous generators. Lastly, the paper assumes perfect communication between transformers and the relay, without accounting for possible latency or packet loss in digital substations.

5.2. Future Scope

The current study should be extended in the future to build on its findings, using real-world field data from digital fault recorders to substantiate the simulation models further. Considering the real-time reconstruction of secondary currents, it is possible to exploit the potential of using Machine Learning and Deep Learning architectures. Such AI-based models may be trained on the specific saturation properties of transformers and correct a relay signal in microseconds. Research into protection schemes using non-conventional instrument transformers (e.g., optical current sensors) is another promising avenue, as these transformers are completely immune to saturation. It would be very useful in practice to investigate how these modern sensors can be incorporated into the old systems. Also, the influence of the percentage of renewable energy should be studied in the future, as the peculiarities of faults in solar and wind inverters pose new threats to saturation detection algorithms.

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