

# An Enhanced Protection Scheme for Transformer Integrating Alpha Plane Analysis

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**Abstract** - This paper presents an enhanced protection scheme for transformers using the alpha-plane method to improve the reliability of differential protection. A three-phase transformer model is developed to analyse both steady-state full-load operation and transient energization conditions. Particular focus is given to magnetizing inrush current, which occurs during transformer energization due to core saturation and residual flux. Conventional differential protection schemes often fail to distinguish between inrush current and internal faults, leading to incorrect tripping. The proposed alpha-plane technique addresses this limitation by comparing differential and restraint currents in a two-dimensional plane, enabling clear discrimination between fault and non-fault conditions. The method is evaluated under various operating scenarios, including normal operation, inrush conditions, and internal faults. Simulation results demonstrate that the alpha-plane approach effectively prevents false tripping while maintaining high sensitivity to actual faults. This improves both the security and dependability of transformer protection systems. The study confirms that the integration of alpha-plane analysis enhances overall protection performance and ensures reliable operation of power transformers under both steady-state and transient conditions.

**Key Words:** Transformer Protection, Alpha-Plane Method, Differential Protection, Magnetizing Inrush Current, Internal Fault Detection, Power Transformer, Protection Reliability, Transient Conditions

## 1. INTRODUCTION

Transformers play a crucial role in electrical power systems by facilitating the transfer of electrical energy between networks operating at different voltage levels. Due to their high cost and importance, reliable protection of transformers against faults is essential to ensure continuous and stable power system operation. Transformer faults such as internal winding faults, ground faults, and turn-to-turn faults can lead to severe damage if not detected and isolated quickly.

The most commonly used protection technique is percentage differential (PD) protection, which compares the currents entering and leaving the transformer. Although PD

protection is widely used, it faces several challenges such as incorrect operation during current transformer (CT) saturation, difficulty in detecting high-resistance faults, and inability to clearly distinguish between magnetizing inrush currents and internal faults. These limitations can lead to maloperation or failure in fault detection.

To overcome these issues, advanced protection techniques have been developed. One such method is alpha plane (AP) analysis, which represents the relationship between transformer currents in the complex plane. By analyzing the complex ratio of currents, the AP method provides improved discrimination between normal operating conditions, internal faults, and external faults. This approach enhances both the sensitivity and stability of transformer protection systems.

In this work, an enhanced transformer protection scheme is proposed by integrating alpha plane analysis with differential protection principles. Unlike conventional approaches that rely on MATLAB/SIMULINK, the proposed method is implemented using Python. The use of Python offers flexibility in numerical computation, efficient data handling, and powerful visualization capabilities through libraries such as NumPy and Matplotlib.

The proposed system models transformer behaviour under various operating and fault conditions, including internal faults, external faults, and CT saturation. The alpha-plane characteristics are analyzed to identify fault conditions accurately. This approach provides a cost-effective and open-source alternative for transformer protection studies while maintaining high accuracy and reliability.

## 2. LITERATURE REVIEW

Many researchers have proposed different techniques for transformer protection to improve reliability and fault detection accuracy. The conventional Percentage Differential (PD) protection method is widely used in power systems due to its simplicity and effectiveness in detecting internal faults. However, this method faces several challenges such as difficulty in distinguishing between inrush current and

internal faults, and maloperation during current transformer (CT) saturation under external fault conditions.

To overcome these issues, advanced methods like Artificial Neural Networks (ANN), Fuzzy Logic, and Discrete Wavelet Transform (DWT) have been introduced. These techniques improve fault classification and help in separating inrush and fault currents more accurately. Some studies also use voltage and current signals together for better fault detection. Although these methods enhance performance, they increase system complexity and require more computational effort. Recently, the Alpha Plane (AP) concept has been applied in transmission line protection due to its ability to represent current relationships in a complex plane and improve fault detection sensitivity. However, its application in transformer protection is still limited. Therefore, this paper proposes an enhanced transformer protection scheme using the Alpha Plane approach integrated with differential protection. This method aims to improve sensitivity, reduce the impact of CT saturation, and provide more reliable operation compared to existing techniques.

### 3. PROPOSED METHODOLOGY

The proposed methodology enhances transformer protection by integrating the alpha plane (AP) concept with conventional differential protection techniques. Traditional percentage differential protection faces challenges such as misoperation during current transformer (CT) saturation and reduced sensitivity to high-resistance faults. To overcome these limitations, the alpha plane approach is used, which analyzes the relationship between transformer currents in the complex plane to accurately distinguish between normal and fault conditions.

In this method, the transformer currents from different windings are first measured and converted into per-unit values by considering CT ratios and transformer parameters. These currents are then used to calculate differential and restraint currents. The differential and restraint components are further transformed into two equivalent currents, and their complex ratio is computed. This ratio is plotted on the alpha plane, where predefined operating and restraint regions help in identifying the system condition.

During normal operation and external faults, the complex ratio remains within the restraint region, ensuring system stability. In contrast, during internal faults, the ratio shifts to the operating region, triggering a trip signal. The entire methodology is implemented using Python, where numerical computations and visualization are performed efficiently. The proposed approach improves fault detection accuracy, enhances stability during CT saturation, and provides a reliable solution for transformer protection.

### 4. MATHEMATICAL MODELING

The mathematical modelling of the proposed transformer protection scheme is based on the relationship between current magnitude and phase angle, represented as  $M(\theta)$ . These equations are used to characterize different transformer operating and fault conditions. By analyzing the variation of current magnitude with respect to phase angle, the protection system can effectively distinguish between inrush current and internal fault conditions.

The inrush current condition is modelled using a nonlinear expression given by:

$$M(\theta)=960(1-e^{-1.95\theta})+480e^{-1.95\theta}\sin(2.85\theta-1.35) \quad (1)$$

This equation represents the transient behaviour of magnetizing inrush current, where the exponential term models the rise in current and the sinusoidal term captures the oscillatory nature of the waveform during transformer energization.

For internal fault conditions, different mathematical models are derived based on fault type. The single line-to-ground (SLG) fault is expressed as:

$$M(\theta)=200+600e^{-13.6(1.571-\theta)} \quad (2)$$

The double line-to-ground (LLG) fault is given by:

$$M(\theta)=120+480e^{-15.1(1.571-\theta)} \quad (3)$$

The three line-to-line-to-ground (LLLG) fault is represented as:

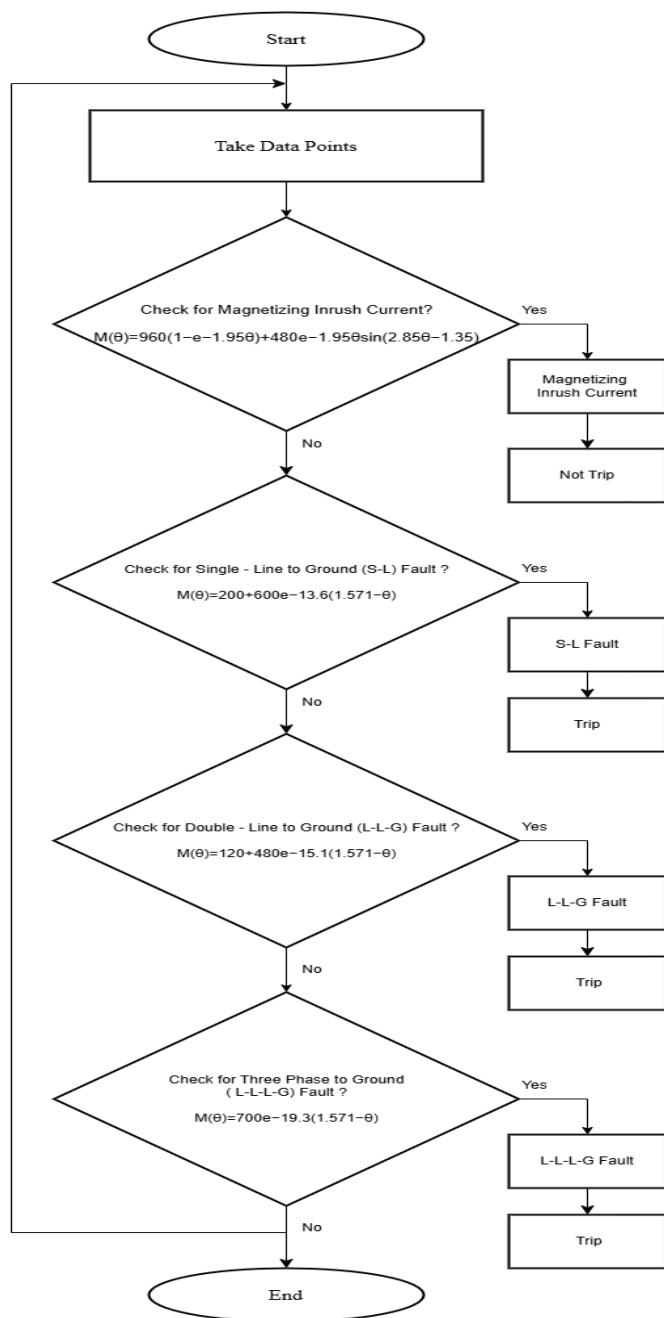
$$M(\theta)=700e^{-19.3(1.571-\theta)} \quad (4)$$

These equations describe the exponential variation of current magnitude under different fault conditions. Each fault type exhibits a unique response, enabling accurate classification and detection within the proposed protection scheme.

### 5. FLOW CHART

The mathematical modelling of the proposed transformer protection scheme is based on the relationship between current magnitude and phase angle, represented as  $M(\theta)$ . The flowchart of the proposed transformer protection scheme illustrates the sequential decision-making process used for fault identification based on the computed current magnitude function  $M(\theta)$ .

The process begins by collecting current data points from the transformer under different operating conditions. These data points are used to compute the magnitude function  $M(\theta)$ , which represents the variation of current with respect to phase angle.



Flowchart of Fault Detection and Decision-Making Process

Initially, the algorithm checks for the presence of magnetizing inrush current using the predefined nonlinear equation. If the computed  $M(\theta)$  satisfies the inrush condition, the system identifies it as a non-fault condition and blocks the tripping signal to ensure stability. If the condition is not satisfied, the algorithm proceeds to evaluate fault conditions in a step-by-step manner.

The next stage involves checking for different types of internal faults using their respective mathematical models. The algorithm first evaluates the Single Line-to-Ground (SLG) fault condition. If the calculated response matches the SLG characteristics, a trip signal is generated. If not, the system proceeds to check for Double Line-to-Ground (LLG) fault, followed by Three Line-to-Ground (LLL) fault. Each fault condition is identified based on the corresponding exponential behavior of  $M(\theta)$ .

If none of the fault conditions are satisfied, the system concludes that the transformer is operating under normal conditions and no trip signal is issued. Thus, the proposed algorithm ensures accurate classification of inrush and fault conditions while avoiding false tripping. The flowchart clearly represents this sequential decision-making process, enabling efficient implementation in Python.

### 6. IMPLEMENTATION USING PYTHON

The proposed transformer protection scheme is implemented using Python to simulate various operating and fault conditions and to visualize their behavior effectively. The implementation utilizes NumPy for numerical computations and Matplotlib for generating graphical representations. A helper function is defined to create uniform polar plots with proper axis orientation, grid structure, and formatting, ensuring consistency across all figures. The transformer current behavior is modeled mathematically by generating a time vector and computing current magnitude and phase angle using exponential, sinusoidal, and piecewise functions. This approach enables accurate simulation of magnetizing inrush and different fault conditions without requiring real-time hardware data.

The computed current values are plotted using polar coordinates, where the phase angle is represented along the angular axis and current magnitude along the radial axis. Distinct colors, markers, and labels are used to differentiate between pre-fault, fault, and steady-state conditions. Additionally, a two-slope percentage differential relay characteristic is plotted to analyze the tripping behavior under different operating conditions. The implementation clearly demonstrates the variation in current trajectories for inrush and fault conditions, thereby validating the effectiveness of the proposed protection scheme.

### 7. RESULTS AND DISCUSSION

The obtained results demonstrate the effectiveness of the proposed transformer protection scheme under different operating and fault conditions. The polar plots generated using Python provide a clear visualization of current magnitude variation with respect to phase angle  $\theta$ . These plots help in distinguishing between magnetizing inrush current and various fault conditions such as SLG, LLG, and LLLG faults.

### 7.1 Transformer Magnetizing Inrush

The polar plot represents the transient magnetizing inrush current during transformer energization. The red point indicates the starting instant of energization, while the trajectory shows the variation of current magnitude with phase angle. The steady-state point represents the magnetizing reactance. It can be observed that the current initially starts from a low value and gradually rises with oscillatory behavior before reaching steady state. This characteristic confirms that inrush current is a non-fault condition and should not result in tripping

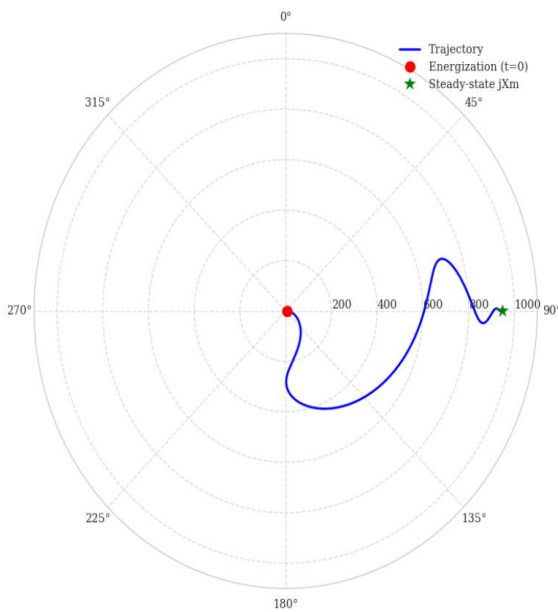


Fig. 1. Polar plot of transformer magnetizing inrush current

### 7.2 Light Load to Single Line-to-Ground Fault

This plot shows the transition from light-load operation to a single line-to-ground fault. The initial point represents normal operating condition, while the trajectory shifts toward the fault point after fault occurrence. A significant change in magnitude is observed, indicating the presence of a fault. The distinct variation in radial position helps in identifying the SLG fault condition.

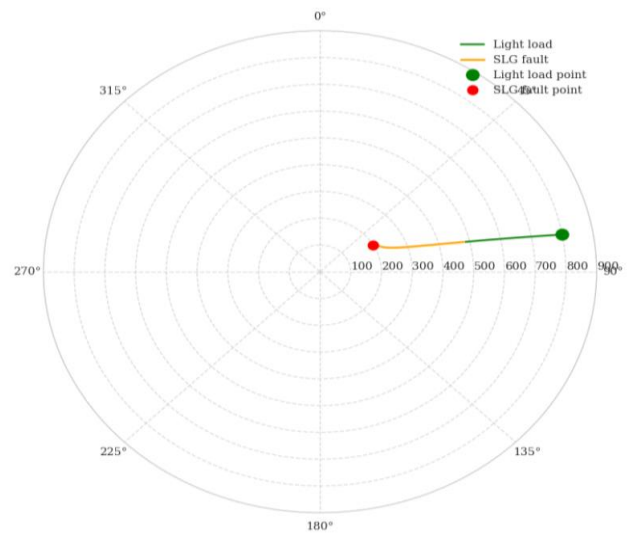


Fig. 2. Polar plot of transition from light load to SLG fault

### 7.3 Double Line-to-Ground Fault

The plot illustrates the transition from pre-fault condition to a double line-to-ground fault. Compared to SLG fault, the magnitude reduction is more pronounced, and the trajectory shows a sharper deviation. The fault point is clearly distinguishable from the normal operating point, enabling accurate detection of LLG faults.

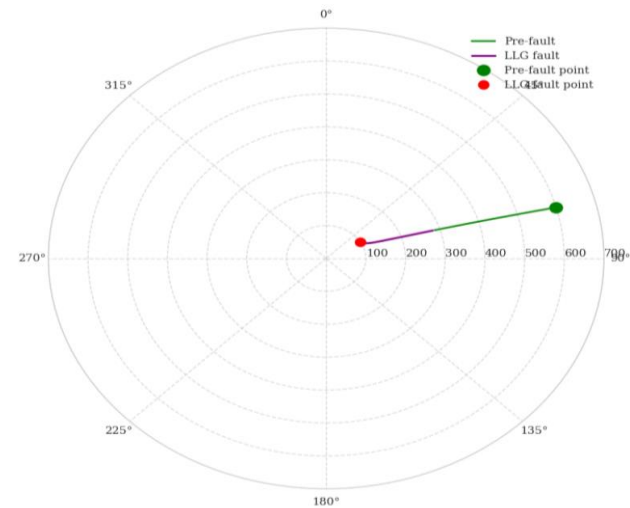


Fig. 3. Polar plot of double line-to-ground fault

### 7.4 Three-Phase-to-Ground Fault

This plot represents the most severe fault condition. The trajectory moves rapidly toward the origin, indicating a drastic reduction in current magnitude. This behavior signifies a strong internal fault condition, which requires immediate tripping. The clear separation between pre-fault and fault points ensures reliable fault identification.

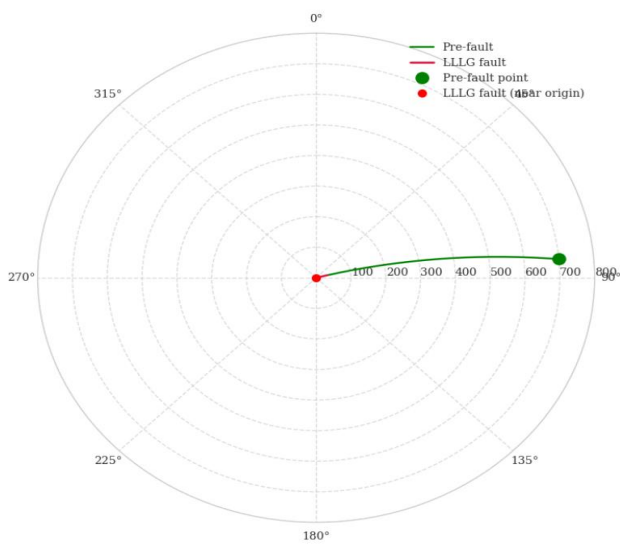


Fig. 4. Polar plot of three-phase-to-ground fault

### 7.5 Discussion

From the obtained results, it is evident that each operating condition produces a unique polar trajectory. The magnetizing inrush current exhibits a gradual oscillatory pattern, whereas fault conditions show sharp and distinct changes in magnitude and direction. Among the faults, the severity increases from SLG to LLG and is highest in LLLG fault, as observed from the magnitude variation. These differences enable accurate classification of transformer conditions and reduce the chances of false tripping. Thus, the proposed method demonstrates improved reliability and effectiveness in transformer protection.

## 8. COMPARISON AND ADVANTAGES

A comparison between the conventional Percentage Differential (PD) protection method and the proposed Alpha Plane-based protection implemented using Python is presented to evaluate the effectiveness of the proposed approach.

### 8.1 Comparison with Existing Method

Parameter	Conventional PD Method	Proposed Alpha Plane + Python Method
Accuracy	Moderate accuracy; affected by CT errors and operating conditions	High accuracy due to complex plane analysis and distinct trajectory patterns
Speed	Slower response due to reliance on threshold comparison	Faster detection through direct pattern recognition of current characteristics

Fault Detection Capability	Limited in detecting high-resistance and minor faults	Improved detection of SLG, LLG, and LLLG faults with clear distinction
Inrush Discrimination	Difficulty in distinguishing inrush from internal faults	Effective separation using characteristic trajectory behavior
Stability	Susceptible to misoperation during abnormal conditions	More stable due to clear operating and restraint region separation
Cost	Requires licensed software (e.g., MATLAB)	Cost-effective using open-source Python tools

### 8.2 Advantages of Proposed Method

The proposed Alpha Plane-based transformer protection scheme offers several advantages over conventional methods:

**8.2.1 Improved Accuracy** The proposed method utilizes current magnitude trajectories in the polar plane, which allows precise differentiation between normal and fault conditions. This reduces the chances of misclassification and improves overall protection accuracy.

**8.2.2 Faster Response** The method identifies faults based on pattern variation in current characteristics rather than relying only on threshold comparison, enabling faster detection and quicker relay operation.

**8.2.3 Enhanced Fault Detection Capability** The proposed approach effectively detects various fault types such as Single Line-to-Ground (SLG), Double Line-to-Ground (LLG), and Three Line-to-Ground (LLLG) faults with clear distinction between each condition.

**8.2.4 Reliable Inrush Discrimination** The method accurately distinguishes magnetizing inrush current from internal faults by analyzing its unique oscillatory behavior, thereby preventing unnecessary tripping.

**8.2.5 Improved Stability** The system remains stable during normal operating conditions and avoids false operation, as the trajectories for non-fault conditions remain clearly separated from fault regions.

**8.2.6 Robust Performance** The proposed method performs consistently under different operating conditions, ensuring reliable transformer protection even under varying system scenarios.

**8.2.7 Clear Visualization** The use of polar plots provides a clear graphical representation of current behavior, making it

easier to analyze and understand different operating and fault conditions.

**8.2.8 Cost-Effective Implementation** The use of Python as an open-source tool eliminates the need for expensive licensed software, making the proposed method economical and accessible for practical applications.

## 9. CONCLUSION

In this work, an enhanced transformer protection scheme based on alpha plane analysis has been presented and implemented using Python. The proposed method overcomes the limitations of conventional percentage differential protection by utilizing current magnitude characteristics to accurately distinguish between normal operating conditions and various fault types. The mathematical modeling of inrush current, SLG, LLG, and LLLG faults enables clear identification of each condition based on its unique trajectory behavior.

The Python-based implementation successfully simulates transformer current behavior and generates polar plots that provide intuitive visualization of different operating scenarios. The results demonstrate that magnetizing inrush current can be effectively differentiated from internal faults, thereby preventing false tripping. Additionally, the proposed method shows improved capability in detecting different fault conditions with higher accuracy and faster response.

Overall, the proposed alpha plane-based protection scheme offers a reliable, efficient, and cost-effective solution for transformer protection. The use of Python further enhances flexibility and accessibility, making the approach suitable for modern power system applications and future research developments.

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