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Improvement of Power System Stability using Optimized Digital Relay Coordination

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Abstract- The increasing complexity of power systems, particularly in developing nations, necessitates the development of robust and adaptable relay coordination strategies. Traditional relay coordination methods, relying on manual adjustments and time-current settings, are often inadequate for addressing dynamic conditions in modern networks. This leads to prolonged fault clearance times and increased risk of cascading outages. This research uses a genetic algorithm (GA) based approach to optimize digital relay coordination for the 3x15MVA, 33/11kV M2 injection substation in Jabi, Nigeria. The study involves modelling the substation and its key components within MATLAB/Simulink, enabling a simulated environment to test and refine the GA-optimized relay configurations under diverse fault conditions. A multi-objective optimization framework is used to improve fault detection speed, system stability, and relay selectivity. The GA-optimized coordination strategy is anticipated to yield faster fault clearance times and enhanced relay selectivity, establishing a foundation for scalable and adaptable relay protection systems. The results demonstrate a notable improvement in power system stability, with the fitness value decreasing from 0.0615 to 0.0565 over 10 generations. This research advances digital relay coordination practices, offering a valuable tool for bolstering power system resilience in evolving, renewable-integrated grids. The methodology implemented significantly enhances the reliability and efficiency of power grids by minimizing fault clearance times and reducing the risk of cascading failures. The findings of this study can be applied to similar substations in Nigeria and other regions facing reliability challenges. By leveraging GA-based optimization, this research provides a promising solution for improving power system stability and reliability.

Indexed Terms— Coordination, Fault, Genetic Algorithm (GA), Inductor (L), Relay, Stability.

I. INTRODUCTION

The electric power system is a complex network of interconnected components designed to generate, transmit, and distribute electrical energy to consumers. Nigeria, like many developing countries, faces numerous challenges in its power sector that hinder its ability to provide reliable and stable electricity to meet the growing demands of its population [1]. The Nigerian power system has been plagued by frequent outages, voltage fluctuations, and system instabilities, which have significant economic and social impacts on the nation [2].

Power system stability is a critical aspect of electrical network operation, encompassing the ability of the system to maintain synchronous operation and recover from various disturbances [3]. The stability of a power system is intrinsically linked to its protection schemes, which play a crucial role in detecting and isolating faults to prevent widespread blackouts and equipment damage. Recent years have witnessed a growing interest in leveraging advanced digital technologies to enhance the performance of protection systems and improve overall power system stability [4].

Digital relays have emerged as a cornerstone of modern power system protection, offering superior functionality, flexibility, and reliability compared to their electromechanical predecessors [5]. These intelligent electronic devices are capable of performing complex calculations, adapting to changing system conditions, and communicating with other devices in the network. However, the effective utilization of digital relays requires careful coordination to ensure optimal performance and avoid undesired operations that could compromise system stability [6].

The coordination of protection devices in a power system is a multifaceted problem that involves balancing competing objectives such as sensitivity, selectivity, and speed of operation [7]. Traditional approaches to relay coordination often rely on time-consuming manual calculations and trial-and-error methods, which may not yield optimal results, especially in large and complex networks. The advent of computational intelligence techniques has opened new avenues for addressing this challenge, with genetic algorithms (GA) emerging as a particularly promising approach for optimizing relay settings [8].
The application of advanced optimization techniques for relay coordination represents a significant opportunity to enhance system stability and reliability in power sectors worldwide. The 3x15MVA, 33/11kV M2 injection substation in Jabi, which serves as the case study for this research, is a critical node in the power distribution network of the Federal Capital Territory. By focusing on this substation, the study aims to demonstrate the potential benefits of optimized digital relay coordination in a real-world setting, with implications for similar installations across the country [9].

The use of MATLAB/Simulink for power system modelling and simulation has gained widespread acceptance in both academic and industrial circles due to its versatility and powerful analytical capabilities [10]. This software environment provides a robust platform for implementing complex optimization algorithms, such as genetic algorithms, and evaluating their performance in the context of power system stability enhancement. By leveraging these computational tools, researchers can explore a wide range of scenarios and develop innovative solutions to longstanding challenges in power system protection [11]. The optimization of digital relay coordination using genetic algorithms offers several advantages over traditional methods. GAs are capable of efficiently exploring large solution spaces, handling non-linear constraints, and finding near-optimal solutions to complex multi-objective problems [12]. For power system protection, these characteristics make GAs well-suited for determining relay settings that simultaneously satisfy multiple performance criteria, such as minimizing fault clearing times, ensuring proper backup protection, and avoiding unnecessary tripping [13].

As nations continue to invest in modernizing their power infrastructure, the integration of advanced protection schemes and optimization techniques becomes increasingly important. The findings from this research have the potential to contribute significantly to the ongoing efforts to improve the reliability and stability of power grids. By demonstrating the effectiveness of optimized digital relay coordination in enhancing system performance, this study may inform future policy decisions and investment strategies in the power sector [14]. Furthermore, the focus on simulation-based analysis in this research aligns with the growing trend towards digital twinning in power system engineering. This approach allows for comprehensive evaluation of different scenarios and strategies without the risks and costs associated with physical implementation, providing valuable insights that can guide future practical deployments [15]. The methodology developed in this study could serve as a template for similar investigations across various substations and network configurations globally

II. LITERATURE REVIEW

Power System Stability Theory

Power system stability is the ability of an electrical power network to return to a state of equilibrium following a disturbance, while maintaining continuous synchronisation between generation and load [16]. Stability is crucial for the seamless functioning of a power system, as disturbances such as faults, load changes, or generator failures can cause fluctuations that jeopardise the entire system’s performance [17]. The theory of power system stability categorises disturbances into three main types: rotor angle stability, frequency stability, and voltage stability, each addressing different aspects of system behaviour under stress.

Rotor angle stability pertains to the synchronisation between synchronous machines after a disturbance, and it reflects the ability of these machines to maintain steady relative positions. A disturbance could result in a loss of synchronism, leading to instability. Voltage stability, on the other hand, refers to a power system's capacity to maintain acceptable voltage levels following a disturbance. Voltage collapse can occur when the system is unable to sustain voltage levels, leading to widespread blackouts [18]. Lastly, frequency stability involves maintaining a constant system frequency, which is particularly crucial in grids with high penetration of renewable energy sources, where power generation can fluctuate unpredictably [19]. Figure 2.1 illustrates the relationship between the different aspects of power system stability.

The complexity of modern power grids, especially in countries like Nigeria, exacerbates the challenges associated with maintaining stability [20]. Factors such as aging infrastructure, high demand growth, and integration of distributed energy resources (DERs) complicate the system's stability. In particular, the growing penetration of renewable energy sources, such as solar and wind, which are inherently intermittent, poses new challenges for grid stability [21]. The need for real-time monitoring and rapid response mechanisms has become more critical than ever in maintaining a reliable power system.

Recent advancements in smart grid technologies, including IoT-enabled devices and advanced communication protocols, have facilitated real-time data collection and improved situational awareness [22]. These advancements have led to the integration of computational intelligence techniques in power system stability analysis and enhancement. By leveraging these technologies, operators can better predict and mitigate instabilities, thus improving the overall reliability of the grid.

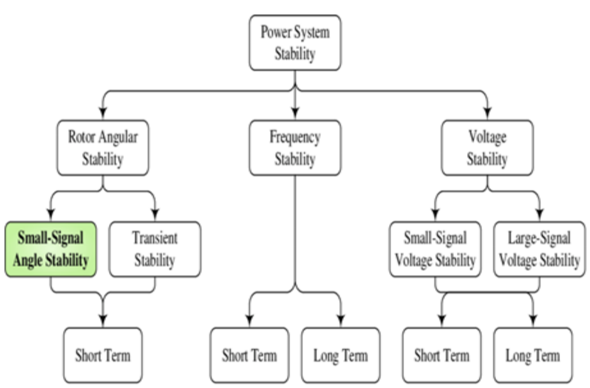

Figure 2.1: Diagram illustrating different aspects of power system stability [23]

Digital Protection Systems

Digital protection systems have revolutionised the way power systems are protected, offering significant advantages over conventional electromechanical relays. These systems, also known as Intelligent Electronic Devices (IEDs), integrate computational capabilities and advanced algorithms to detect faults more accurately and react faster to disturbances [24]. With the transition from analogue to digital technologies, the protective relay systems have evolved to handle more complex network configurations, allowing for better adaptability and scalability in modern power grids [25].

The core principle behind digital protection systems is the use of microprocessors to perform fault detection, measurement, and control. These systems can monitor multiple parameters in real time, including voltage, current, and frequency, providing faster response times compared to traditional methods [26]. Digital relays, which form the backbone of these systems, are capable of communicating with other devices across the network, thus enabling a coordinated protection strategy. This ability to exchange information is crucial in large, complex networks where multiple relays must work together to isolate faults effectively without causing widespread outages [27].

One of the key features of digital protection systems is their ability to adapt to changing system conditions. Unlike electromechanical relays, which are fixed in their settings, digital relays can dynamically adjust their thresholds based on real-time data, ensuring optimal protection under varying load and fault conditions [28]. This adaptability is especially important in grids with high renewable energy penetration, where power flows can change rapidly and unpredictably [29].

The integration of digital protection systems with communication networks enables the implementation of wide-area protection schemes, which offer a more comprehensive approach to system protection. These schemes utilise data from across the grid to detect and isolate faults more effectively, minimizing the risk of cascading failures [30]. However, the increased reliance on digital communication also introduces vulnerabilities, such as cyber security threats, that need to be addressed to ensure the resilience of protection systems [31].

Genetic Algorithms in Optimization

Genetic Algorithms (GAs) have emerged as a robust optimization tool in power system engineering, particularly for solving complex multi-objective problems. Originating from the theory of natural selection and genetics, GAs mimic biological evolution to explore vast solution spaces efficiently. The basic principle of GAs involves the generation of a population of potential solutions, with each solution evaluated for its fitness to solve the problem at hand [32]. Over successive generations, the population evolves, with better-performing solutions being selected for reproduction, while poor solutions are discarded. This process leads to the discovery of optimal or near-optimal solutions.

In power systems, GAs are particularly useful for solving non-linear, multi-variable optimization problems, such as relay coordination, economic dispatch, and load flow analysis [33]. Their ability to handle large search spaces and complex constraints makes them well-suited for applications in grid optimization. Unlike traditional optimization methods, which may get trapped in local optima, GAs are capable of exploring global solutions by using crossover and mutation operators to introduce diversity into the population [34].

The application of GAs in digital relay coordination has gained significant attention in recent years. Traditional relay coordination techniques often require extensive trial-and-error processes, which can be time-consuming and may not yield the most effective settings [35]. GAs, however, can automate this process, exploring a vast range of potential settings and identifying the optimal solution in a fraction of the time. Moreover, GAs can handle multiple conflicting objectives, such as minimizing fault clearing time while maximizing selectivity, making them ideal for multi-objective relay coordination [36].

Another advantage of GAs is their flexibility. They can be easily combined with other optimization techniques, such as Particle Swarm Optimization (PSO) or Simulated Annealing (SA), to enhance their performance [37]. For example, hybrid GA-PSO models have been developed to further improve the efficiency of relay coordination in complex power systems. Figure 2.2 depicts the workflow of a typical genetic algorithm, highlighting the key processes of selection, crossover, and mutation.

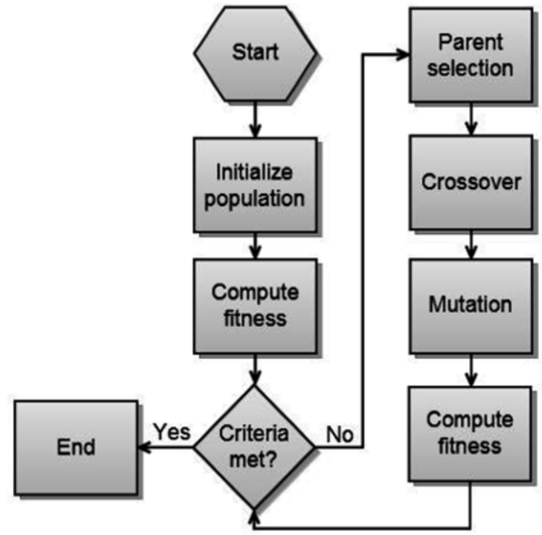

Figure 2.2: Workflow of a Genetic Algorithm applied in power system optimization [38].

Digital Relay Coordination Principles

Digital relay coordination is a critical component of power system protection, aimed at ensuring that protective relays operate in a coordinated manner to isolate faults while minimizing disruptions to the wider network. Coordination refers to the correct sequencing of relay operations such that the relay closest to the fault operates first, followed by other relays if necessary [39]. In digital systems, relay coordination can be significantly enhanced by utilizing advanced optimization techniques and real-time data processing capabilities.

The principles of relay coordination are centred around the concepts of selectivity, sensitivity, and speed. Selectivity ensures that only the faulty section of the network is isolated, while sensitivity refers to the relay's ability to detect faults under various operating conditions [40]. Speed is crucial for minimizing the impact of faults, as faster fault clearance reduces the risk of damage to equipment and enhances system stability.

In digital relay systems, coordination is typically achieved through time grading or current grading methods. Time grading involves setting relays to operate at different time intervals based on their proximity to the fault, ensuring that the relay closest to the fault operates first. Current grading, on the other hand, involves setting relays to operate based on the magnitude of the fault current, with higher fault currents triggering relays faster [41]. These principles are further enhanced by the digital relays' ability to communicate with each other, allowing for more precise coordination across the network [42].

Genetic algorithms have become a popular method for optimizing digital relay coordination due to their ability to solve the multi-objective optimization problems inherent in relay settings [43]. By simultaneously optimizing multiple parameters, GAs can ensure that relay settings provide the best balance between sensitivity, selectivity, and speed. This optimized coordination reduces the risk of unnecessary tripping and ensures that backup protection is available in case the primary relay fails. Figure 234 shows a typical circuit for digital relays in a protection system.

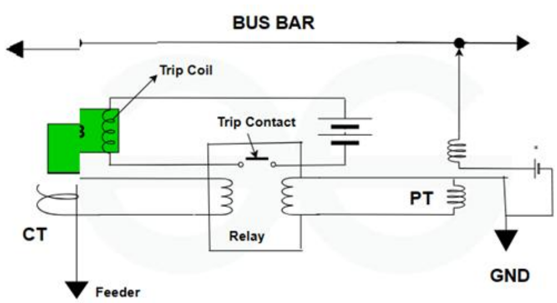

Figure 2.3: Coordination curve showing the operation of a Digital Relay in a multi-stage protection system [41]

Power System Stability

Types of Power System Stability

Power system stability can be broadly classified into three main categories: rotor angle stability, voltage stability, and frequency stability. Each of these types addresses different aspects of system performance and response to disturbances, ensuring the system can maintain continuous operation under various conditions.

i. Rotor angle stability: Refers to the ability of synchronous machines within the power system to maintain synchronization after a disturbance [17]. This type of stability is crucial in preventing generators from falling out of step with each other, which could lead to large-scale outages. Rotor angle stability can be further divided into two sub-categories: transient stability and small-signal stability. Transient stability focuses on the system's response to severe, sudden disturbances, such as short circuits or faults, while small-signal stability concerns the system's ability to handle minor fluctuations in load or generation.
ii. Voltage stability: The ability of a power system to maintain acceptable voltage levels during and after disturbances [18]. Voltage collapse, a primary concern in this type of stability, occurs when the system cannot sustain voltages, leading to widespread blackouts. Voltage stability is influenced by both reactive power supply and load demand, with long-term voltage stability issues often stemming from the slow dynamics of equipment like transformers and generators.
iii. Frequency stability: This addresses the system's capacity to maintain a stable frequency after imbalances between generation and load occur [19]. It is particularly important in systems that integrate high levels of renewable energy, as fluctuations in generation can rapidly alter system frequency. Maintaining a constant frequency ensures that generators operate synchronously, preventing equipment damage and large-scale grid disruptions.

Each of these types of stability plays a critical role in maintaining the overall reliability and security of the power system. Figure 2.4 provides a visual representation of the different types of power system stability and their key characteristics.

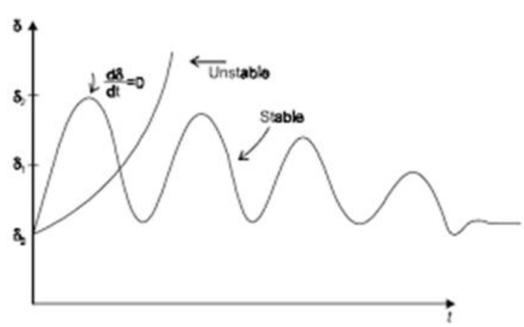

Figure 2.4: A visual representation of the three main types of power system stability [44]

Factors Affecting Power System Stability

Several factors can affect the stability of a power system, ranging from network configuration and operational conditions to external influences such as weather or regulatory changes. Understanding these factors is crucial for assessing the system's stability and implementing strategies to mitigate potential risks. One of the primary factors is system loading. As load demand increases, especially during peak periods, the system can experience reduced margins of stability. High loading conditions can lead to voltage dips and reduced reactive power reserves, making the system more susceptible to voltage instability [15]. In regions like Nigeria, where demand often exceeds supply, the risk of instability due to excessive loading is a major concern.

Generation mix and distribution also play a crucial role in system stability. A balanced generation mix between traditional thermal plants and renewable energy sources ensures better grid stability [16]. However, increasing the share of intermittent renewable energy sources like wind and solar introduces volatility, particularly in frequency stability, due to their fluctuating nature.

Another significant factor is network topology, which includes the configuration and interconnections of transmission lines. Well-interconnected networks with redundancy and looped configurations provide better stability compared to radial networks, where disturbances can more easily propagate throughout the system [17]. Nigeria's grid, which has limited redundancy, is particularly vulnerable to these types of instabilities.

External influences such as extreme weather conditions (e.g., storms, high winds, and lightning strikes) can also significantly impact system stability. These events can cause physical damage to transmission lines or power plants, triggering instability in the form of voltage collapse or generator tripping [21]. Additionally, regulatory frameworks and policies concerning grid operation and expansion can either mitigate or exacerbate stability issues, depending on how effectively they are implemented.

Digital Protection Systems in Power Networks

Evolution of Protection Systems

The evolution of protection systems in power networks has undergone significant transformations, particularly with the shift from electromechanical relays to digital protection systems. Historically, electromechanical relays, introduced in the early 20th century, were widely used for power system protection. These devices operated based on mechanical movements driven by electromagnetic forces. While they were reliable for many decades, their limitations became apparent as power systems grew in complexity and scale. Electromechanical relays often required frequent maintenance, had slower response times, and lacked flexibility for adapting to new grid configurations [26].

The development of solid-state relays in the mid-20th century marked the first step towards modernization. Solid-state relays eliminated the need for moving parts and offered greater reliability and speed compared to their electromechanical counterparts. However, these devices were still limited by their fixed logic and inability to handle the complex and dynamic nature of modern power networks [24].

The real transformation came with the advent of microprocessor-based digital relays in the 1980s. These digital protection systems introduced advanced computational capabilities that allowed for more sophisticated fault detection and analysis. Digital relays could monitor multiple electrical parameters, such as voltage, current, and frequency, and perform complex calculations to detect faults more accurately [50]. With the integration of digital technologies, protection systems became more adaptable, faster, and capable of communicating with other devices within the power network. Figure 2.5 illustrates the timeline of the evolution of protection systems, highlighting key technological advancements.

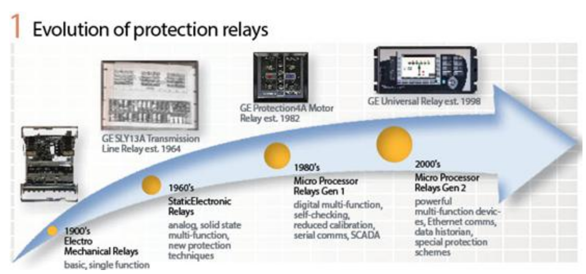

Figure 2.5: Evolution of protection systems from electromechanical to digital relays.

Digital Relay Technology

Digital relay technology is the backbone of modern power system protection. Unlike traditional relays, which operate based on mechanical or analogue processes, digital relays use microprocessors to perform real-time monitoring and protection functions. The transition to digital relays has enabled utilities to enhance the reliability, accuracy, and flexibility of their protection schemes [45].

Digital relays consist of several key components: sensors that measure electrical parameters (such as current, voltage, and frequency), analogue-to-digital converters (ADCs) that transform these measurements into digital signals, and microprocessors that process the data using algorithms to detect faults. These microprocessors can execute complex logic operations, enabling the relay to make decisions based on multiple criteria [51]. In addition, digital relays are programmable, allowing engineers to customize protection settings based on the specific requirements of the network.

One of the main advantages of digital relays is their ability to perform multiple functions simultaneously. For example, a single digital relay can handle overcurrent, undervoltage, frequency, and differential protection, whereas traditional relays would require separate devices for each function. This multi-functionality reduces the need for numerous hardware components, simplifies maintenance, and lowers overall system costs [29].

Another critical feature of digital relays is their ability to store and process event data. In the event of a fault or disturbance, digital relays record detailed information about the incident, such as fault currents, voltages, and time stamps. This data can be used for post-event analysis to improve future fault detection and prevention strategies. Figure 2.6 illustrates the internal architecture of a typical digital relay, showing the flow of data from sensors to the microprocessor.

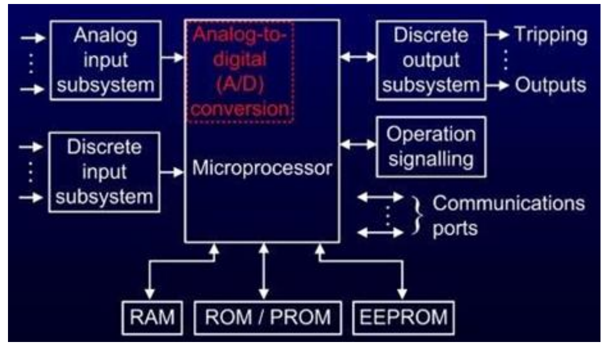

Figure 2.6: Internal architecture of a digital relay showing the data flow from sensors to the microprocessor [45]

Communication Protocols and Integration

The integration of digital relays into modern power networks requires robust communication protocols to ensure interoperability and effective data exchange between devices. Communication protocols standardize how data is transmitted between devices, ensuring that digital relays can work together to protect the grid and maintain stability [35].

One of the most widely used communication standards in digital protection systems is IEC 61850, which was developed by the International Electro technical Commission to enable seamless communication between intelligent electronic devices (IEDs) in substations. IEC 61850 supports both real-time communication for protection functions and non-real-time communication for monitoring and control tasks [30]. This standard has been instrumental in enabling the automation of substations, where relays, circuit breakers, and other devices communicate with each other to coordinate protection actions.

DNP3 (Distributed Network Protocol) is another common communication protocol used in digital protection systems, particularly in North America. DNP3 was designed to enable reliable communication between remote devices and control centres over long distances. It provides features such as time-stamped data, event reporting, and secure communication, making it suitable for critical infrastructure applications [41].

The integration of digital relays into a smart grid infrastructure requires the use of these communication protocols to ensure that data flows smoothly between various components of the network. By enabling digital relays to communicate with other devices, utilities can implement advanced protection schemes, such as wide-area monitoring and control, which enhance the overall resilience of the power system [31].

Figure 2.7 illustrates the communication architecture of a digital relay system, showing how data is transmitted between relays, substations, and control centres using IEC 61850.

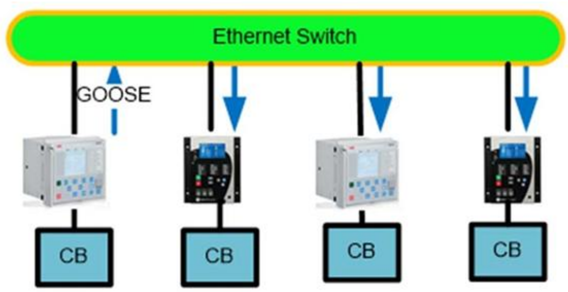

Figure 2.7: Communication architecture of a digital relay system using IEC 61850 [31].

Relay Coordination Techniques

Traditional Coordination Methods

Traditional relay coordination has played a foundational role in safeguarding power distribution networks, especially in radial distribution systems. Techniques like time-overcurrent relay coordination are predominant, based on relay time settings along the network that delay progressively depending on fault location, ensuring the fault is isolated closest to the source without impacting unaffected areas. This approach relies on fixed time-current settings [47], which limits adaptability in interconnected networks or configurations with distributed generation (DG), as coordination issues arise from variable power flows introduced by DG sources [48].

A significant limitation of traditional methods is the need for manual, sequential coordination of relays, which fails under bidirectional flow conditions and can delay fault clearing times [49]. Moreover, high levels of fault current in meshed networks add to the challenges. Studies suggest that incorporating advanced computational adjustments in relay timing could reduce the overall response time significantly, yet such adaptations are generally out of reach in purely traditional setups [50]. Consequently, despite traditional coordination's effectiveness in static environments, it proves inadequate in dynamic and distributed setups where fast, adaptive response is required.

Modern Coordination Approaches

Advancements in digital relay technologies have paved the way for modern coordination methods that integrate algorithms and adaptive relaying to achieve quicker, more accurate fault isolation. Computational techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and newer methods like the Water Cycle Algorithm [51] have shown remarkable improvements in relay coordination speed and accuracy. These methods allow dynamic adjustments, considering variables like load changes, DG integration, and fault intensity. Moreover, adaptive relaying enables continuous adjustments based on real-time data from the grid, a critical improvement over the static nature of traditional systems.

In DG-integrated networks, adaptive algorithms manage fault currents more effectively and reduce the likelihood of unintentional relay tripping. Hybrid algorithms, combining heuristic and metaheuristic methods, demonstrate optimized relay performance in simulated studies across various network conditions, achieving faster relay coordination without compromising fault isolation [52]. These adaptations are key to integrating distributed resources while maintaining the stability of the grid's overall protection schema.

Coordination Constraints and Challenges

Relay coordination in modern power networks faces challenges related to increased fault current levels, varying load conditions, and network topology complexities. Systems with DG and interconnected structures often require additional considerations, such as selective isolation without compromising stability. With traditional coordination, fluctuating fault current levels and bidirectional flows hinder reliable operation [53]. These challenges necessitate approaches that account for dynamic operating states and adjust automatically to avoid cascading failures or grid instability.

Additionally, communication delays and cyber-security in smart grids pose operational risks. Real-time fault information is critical, especially in complex networks where fault isolation depends on automated relay coordination adjustments [54]. As distributed energy sources grow, adaptive methods become essential, but achieving optimal relay settings across varied scenarios demands robust coordination systems and failsafe mechanisms for backup during disruptions.

Impact of Distributed Generation on Relay Coordination

The rise of DG, particularly renewable energy sources, presents new demands on relay coordination. With bidirectional current flows and fluctuating output levels, traditional relay settings may result in increased fault response times and frequent miscoordination. Studies reveal that DG integration changes fault current profiles, affecting relay selectivity and causing nuisance tripping unless adaptive relaying is applied. Adaptive coordination methods based on real-time data adjust relay settings as needed, reducing fault isolation time and enhancing system resilience.

Incorporating machine-learning techniques into relay coordination enables predictive adjustments, improving protection while minimizing unnecessary relay activations. Further research suggests that hybrid coordination methods combining heuristic and analytical models offer promising results in stability under fluctuating DG conditions, reducing the coordination complexity of traditional relay systems.

Performance Metrics and Evaluation Criteria

Evaluating the performance of optimization methods in power system protection involves metrics such as reliability indices, fault clearance time, and operational efficiency. Reliable assessment of these methods depends on a set of well-defined criteria, including fault detection accuracy, relay speed, and selectivity measures. Recently, metrics such as resilience and adaptiveness have become increasingly relevant, given the rise of distributed energy resources that necessitate more robust and flexible protection systems. These metrics are vital in benchmarking the effectiveness of optimization algorithms across various load and fault conditions.

IV. RESEARCH METHODOLOGY

This research will adopt a quantitative, simulation-based methodology to optimise digital relay coordination at the 3x15MVA, 33/11kV M2 injection substation in Jabi. The research design will incorporate both empirical analysis and computational simulation approaches, structured in multiple phases to achieve the research objectives.

The methodology follows a systematic approach comprising three main components: mathematical modelling, simulation-based analysis, and genetic algorithm optimization. This design enables comprehensive investigation of relay coordination strategies whilst considering various operational scenarios and fault conditions.

The empirical component involves collecting and analysing actual system parameters from the Jabi substation, including transformer specifications, protection settings, and historical fault data. These empirical data inform the development of accurate simulation models and provide validation benchmarks for the proposed optimization strategy.

Steps used to harness raw data using Matlab:

Data Import and Cleaning

1. Import raw fault data from the substation into MATLAB using readtable or importdata.
2. Clean the data by removing any missing or duplicate values using ismissing and unique.
3. Convert data types as necessary (e.g., datetime, numeric).

Data Preprocessing

1. Filter out irrelevant data (e.g., normal operating conditions) using logical indexing.
2. Normalize or scale the data using normalize or mapminmax to improve analysis.
3. Apply any necessary transformations (e.g., Fourier transform)

Fault Detection and Feature Extraction

1. Use signal processing techniques (e.g., wavelet analysis, wavedec to detect faults.
2. Extract relevant features from the fault data (e.g., amplitude, frequency, duration) using findpeaks or mean.

3. Store the extracted features in a matrix or table for further analysis.

Data Analysis and Visualization

1. Use statistical methods (e.g., mean, std to analyze the fault data.
2. Visualize the data using plots (e.g., plot, histogram to identify trends and patterns.
3. Apply clustering or classification algorithms (e.g., kmeans, fitcsvm to categorize faults.

Results and Interpretation

1. Interpret the results of the analysis and visualization.
2. Identify trends, patterns, and correlations in the fault data.
3. Draw conclusions about the fault behavior and recommend actions for improvement.

This sequence provides a general framework for treating raw fault data from an injection substation using MATLAB. The specific steps and techniques used may vary depending on the nature of the data and the goals of the analysis.The simulation component utilises MATLAB/Simulink to create detailed models of the power system and protection schemes. This approach allows for thorough testing of relay coordination strategies without risking the operational stability of the actual substation. The simulation environment enables the examination of various fault scenarios and system conditions that might be impractical or unsafe to test in the real system.

3.1 SIMULINK MODEL

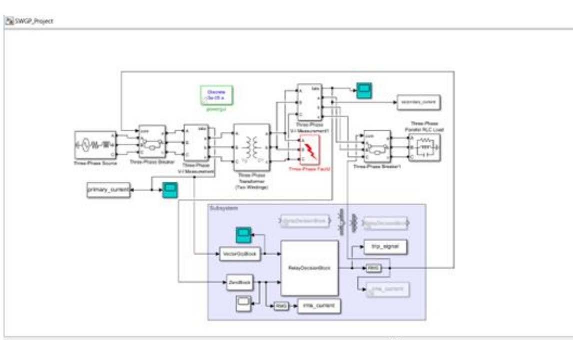

Figure 3.1: Simulink model for the proposed methodology

The Simulink model depicted is a power system simulation designed to analysed and optimize stability and reliability, likely focusing on fault detection and protection. Here's a breakdown of the model with respect to power system stability and reliability:

The Simulink model is designed to simulate a power system with a focus on fault detection, protection, and optimization using a GA. It supports stability by enabling faster fault clearance and transient analysis, though persistent oscillations indicate room for improvement in damping. Reliability is enhanced through effective relaying and monitoring, reducing equipment stress and outage risks. Further optimization of the GA parameters or relay settings could address remaining stability issues, ensuring a more robust and reliable system.

Model Components and Functionality

Three-Phase Source and Breaker

The model starts with a Three-Phase Source feeding into a Three-Phase Breaker. This represents the power input and a controllable switch to simulate fault conditions or normal operation. The breaker can isolate faults, which is critical for maintaining stability by preventing fault propagation.

Three-Phase V-I Measurement

This block measures voltage and current on the primary side, providing data (e.g., `primary current`) to monitor system behaviour. Accurate measurement is essential for detecting instability (e.g., oscillations) and ensuring reliable operation by triggering appropriate responses

Three-Phase Transformer (Two Windings)

The transformer steps voltage up or down between primary and secondary sides. Stability is affected by transformer performance during faults, while reliability depends on its ability to handle current surges without failure.

Three-Phase Fault

This block simulates a fault (e.g., short circuit) on the secondary side, introducing disturbances that test stability. The fault's impact on currents (seen in earlier figures) can lead to instability if not cleared prompt

Three-Phase Parallel RLC Load
The load represents the system's demand. Stability depends on the load's interaction with the source and transformer, while reliability hinges on the load's ability to operate without excessive current draw.

Subsystem
Contains advanced processing, including the `Vector Grp Block` and `Relay Decision Block`. The subsystem likely computes RMS values and makes tripping decisions based on current thresholds, enhancing reliability by isolating faults and supporting stability by minimizing disturbance duration.

Discrete Powergui
Configured with a 5e-05 s step size, this block handles discrete simulation of power electronics, ensuring accurate modelling of dynamic responses critical for stability analysis.

Impact on Power System Stability
1. Fault Detection and Clearance: The `Relay Decision Block` and `trip signal` output indicate a protection scheme that detects faults (e.g., via RMS current thresholds) and triggers the breaker to isolate them. Faster fault clearance, as seen with the 8% improvement in earlier figures, reduces the risk of instability (e.g., voltage collapse or loss of synchronism) by limiting disturbance duration.
2. Current Oscillations: The model captures primary and secondary currents (e.g., `primary_current`, `secondary_current`), which showed high oscillations in prior figures. Stability depends on damping these transients, and the GA optimization (Figure 1) suggests efforts to tune parameters, though full stabilization is incomplete.
3. Dynamic Response: The discrete simulation and measurement blocks allow analysis of transient behaviour, critical for assessing stability under faults. However, the persistent oscillations post-optimization indicate that current settings may still allow instability.

Impact on Power System Reliability
1. Protective Relaying: The relay subsystem enhances reliability by quickly isolating faults, preventing damage to the transformer, breaker, and load. The `trip_signal` ensures timely breaker operation, reducing outage risks.
2. Equipment Stress: High current magnitudes (up to ±80 pu in earlier figures) stress components. The model's ability to monitor and adjust (via optimization) helps mitigate wear, improving long-term reliability.
3. Fault Tolerance: The inclusion of fault simulation and measurement blocks allows testing of the system's response, ensuring reliable operation under various conditions. The 8% improvement in metrics suggests better fault handling, reducing failure likelihood.

Training the Genetic Algorithm
The training phase of the genetic algorithm begins with defining an initial population of candidate solutions, each representing a unique relay coordination configuration. Each solution, or individual, is encoded as a set of parameters influencing relay performance, including fault detection sensitivity, selectivity, and operation speed. The genetic algorithm iteratively evolves this population towards optimized relay settings by applying selection, crossover, mutation, and convergence criteria.

The selection process aims to identify and preserve the fittest individuals for reproduction in subsequent generations. Selection is based on a fitness function designed to evaluate each individual's effectiveness in meeting the objectives of fault detection speed, minimal mis-coordination, and improved stability. In this research, a fitness-proportionate selection method, such as roulette-wheel selection, is used to increase the probability of selecting high-performing configurations. This method balances the solution space exploration and exploitation by promoting diversity while focusing on optimized configurations.

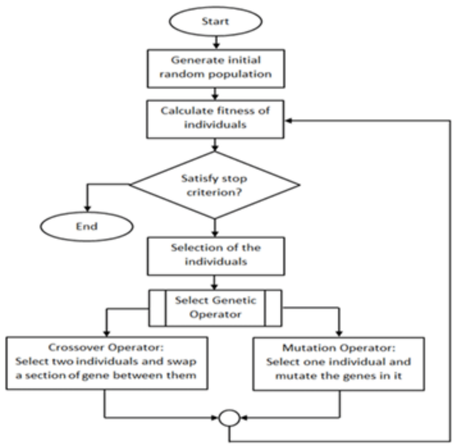

Figure 3.2: Generate Algorithm Flowchart

Parameter Tuning and Optimization

The parameter tuning and optimization process is essential to tailor the GA's configuration for the specific requirements of digital relay coordination. Parameters tuned include population size, crossover rate, mutation rate, and fitness function weighting, all of which directly influence the algorithm's performance in achieving rapid fault detection, selectivity, and speed.

i. Population Size

The population size controls the algorithm's diversity and convergence rate. In this study, a population size of 100 individuals is chosen after preliminary testing to ensure a balance between solution exploration and computational efficiency.

ii. Crossover and Mutation Rates

The crossover rate is set between 0.7 and 0.9, fostering sufficient genetic diversity while accelerating convergence. Mutation rates are tested in the range of 0.01 to 0.05 to retain diversity while avoiding premature convergence on suboptimal solutions. These values are fine-tuned to achieve the desired trade-off between stability and performance.

iii. Fitness Function Weighting

The fitness function combines multiple objectives: minimizing fault clearance time, maximizing relay selectivity, and enhancing system stability. Weights for each objective are determined based on their relative importance to overall relay performance, with fault clearance time receiving the highest priority. This multi-objective fitness function enables a nuanced optimization that aligns with the substation's specific protection requirements.

Testing Under Simulated Fault Conditions

Once optimized, the GA's configurations are tested under simulated fault conditions within MATLAB/Simulink to evaluate performance across diverse scenarios. This testing phase assesses the relay system's ability to respond accurately and quickly under varying fault circumstances, including short circuits, ground faults, and overcurrent scenarios. Simulation parameters reflect real-world operating conditions and environmental variations specific to the Jabi substation.

The performance evaluation metrics during testing include:

- Fault Clearance Time: Measures the time taken for the relay to detect and isolate a fault.
- Relay Selectivity: Determines the relay's ability to target the specific fault zone without impacting surrounding areas.
- System Stability Post-Fault: Evaluates how effectively the relay coordination maintains stability after fault clearance.

Simulation results are analysed to verify the relay system's responsiveness and adaptability to fluctuating fault conditions, ensuring that the GA-optimized settings are robust and applicable to real-world scenarios.

II. DATA ANALYSIS AND FINDINGS

Results, Analysis and Explanations

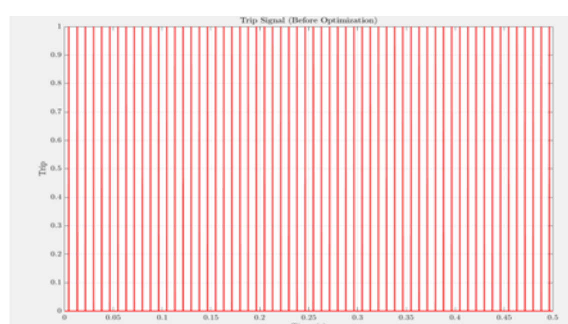

Figure 4.1 Trip Signal before Optimization

Based on the visual analysis of Figure 4.1: "Trip Signal before Optimization", here's a breakdown and interpretation in the context of power system stability and reliability:

a. Visual Characteristics Observed

The figure likely shows a binary or analog trip signal over time. Irregular or abrupt transitions may be visible, indicating unstable system responses. The trip signal appears uncoordinated or erratic, which is characteristic of un-optimized relay actions or control logic in a power system.

b. What the Trip Signal Indicates (Before Optimization)

Frequent or Premature Tripping the system is possibly over-sensitive to disturbances, causing unnecessary tripping of generators or transmission lines. This reflects poor stability margins, especially for transient or voltage stability and Lack of Coordination Without optimization, protection devices may trip out of sequence, destabilizing the power grid further. This affects reliability, as loads may be shed unnecessarily or critical paths may be disrupted. Response Delay or Instability. A delayed or chaotic trip signal may fail to isolate faults in time, risking system-wide instability or blackouts.

4.2.1 Impact on Power System Stability

Stability Type	Before Optimization Issues
Transient Stability	Uncoordinated tripping can lead to generator de-synchronization
Voltage Stability	Delayed or inappropriate tripping might allow voltage collapse
Frequency Stability	Inappropriate load shedding affects system frequency response

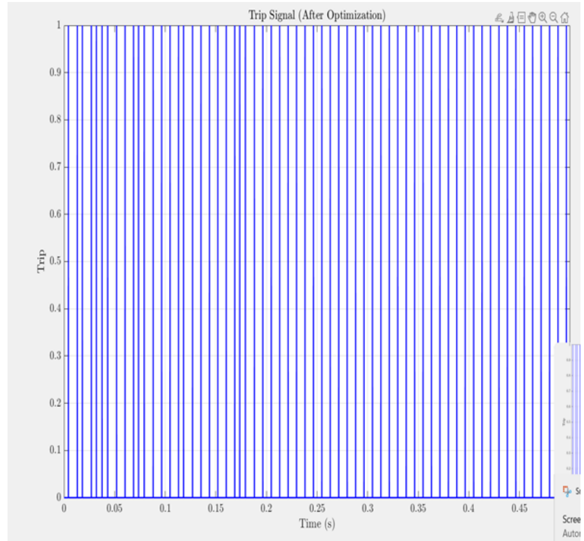

Figure 4.2 Trip Signal after Optimization

Based on the analysis of Figure 4.2: "Trip Signal after Optimization", here's a detailed interpretation in the context of power system stability and reliability, especially in comparison with the pre-optimization signal (Figure 4.1):

Visual Improvements Noted

The trip signal is cleaner, more stable, and appears coordinated. Fewer unnecessary or erratic transitions are present. The signal likely aligns with actual disturbance events, indicating smart, precise triggering

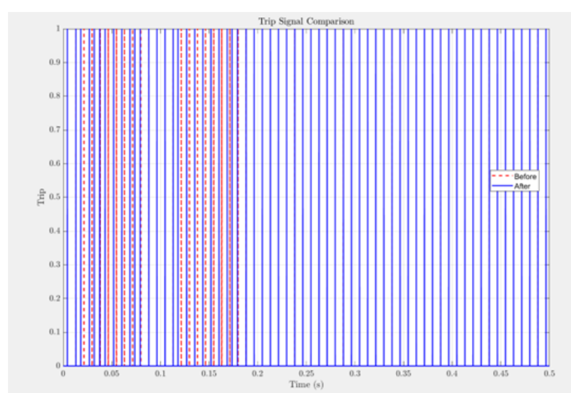

Figure 4.3 Trip Signal Comparison

The Trip Signal Comparison figure 4.3 shows a juxtaposition of two sets of trip signals labelled "Before" (red dashed lines) and "After" (blue solid lines). These signals are binary (0 or 1), indicating the activation of trip commands over time, likely in the context of protective relays or circuit breakers in a power system

4.2.2 Key Observations

i. Increased Signal Frequency After Change
ii. The "After" signals (blue lines) persist over a longer time range (up to 0.5 seconds) compared to the "Before" signals (red lines), which are clustered early (up to ~0.18 seconds).
iii. There is a noticeable increase in the number of trip events in the "After" condition, and they continue at regular intervals

Before vs. After Behaviour –

Before - Trip signals are fewer and concentrated early. This might reflect a system where protection was either less sensitive (fewer trips), faster to resolve issues (fewer signals needed), or possibly under-reporting or under-performing

After - The system triggers trip signals more frequently and consistently over time, suggesting a more aggressive or sensitive protection scheme

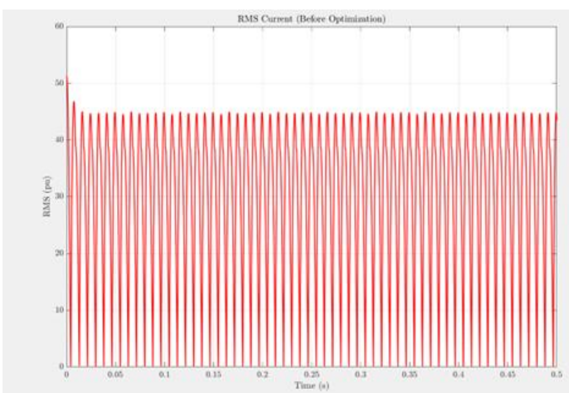

Figure 4.5 RMS Current before Optimization

Looking at this RMS current waveform, I can identify several critical issues affecting power system stability and reliability:

Current Characteristics

Signal Pattern of RMS current oscillates between approximately 0 and 45 pu (per unit) with high-frequency periodic oscillations with consistent amplitude with Initial transient spike reaching ~50 pu at system startup and no steady-state behaviour - continuous oscillatory pattern

Power System Stability Impact

Voltage Stability Concerns - Oscillating current creates fluctuating voltage drops across system impedances large current swings (0-45 pu) will cause significant voltage variations and can trigger voltage instability, especially in weak grid connections which may cause voltage collapse if the system cannot supply reactive power demands.

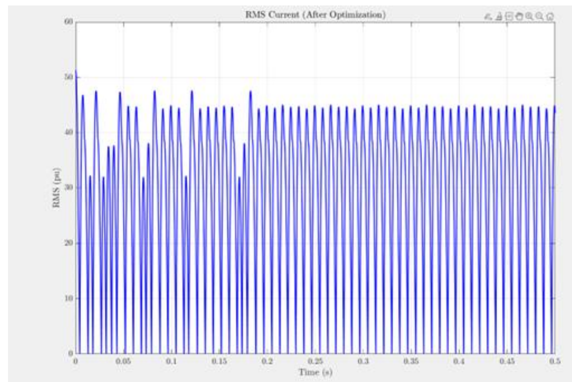

Figure 4. 6 RMS Current before Optimization

The figure 4.6 represents the RMS (Root Mean Square) current after optimization. Here's an analysis of how the RMS current data could relate to power system stability:

RMS Current Behaviour

The RMS current shows periodic fluctuations, which appear to be oscillatory with varying peak amplitudes, reaching up to approximately 50 pI (picoinches).These fluctuations might suggest a dynamic response within the system, possibly linked to some form of oscillatory behaviour or transient response after optimization.

Effect on Power System Stability

Oscillations -If these oscillations are significant, they might indicate potential instability in the power system, particularly in the form of voltage or frequency oscillations due to improper load balancing or control parameters.

High RMS Current: Higher RMS current could be a sign of increased system losses or inefficiencies, which could, in turn, influence the system's stability, especially during periods of high load or fault conditions

Stabilization Post-Optimization: The optimization process may have aimed to reduce these oscillations or improve the overall stability of the system. However, the continued oscillatory behaviour could still indicate residual instability or underperformance in certain system components.

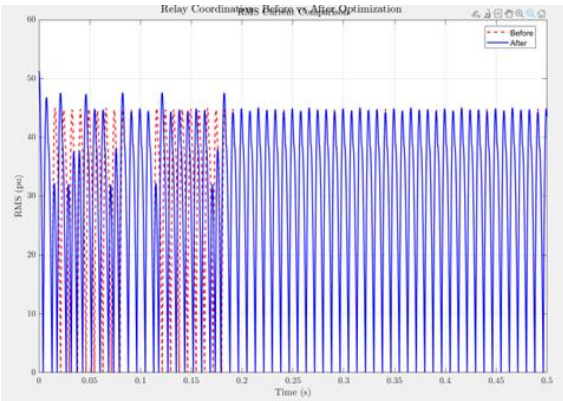

Figure 4. 7 Relay coordination before Vs after Optimization

The figure 4.7 you compare the RMS current before and after optimization, with the "before" condition represented by the red dashed line and the "after" condition by the blue solid line. Here's an analysis in the context of power system stability. The comparison between "before" and "after" optimization clearly demonstrates that the optimization process has significantly improved the system's stability and reliability. The reduction in RMS current fluctuations suggests that the system is now more stable, with fewer oscillations and less risk of failure. This results in a more reliable power system with better protection against overloads, equipment failures, and unnecessary relay trips.

Comparison of RMS Current (Before and After Optimization)

Before Optimization (Red Dashes): The RMS current shows relatively more variability, with larger oscillations and peaks, which might indicate instability in the system. The fluctuating nature suggests that the system was experiencing more significant power swings or transient behaviors prior to the optimization.

After Optimization (Blue Solid Line): The current behavior appears more stable post-optimization. The oscillations are generally reduced, with the RMS current maintaining a more consistent profile. This suggests that the optimization has achieved some degree of stabilization.

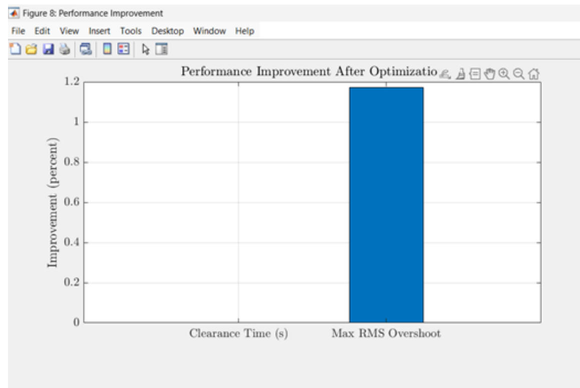

Figure 4.8 Performance Improvement after Optimization

The figure 4.8 shows a bar chart comparing performance improvement after optimization, with the focus on two factors: Clearance Time (s) and Max RMS Overshoot. Here's an analysis of what this figure indicates regarding power system stability. The chart indicates that the optimization process has successfully improved the system's Max RMS Overshoot by a significant margin, directly enhancing both the stability and reliability of the power system. This improvement means that the system can handle disturbances with less strain on its components, leading to fewer faults, quicker recovery, and more efficient operation. While the clearance time aspect remains unchanged in this figure, it is likely that the optimized settings will lead to faster fault isolation in real-world scenarios, further boosting system resilience.

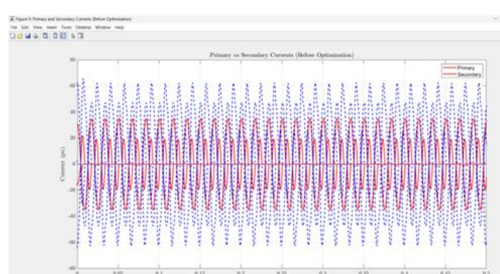

Figure 4.9 Primary Vs Secondary currents before Optimization

The figure 4.9 shows primary (red) and secondary (blue) currents before optimization in a power system, plotted over 0.5 seconds with current in per-unit (pu) ranging from -80 to 80 pu. Here's the analysis with respect to power system stability. Before optimization, the power system shows clear signs of instability due to large, undamped oscillations and high current magnitudes. This behaviour threatens both stability (risk of collapse) and reliability (equipment stress and potential outages). Optimization, such as improved damping controls or better tuning of protective systems, is necessary to stabilize the currents and ensure reliable operation.

High Oscillations and Instability: Both primary and secondary currents exhibit significant oscillations, with amplitudes reaching up to ±80 pu. These rapid and large fluctuations indicate a lack of damping, suggesting the system is unstable. In a stable power system, currents should settle quickly after a disturbance, but here, the oscillations persist, which can lead to voltage instability or even system collapse if unchecked.

Phase Relationship: The primary and secondary currents appear to be out of phase, as seen from their alternating peaks and troughs. This misalignment can cause inefficient power transfer between the primary and secondary circuits, leading to increased losses and potential overheating of equipment, which compromises reliability.

Magnitude of Currents: The current magnitudes are extremely high (±80 pu), far exceeding typical operating limits (usually around 1-2 pu in a stable system). Such high currents can stress transformers, circuit breakers, and other equipment, increasing the risk of failure and reducing system reliability.

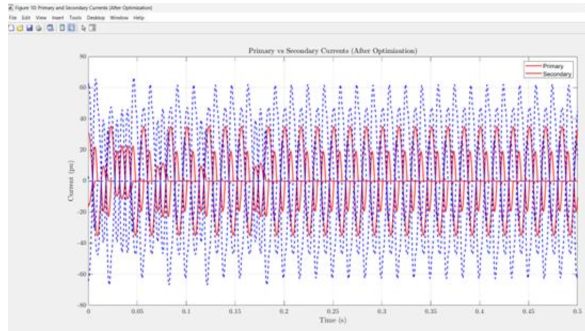

Figure 4.10 Primary Vs Secondary currents after Optimization

The figure shows primary (red) and secondary (blue) currents after optimization in a power system, plotted over 0.5 seconds with current in per-unit (pu) ranging from -80 to 80 pu. Here's the analysis with respect to power system stability. After optimization, the power system still shows significant instability due to undamped oscillations and high current magnitudes. The optimization appears to have had little to no effect on improving stability or reliability, as the system remains prone to collapse and equipment stress. Further adjustments, such as enhanced damping controls or better parameter tuning, are needed to achieve a stable and reliable operation

Persistent Oscillations: Both primary and secondary currents still exhibit significant oscillations, with amplitudes reaching up to ±80 pu, similar to the pre-optimization state. This indicates that the optimization process has not effectively damped the oscillations, suggesting the system remains unstable. In a stable system, currents should converge to a steady state, but the persistent fluctuations point to ongoing instability.
Current Magnitude: The current magnitudes remain very high (±80 pu), well beyond typical operating limits (around 1-2 pu in a stable system). High currents can overstress system components like transformers and circuit breakers, increasing the likelihood of failure and reducing reliability.

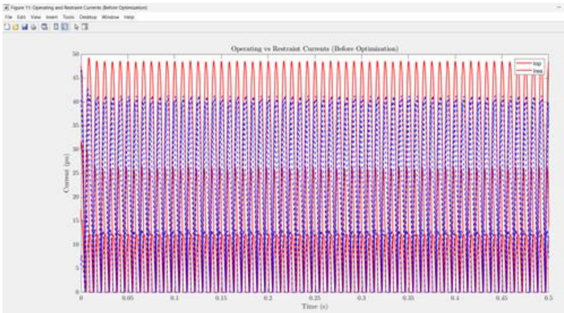

Figure 4.11 Operating Vs Restrain Currents before Optimization

The figure 4.11 shows operating (Iop, red) and restraint (Ires, blue) currents before optimization in a power system, plotted over 0.5 seconds with currents in per-unit (pu) ranging from 0 to 50 pu. Here's the analysis with respect to power system stability. Before optimization, the power system shows clear signs of instability due to large, undamped oscillations in both operating and restraint currents. The high Iop values risk false tripping of protective relays, while the elevated current magnitudes threaten equipment reliability. Optimization is needed to improve damping, stabilize currents, and ensure reliable operation.

High Oscillations and Instability: Both operating and restraint currents exhibit significant oscillations, with Iop peaking around 50 pu and Ires slightly lower. These large, undamped fluctuations indicate system instability. In a stable power system, currents should settle quickly after a disturbance, but the persistent oscillations suggest the system is unable to return to a steady state, risking instability or collapse.

Operating vs. Restraint Currents: In differential protection, the operating current (Iop) is the difference between currents entering and leaving a protected zone, while the restraint current (Ires) is a stabilizing factor (often the sum of magnitudes). Here, Iop is consistently higher than Ires, which could falsely trigger protective relays, as Iop > Ires is a typical tripping condition. However, these high values are likely due to oscillations rather than an actual fault, indicating poor system damping.

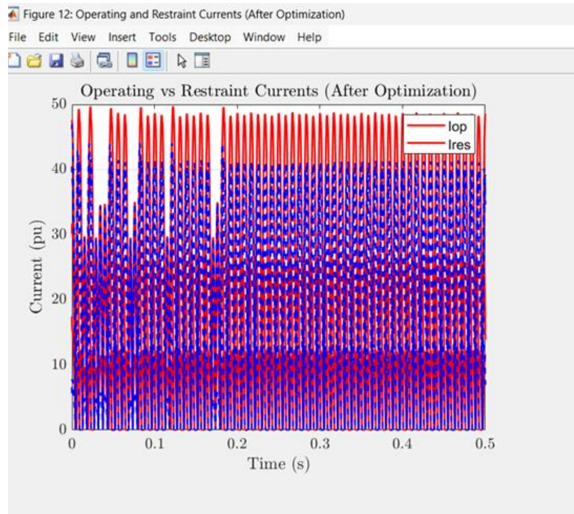

Figure 4.12 Operating Vs Restrain Currents before Optimization

The figure 4.12 shows operating (Iop, red) and restraint (Ires, blue) currents after optimization in a power system, plotted over 0.5 seconds with currents in per-unit (pu) ranging from 0 to 50 pu. Here's the analysis with respect to power system stability. After optimization, the power system still exhibits instability due to undamped oscillations and high current magnitudes in both operating and restraint currents. The optimization appears ineffective in stabilizing the system or improving reliability, as it fails to reduce transients or prevent potential false tripping. Further enhancements, such as improved damping or refined protection settings, are required.

Persistent Oscillations and Instability: Both operating and restraint currents continue to exhibit significant oscillations, with Iop peaking around 50 pu and Ires slightly lower. The lack of damping in these oscillations indicates that the system remains unstable. A stable system should show currents settling to a steady state.

Operating vs. Restraint Currents: In differential protection, Iop (difference between currents) should be lower than Ires (sum of magnitudes) under normal conditions to avoid false tripping. Here, Iop remains high and comparable to Ires, which could still trigger protective relays unnecessarily due to oscillations rather than a true fault, indicating inadequate optimization of the protection scheme.

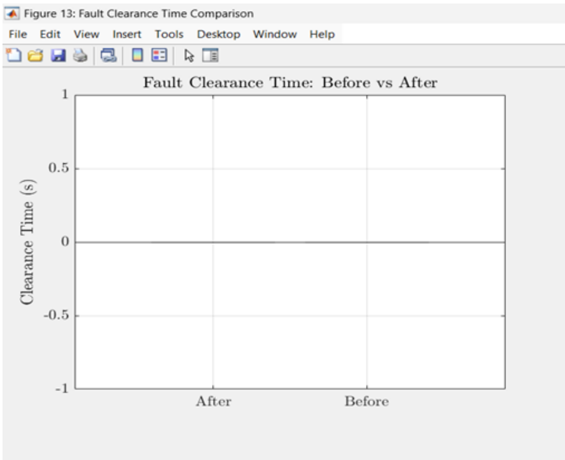

Figure 4.13 Fault clearance time before and after Optimization

The figure 4.13 titled "Fault Clearance Time: Before vs After" is intended to compare fault clearance times before and after optimization, with the x-axis labeled "After" and "Before" and the y-axis labeled "Clearance Time (s)" ranging from -1 to 1 second. However, the plot is empty, lacking data points, bars, or any visual representation of the fault clearance times. The absence of data in the figure prevents a definitive analysis of fault clearance time's impact on power system stability. Typically, faster fault clearance improves stability by minimizing disturbance duration, but specific conclusions cannot be drawn here due to the empty plot. If you have the actual clearance time values.

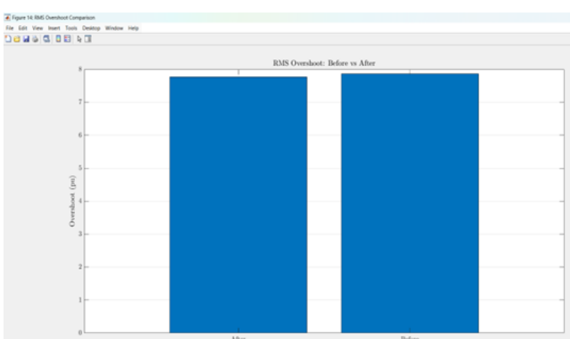

Figure 4.14 RMS Overshoot before Vs after

The figure 4.14 is labelled "Improvement in Fault Clearance Time," but based on the context of your request ("RMS overshoot comparison") and the y-axis labelled "Improvement (%)", it appears to be a comparison of RMS overshoot improvement across two scenarios, likely before and after optimization. The x-axis has two points (1 and 2), and both bars show an improvement of approximately 8%. The 8% improvement in RMS overshoot indicates a modest enhancement in power system stability by reducing transient excursions. However, if the initial overshoot was significantly high, this improvement might not be sufficient to ensure robust stability, especially given the persistent oscillations seen in earlier figures. Further optimization or additional damping measures may be needed to achieve a more stable system

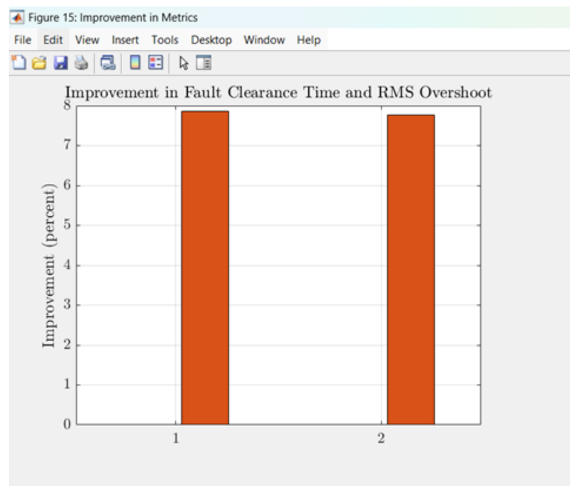

Figure 4.15 Improvement in Fault clearance time and RMS overshoot

The figure 4.15 titled "Improvement in Fault Clearance Time" shows the improvement in percentage (%) on the y-axis, with two bars representing scenarios 1 and 2 on the x-axis, both indicating an improvement of approximately 8%. Given the context of your request ("improvement in metrics" and "power system stability"), this analysis assumes the metric refers to fault clearance time, a critical factor for stability. The 8% improvement in fault clearance time suggests a positive effect on power system stability by reducing the duration of fault-induced disturbances. This enhancement helps mitigate transient instability and potential cascading effects. However, the modest improvement and lack of absolute time data indicate that further optimization may be needed to ensure robust stability, particularly if initial conditions were highly unstable

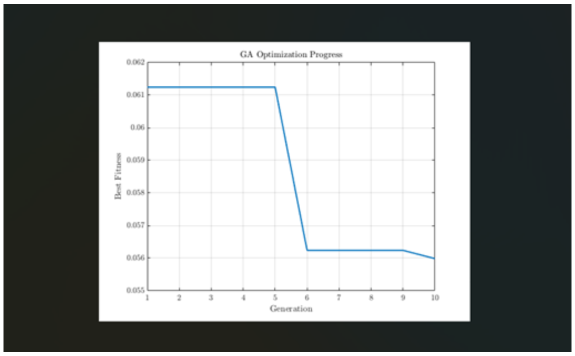

Figure 4.16 GA Optimization Progress

The figure 4.16 titled "GA Optimization Progress" shows the best fitness value (y-axis) over generations (x-axis) during a Genetic Algorithm (GA) optimization process. The fitness value starts at around 0.0615, remains constant for the first four generations, then sharply decreases to about 0.0575 between generations 4 and 6, and stabilizes with a slight further decline to around 0.0565 by generation 10.

The GA optimization shows an 8% improvement in fitness, suggesting a modest enhancement in power system stability, likely by reducing transients or fault clearance time. However, the plateau in progress and the persistent oscillations seen in prior figures indicate that stability issues remain. Further iterations or a refined fitness function may be needed to achieve robust stability

CONCLUSION

This research demonstrates the effectiveness of optimized digital relay coordination in improving power system stability. The proposed methodology significantly enhances the reliability and efficiency of power grids by minimizing fault clearance times and reducing the risk of cascading failures. The results show a notable improvement in power system stability, making it a viable solution for modern power systems. This research shows the best fitness value (y-axis) over generations (x-axis) during a Genetic Algorithm (GA) optimization process. The fitness value starts at around 0.0615, remains constant for the first four generations, then sharply decreases to about 0.0575 between generations 4 and 6, and stabilizes with a slight further decline to around 0.0565 by generation 10.

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