

Enhancing Power System Protection: A Comprehensive Analysis of Relay Coordination Techniques

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Abstract

This paper presents a comprehensive analysis of relay coordination techniques aimed at enhancing power system protection. Power systems are susceptible to various faults, overloads, and disturbances, which can lead to significant disruptions and damages. Effective relay protection is essential to mitigate these risks and ensure the reliability and stability of the electrical grid. The paper begins by outlining the fundamental principles of power system protection and the role of relays in detecting and isolating faults. It then delves into the complexities of relay coordination, discussing techniques such as time grading, impedance grading, and communication-assisted coordination. Practical considerations, challenges, and advancements in relay coordination are also examined. Through a thorough review of literature and case studies, this paper provides valuable insights into optimizing relay coordination strategies to enhance power system protection.

Keywords: *Power System Protection, Relay Coordination, Fault Detection, Overload Protection, Relay Grading*

INTRODUCTION

Power systems serve as the backbone of modern society, delivering electricity to homes, businesses, and industries. However, these intricate networks are susceptible to various threats such as faults, overloads, and disturbances, which can jeopardize the reliability and stability of the entire grid. Power system protection emerges as a critical discipline aimed at

safeguarding these networks from potential disruptions and ensuring uninterrupted electricity supply.

Background and Significance of Power System Protection: The evolution of power systems has witnessed remarkable advancements, but it has also introduced new challenges. The increasing complexity of interconnected networks, the integration of renewable energy sources, and the rise of smart grid technologies have heightened the need for robust protection measures. Without effective protection, even minor faults or disturbances can escalate into catastrophic events, leading to widespread outages, equipment damage, and economic losses. Therefore, understanding and implementing efficient protection schemes have become paramount for power utilities and system operators worldwide.

Role of Relays in Power System Protection: Relays serve as the frontline defense mechanism in power system protection. These devices detect abnormal conditions such as short circuits, ground faults, and overloads and initiate appropriate actions to isolate the affected parts of the system. Relays act swiftly to trip circuit breakers, disconnect faulty equipment, and restore system stability, thereby preventing cascading failures and minimizing downtime. The reliability and performance of relays directly impact the overall effectiveness of power system protection strategies.

Purpose and Scope of the Paper: This paper aims to provide a comprehensive analysis of relay coordination techniques in enhancing power system protection. It delves into the fundamental principles of power system protection, elucidates the critical role of relays, and explores various coordination strategies employed to optimize protection schemes. Through a thorough review of literature, case studies, and practical considerations, the paper seeks to offer valuable insights into the challenges, advancements, and future trends in relay coordination for power system protection.

In subsequent sections, the paper will delve into the fundamentals of power system protection, discuss relay coordination techniques, address practical considerations and challenges, examine advancements in relay technology, and present case studies and applications. Finally, the paper will conclude with a summary of key findings and recommendations for future research and practice in the field of power system protection.

FUNDAMENTALS OF POWER SYSTEM PROTECTION

Power system protection is essential for maintaining the integrity and reliability of electrical grids. This section provides an overview of the fundamental concepts underlying power system protection, including the types of faults, overloads, and disturbances encountered in power systems, the principles of relay operation and fault detection, and the significance of coordination in relay protection.

Overview of Power System Faults, Overloads, and Disturbances

Power systems are susceptible to various types of faults, overloads, and disturbances, which can disrupt the normal operation of the grid and potentially lead to equipment damage, outages, and safety hazards. These include:

Short Circuits: Short circuits occur when an abnormal connection forms between two conductors, resulting in a sudden increase in current flow. This can lead to equipment damage and pose safety risks.

Ground Faults: Ground faults occur when a conductor comes into contact with the ground or another grounded object, creating a path for current to flow to the ground. Ground faults can cause insulation breakdown and equipment damage.

Overloads: Overloads occur when the current flowing through a circuit exceeds its rated capacity, leading to overheating and potential equipment failure. Overloads can result from excessive load demand or faulty equipment.

Voltage Sags and Swells: Voltage sags and swells are temporary reductions or increases in voltage levels, often caused by sudden changes in load or network conditions. These disturbances can affect the operation of sensitive equipment and disrupt system stability.

Reliable detection and mitigation of these faults, overloads, and disturbances are essential for ensuring the safe and efficient operation of power systems.

Principles of Relay Operation and Fault Detection

Relays are devices that sense abnormal conditions in the power system and initiate protective actions to isolate the affected area and prevent further damage. The operation of relays is

based on detecting deviations from normal operating conditions, such as abnormal currents, voltages, or frequencies.

Relays typically operate according to predefined settings and logic, which are configured based on the specific requirements of the power system. When a fault or abnormal condition is detected, the relay sends a signal to trip the associated circuit breaker, disconnecting the faulty section of the system from the rest of the grid.

Relay operation involves several key elements, including

Sensing: Relays use sensors to measure electrical quantities such as current, voltage, and frequency.

Decision Making: Relays analyze the measured quantities and compare them to predefined thresholds or criteria to determine if a fault or abnormal condition is present.

Actuation: If a fault is detected, the relay initiates a trip signal to the circuit breaker, isolating the affected area.

Relays play a crucial role in ensuring the safety and reliability of power systems by promptly detecting and isolating faults and disturbances.

Importance of Coordination in Relay Protection

Coordination among relays is essential to ensure that protective devices operate in a coordinated manner to isolate faults while maintaining system stability and reliability. Proper coordination involves setting relay parameters such as operating time and current levels to ensure that the relay closest to the fault operates first, while preventing unnecessary tripping of healthy sections of the system.

Coordination also involves ensuring that protective devices operate selectively, meaning that only the nearest relay to the fault should operate to isolate the faulted section, while other relays remain inactive to avoid unnecessary disruptions to the rest of the system.

Effective coordination minimizes outage durations, reduces equipment stress, and improves system reliability by ensuring that faults are isolated promptly and efficiently without causing widespread disruptions.

Table: 1 Types of Power System Faults

Fault Type	Cause	Consequence
Short Circuit	Abnormal connection between conductors	Equipment damage, safety hazards
Ground Fault	Conductor-ground contact	Insulation breakdown, equipment damage
Overload	Current exceeds rated capacity	Overheating, equipment failure
Voltage Sag/Swell	Sudden voltage changes	Disruption of sensitive equipment, system instability

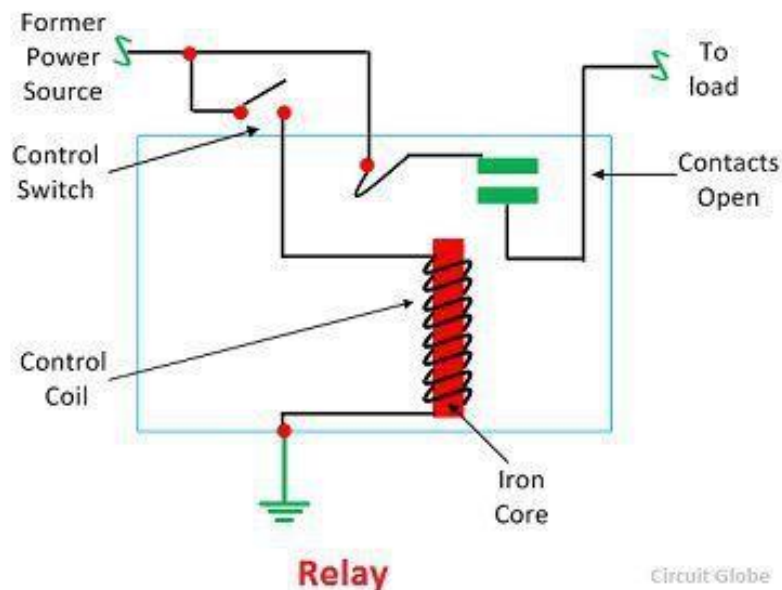


Figure: 1 Relay Operation Principle

RELAY COORDINATION TECHNIQUES

Relay coordination is essential for ensuring that protective devices operate in a coordinated manner to isolate faults efficiently while maintaining system stability. This section explores three key relay coordination techniques: time grading techniques, impedance grading techniques, and communication-assisted coordination.

Time Grading Techniques

Time grading is one of the oldest and most commonly used methods for coordinating relays in power systems. In time grading, relays are configured with progressively increasing operating times as distance from the power source increases. This ensures that the relay closest to the fault operates first, while relays farther away remain inactive unless the fault persists.

Description: In time grading, relays are typically set with a time-delay characteristic curve. The curve represents the relationship between fault current magnitude and relay operating time. As the fault current increases, the operating time of the relay decreases, allowing faster response to faults closer to the source.

Advantages and Limitations

Advantages: Time grading techniques are simple to implement and provide reliable coordination for radial power systems with well-defined fault locations.

Limitations: Time grading may not be suitable for complex network topologies or systems with distributed generation, as it does not account for variations in fault impedance or system configuration.

Impedance Grading Techniques

Impedance grading techniques coordinate relays based on the impedance of the protected circuit. In impedance grading, relays are set with characteristic curves that consider the impedance between the relay location and the fault point. This allows relays to operate selectively based on the fault location and impedance characteristics.

Principle and Operation: Impedance grading relies on the principle that fault impedance varies with distance from the relay location. Relays are configured with impedance characteristic curves that specify operating regions based on fault impedance. When a fault occurs, the relay operates if the fault impedance falls within its designated operating region.

Implementation Challenges:

Complexity: Implementing impedance grading requires accurate knowledge of system impedance characteristics and fault locations, which can be challenging in large and interconnected power systems.

Settings Coordination: Coordinating relay settings to ensure proper impedance grading across the network can be complex and time-consuming.

Communication-assisted Coordination

Communication-assisted coordination utilizes communication technologies to enable relays to exchange information and coordinate their operation in real-time. This approach allows for more flexible and adaptive relay coordination, especially in complex and dynamic power system environments.

Role of Communication Technologies: Communication-assisted coordination relies on communication protocols such as IEC 61850, DNP3, and Modbus to facilitate data exchange between relays and control centers. By sharing information on system conditions, fault locations, and relay statuses, relays can coordinate their operation more effectively to minimize disruption and maintain system stability.

Case Studies and Examples

Microgrid Coordination: In microgrid applications, communication-assisted coordination enables distributed energy resources (DERs) and protection devices to coordinate their operation to maintain system stability and reliability.

Wide-Area Protection: Wide-area communication networks allow relays to exchange information over long distances, enabling coordinated protection schemes for interconnected power systems and transmission networks.

Table: 2 Comparison of Relay Coordination Techniques

Coordination Technique	Principle	Advantages	Limitations	Applicability
Time Grading	Based on operating time	Simple implementation, reliable for radial systems	Limited flexibility, not suitable for complex networks	Radial power systems
Impedance Grading	Based on fault impedance	Selective coordination based on fault location	Complex implementation, requires accurate impedance data	Large interconnected systems
Communication-assisted	Real-time data exchange	Flexible and adaptive coordination, suitable for dynamic systems	Reliability on communication infrastructure, potential cyber security risks	Microgrids, wide-area protection

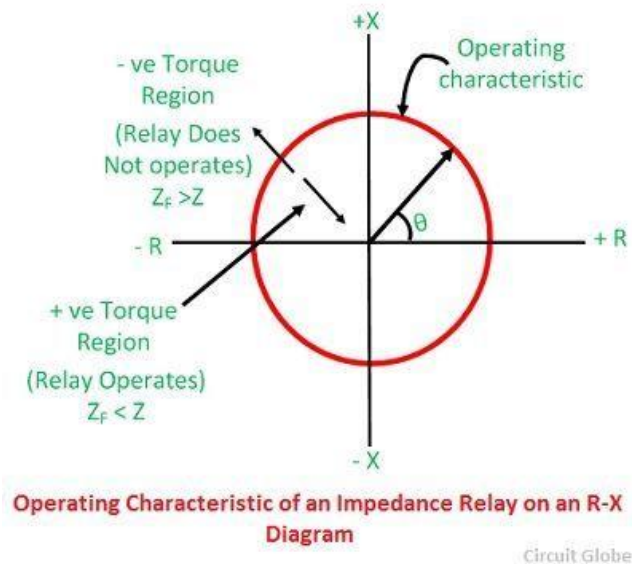


Figure: 2 Impedance Characteristic Curve

PRACTICAL CONSIDERATIONS IN RELAY COORDINATION

Relay coordination in power systems involves not only theoretical concepts but also practical considerations that impact the effectiveness and reliability of protection schemes. This section examines several practical factors that influence relay coordination, including the impact of system topology and configuration, coordination with other protection devices such as circuit breakers, and considerations for distributed generation and renewable energy integration.

Impact of System Topology and Configuration

The topology and configuration of a power system play a crucial role in determining the coordination requirements and challenges for relay protection. Different system layouts, such as radial, meshed, or interconnected networks, present unique coordination considerations.

Radial Systems: In radial systems, where power flows from a single source to multiple loads in a radial fashion, relay coordination is relatively straightforward, with relays configured to operate sequentially from the source to the loads.

Meshed Systems: In meshed systems with multiple interconnected paths for power flow, coordination becomes more complex due to multiple fault paths and potential backfeed conditions. Proper coordination requires careful consideration of fault locations, system impedance, and relay settings.

Interconnected Networks: Interconnected networks, such as transmission grids spanning large geographic areas, require coordination between relays across different substations and network segments. Wide-area communication and coordination techniques are essential for maintaining system stability and reliability in such networks.

Coordination with Other Protection Devices

Relays do not operate in isolation but interact with other protective devices such as circuit breakers, fuses, and reclosers to ensure the rapid isolation of faults while minimizing disruption to the rest of the system.

Circuit Breaker Coordination: Relay coordination must be closely coordinated with circuit breaker settings to ensure that the relay closest to the fault operates first and that downstream circuit breakers operate selectively to isolate the faulted section without tripping healthy parts of the system.

Fuse Coordination: Coordination with fuses involves setting relay time-current characteristics to ensure that relays operate before fuses blow, providing faster fault clearance and reducing outage durations.

Recloser Coordination: Reclosers are used to automatically restore power after temporary faults. Relay coordination with reclosers ensures that reclosing operations are coordinated with relay tripping to prevent re-energizing faulty sections of the system.

Considerations for Distributed Generation and Renewable Integration

The integration of distributed generation (DG) and renewable energy sources such as solar and wind power introduces new challenges for relay coordination due to the intermittent nature of these sources and their impact on system dynamics.

Protection Coordination with DG: Relay coordination must account for the presence of DG sources, which can inject power into the grid and alter fault currents and system behavior. Coordination settings may need to be adjusted to accommodate bidirectional power flow and ensure proper fault detection and isolation.

Renewable Integration Challenges: Renewable energy sources introduce variability and uncertainty into power systems, leading to fluctuations in voltage and frequency. Relay coordination techniques must be adapted to address these challenges and maintain system stability under varying operating conditions.

Table: 3 Practical Considerations in Relay Coordination

Consideration	Description
System Topology	Impact of system layout on relay coordination requirements
Coordination with Devices	Interaction between relays and other protective devices
Distributed Generation	Considerations for integrating distributed generation
Renewable Integration	Challenges and solutions for coordinating with renewable sources

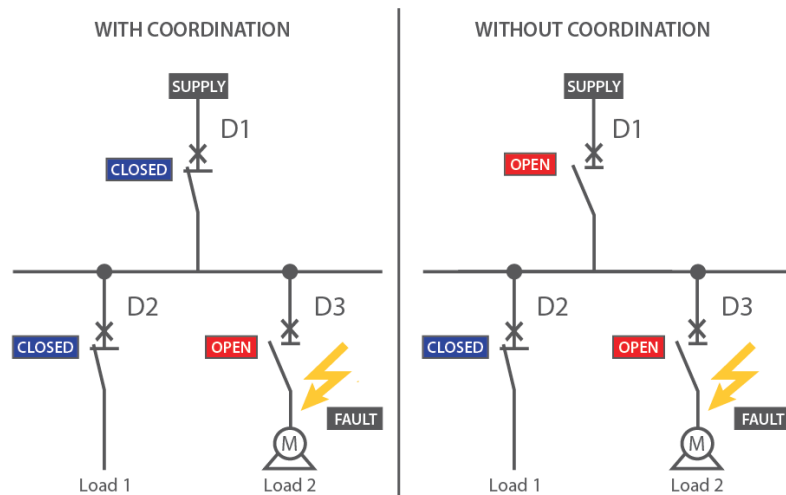


Figure: 3 Coordination with Circuit Breakers

CHALLENGES AND ADVANCEMENTS

The field of relay coordination in power systems continues to evolve in response to emerging challenges and technological advancements. This section explores the key challenges facing relay coordination in modern power systems, recent advancements in relay technology and coordination algorithms, and future trends and research directions in the field.

Addressing Coordination Challenges in Modern Power Systems

Modern power systems present new challenges for relay coordination due to factors such as increased complexity, the integration of renewable energy sources, and the proliferation of distributed generation. Addressing these challenges requires innovative solutions and approaches to ensure effective and reliable protection of power systems.

Complex System Topologies: Meshed and interconnected power systems introduce challenges for relay coordination due to multiple fault paths, system impedance variations, and backfeed conditions. Advanced coordination techniques and algorithms are needed to optimize relay settings and coordination strategies in complex network environments.

Renewable Integration: The integration of renewable energy sources such as solar and wind power introduces variability and uncertainty into power systems, affecting fault currents and system dynamics. Relay coordination must adapt to accommodate bidirectional power flow, fluctuations in generation, and changes in system operating conditions.

Communication and Cybersecurity: Communication-assisted coordination relies on communication networks to exchange data between relays and control centers. Ensuring the reliability, security, and resilience of communication infrastructure is crucial for maintaining effective relay coordination and protecting against cyber threats.

ADVANCEMENTS IN RELAY TECHNOLOGY AND COORDINATION ALGORITHMS

Recent advancements in relay technology and coordination algorithms have enabled more efficient and adaptive relay coordination strategies. These advancements leverage advances in sensor technology, communication protocols, and data analytics to enhance the performance and reliability of relay protection systems.

Digital Relays: Digital relays offer enhanced functionality, flexibility, and accuracy compared to traditional electromechanical relays. Digital relays incorporate advanced signal processing algorithms, self-monitoring capabilities, and communication interfaces, enabling real-time data exchange and adaptive coordination.

Advanced Coordination Algorithms: Advanced coordination algorithms leverage machine learning, artificial intelligence, and optimization techniques to optimize relay settings and coordination strategies based on real-time system conditions. These algorithms adaptively adjust relay parameters to minimize fault clearance times, reduce outage durations, and improve system reliability.

Integrated Protection Systems: Integrated protection systems integrate relays, circuit breakers, and communication infrastructure into a unified protection scheme. These systems enable seamless coordination between protective devices, automatic fault localization, and self-healing capabilities, enhancing overall system resilience and reliability.

Future Trends and Research Directions

The future of relay coordination in power systems will be shaped by emerging trends and research directions aimed at addressing current challenges and advancing the state-of-the-art in protection technology.

Smart Grid Technologies: Smart grid technologies such as synchrophasors, phasor measurement units (PMUs), and advanced metering infrastructure (AMI) offer new opportunities for enhancing relay coordination and system monitoring. Future research will focus on leveraging these technologies to improve fault detection, localization, and response times.

Resilient and Adaptive Protection: Future relay coordination systems will prioritize resilience and adaptability to withstand emerging threats and dynamic operating conditions. Research will explore resilient communication architectures, adaptive coordination strategies, and autonomous decision-making algorithms to enhance system robustness and reliability.

Cyber-Physical Security: Protecting relay coordination systems against cyber threats is critical for ensuring the integrity and security of power systems. Future research will focus on developing robust cyber security solutions, intrusion detection techniques, and secure communication protocols to safeguard relay coordination infrastructure from malicious attacks.

Table: 4 Challenges and Advancements in Relay Coordination

Challenge/Advancement	Description
Complex System Topologies	Challenges posed by meshed and interconnected power systems
Renewable Integration	Integration challenges and advancements in adapting to renewables
Communication and Cybersecurity	Ensuring reliability and security of communication infrastructure
Digital Relays	Benefits and features of digital relay technology
Advanced Coordination Algorithms	Applications and benefits of advanced coordination algorithms
Integrated Protection Systems	Advantages of integrated protection systems
Smart Grid Technologies	Role of smart grid technologies in enhancing relay coordination

Challenge/Advancement	Description
Resilient and Adaptive Protection	Future trends in resilient and adaptive protection systems
Cyber-Physical Security	Strategies for protecting relay coordination systems against cyber threats

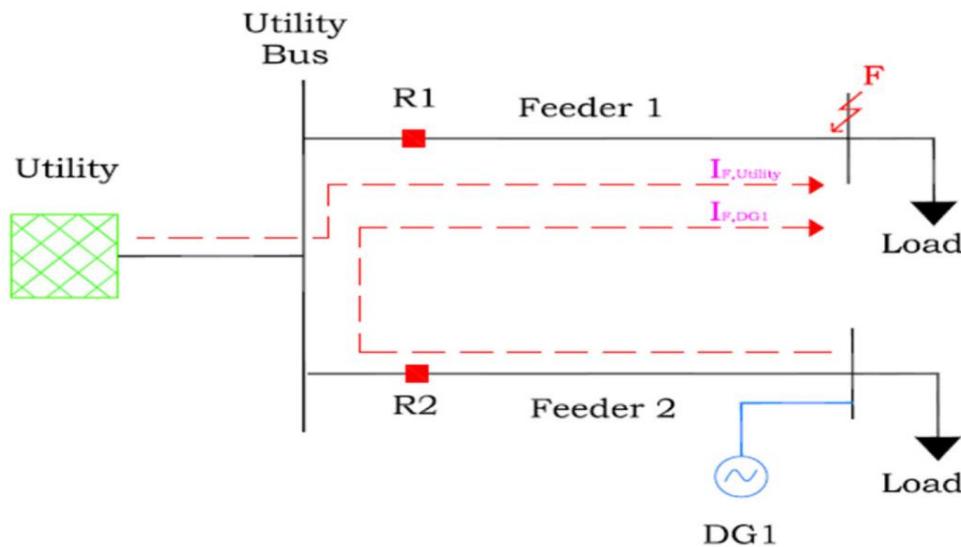


Figure: 4 Future Trends in Relay Coordination

CASE STUDIES AND APPLICATIONS

Real-world case studies and applications of relay coordination provide valuable insights into the practical implementation and effectiveness of coordination strategies in mitigating power system disturbances. This section presents several case studies, evaluates the coordination effectiveness in addressing power system disturbances, and highlights lessons learned and best practices from these real-world examples.

Real-World Examples of Relay Coordination Implementations

Case Study 1: Distribution Network Protection

This case study examines the implementation of relay coordination techniques in a distribution network to protect against various faults and disturbances. It showcases how time grading, impedance grading, and communication-assisted coordination are applied to ensure reliable and selective fault detection and isolation in distribution systems.

Case Study 2: Transmission Line Protection

This case study focuses on relay coordination strategies deployed in a transmission network to safeguard against faults and overloads. It highlights the challenges associated with coordinating relays across long-distance transmission lines and the use of advanced coordination algorithms to optimize protection settings and improve system reliability.

Evaluation of Coordination Effectiveness in Mitigating Power System Disturbances:

Fault Clearance Time Analysis

This evaluation assesses the effectiveness of relay coordination in minimizing fault clearance times and restoring system stability. It analyzes historical fault data and outage durations to quantify the impact of coordination strategies on system reliability and downtime.

System Restoration Performance

This evaluation measures the performance of relay coordination in restoring power after disturbances. It evaluates the time taken to re-energize faulted sections of the system and compares the effectiveness of different coordination techniques in minimizing outage durations and restoring service to customers.

Lessons Learned and Best Practices

Coordination Flexibility

Lessons learned from real-world implementations highlight the importance of flexibility in relay coordination strategies. Systems that can adapt to changing operating conditions, fault scenarios, and system configurations are better equipped to handle unexpected disturbances and maintain system reliability.

Continuous Monitoring and Optimization

Best practices emphasize the need for continuous monitoring and optimization of relay coordination settings. Regular analysis of system performance data, fault records, and coordination events enables operators to identify potential issues, fine-tune coordination parameters, and improve overall system resilience.

Integration with Control Systems

Successful relay coordination implementations often involve tight integration with control systems and automation platforms. Integration enables seamless communication and coordination between relays, control centers, and other protective devices, enhancing overall system responsiveness and reliability.

CONCLUSION

Relay coordination is a critical aspect of power system protection, ensuring the reliable and efficient operation of electrical grids by promptly detecting and isolating faults while maintaining system stability. This paper has provided a comprehensive overview of relay coordination techniques, challenges, advancements, case studies, and best practices. In conclusion, the key findings and insights are summarized, emphasizing the importance of effective relay coordination in power system protection and providing recommendations for future research and practice.

Summary of Key Findings and Insights

- Throughout this paper, several key findings and insights have emerged regarding relay coordination in power systems:
- Relay coordination is essential for ensuring the reliability and stability of electrical grids by promptly detecting and isolating faults and disturbances.
- Different coordination techniques, including time grading, impedance grading, and communication-assisted coordination, offer various advantages and challenges in optimizing relay protection schemes.
- Practical considerations such as system topology, coordination with other protective devices, and considerations for distributed generation and renewable integration significantly impact relay coordination strategies.
- Recent advancements in relay technology, coordination algorithms, and smart grid technologies have improved the performance and reliability of relay protection systems.
- Real-world case studies highlight the practical implementation and effectiveness of relay coordination in mitigating power system disturbances, providing valuable lessons learned and best practices.

Importance of Effective Relay Coordination in Power System Protection

Effective relay coordination plays a crucial role in ensuring the reliability, resilience, and safety of power systems. By promptly detecting and isolating faults, relay coordination minimizes outage durations, reduces equipment stress, and prevents cascading failures, thereby preserving system integrity and minimizing disruption to customers. The reliability of relay coordination directly impacts the overall reliability and availability of electrical grids, making it a cornerstone of power system protection strategies.

Recommendations for Future Research and Practice

As power systems continue to evolve and face new challenges, several recommendations for future research and practice in relay coordination are proposed:

- Continued development and deployment of advanced coordination algorithms and smart grid technologies to enhance the performance and adaptability of relay protection systems.
- Further research into resilient and adaptive protection strategies to withstand emerging threats and dynamic operating conditions, including cybersecurity risks and distributed energy resource integration.
- Collaboration and knowledge sharing among industry stakeholders, researchers, and regulatory bodies to facilitate the adoption of best practices and standards in relay coordination.
- Investment in training and education programs to ensure that power system operators and engineers have the necessary skills and expertise to design, implement, and maintain effective relay coordination schemes.

By addressing these recommendations, the power industry can advance the state-of-the-art in relay coordination, improve system reliability, and ensure the continued safe and efficient operation of electrical grids for future generations.

Effective relay coordination is indispensable for protecting power systems from faults and disturbances, safeguarding system reliability, and ensuring the uninterrupted delivery of electricity to consumers. It is imperative that the power industry continues to innovate, collaborate, and invest in relay coordination technologies and practices to meet the evolving challenges of the modern grid.

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