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Overcurrent Relay Coordination in Transmission and Distribution System: A Comprehensive Review

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Abstract:- In recent decades, the power system has undergone wide restructuring. This is mainly because of distributed generation and demand increment, led by the increasing dependency of mankind on electricity. Power system restructuring includes several new aspects of a conventional power system, especially in the area of transmission and distribution system protection. Several techniques and schemes are used for the protection of transmission and distribution. However, with the restructuring, several improved protection techniques are sought for better operation of the restructured power system. Overcurrent relays are critical components in the protection of electrical transmission and distribution networks, ensuring the reliability and safety of power systems. Effective relay coordination minimizes unnecessary outages and protects infrastructure by isolating faults quickly and accurately. This review underscores the importance of innovative coordination strategies to enhance the efficiency, reliability, and resilience of modern power systems. This review discusses the background in this direction along with the introduction to the existing power system, its main protective components, and various existing protection schemes. The challenges of achieving optimal coordination in complex and interconnected networks are addressed, with a focus on the impact of renewable energy integration, load variability, and system topology changes. Emerging trends, such as adaptive relay schemes and the role of smart grid technologies, are also highlighted.

Keywords*: overcurrent relay coordination, coordination time interval, time multiplier setting, plug setting multiplier.*

1. Introduction

The transmission and distribution segments of the power system are particularly vulnerable and demand significant research attention. Faults in a power system can generally be categorized into two types: (i) symmetrical faults and (ii) unsymmetrical faults. Transmission and distribution system protection primarily relies on circuit breakers (CB), distance relays (DR), and overcurrent relays (OCR) to ensure efficient power transfer from the sending to the receiving end without disruptions or hazards to the power system [1]. However, integrating distributed generators (DGs) poses additional protection challenges due to changes in system topology, such as radial distribution systems (RDS) or meshed distribution systems (MDS). Common disturbances in power networks include false tripping of feeders and generation units, protection blinding, fluctuations in short-circuit (SC) levels, protection coordination issues, unintentional network islanding, and asynchronous reclosing. Future power distribution

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systems are expected to incorporate advanced metering, distribution automation, and distributed generation technologies extensively. Traditional distribution systems were typically designed as meshed networks without accounting for DG integration, with protection schemes primarily focusing on selectivity and sensitivity. These schemes, including fixed overcurrent protective device (OCPD) settings, were based on the maximum downstream load, with minimal consideration for configuration changes [2]. The inclusion of DGs in MDSs introduces bidirectional power flows and variable SC currents, disrupting established protection principles [3]. Researchers have explored strategies to maintain OCR and DR protection coordination in MDSs with DGs, but this often reduces the sensitivity of protective devices due to changes in system configuration. A proposed approach utilizes smart metering data to adjust substation relay pickup settings in response to configuration changes in systems with DGs.

Conventional power systems operate as interconnected generating stations supplying distant loads through extensive transmission and distribution networks [3]-[4]. These systems primarily depend on traditional energy sources, such as coal, gas, hydroelectric, or nuclear power, which are increasingly uneconomical due to resource scarcity. Conventional energy sources also contribute to environmental pollution, rising power generation costs, concerns about resource sustainability, and challenges associated with centralized power generation.

In the above context, to meet the energy requirement, some unconventional power generations in the form of DGs, mainly from renewable types, require to be emphasized [5]. The modern development in the technology of small-level power generation is the main reason that fulfils the energy sector demand with the help of alternative power generation systems [5]. The small-scale power which is generated near the load end is known as distributed generation. Distributed generation (DG) systems can supply power to local loads and, when required, integrate with the conventional power grid [6]. In the future, the growing demand for electrical energy is expected to be fulfilled predominantly by renewable energy sources such as wind, solar photovoltaic (PV), tidal, small hydro, and geothermal power.

Among the available renewable energy resources; two power generation systems are widely used nowadays, and they are wind power generation (WPG) and PV systems. These have many advantages:

- One time installation cost
- Long life and easy to install
- Maintenance cost is less
- No environmental pollution
- High reliability and sustainability

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Therefore, grid-connected PV and WPG systems are significantly recognized for their contribution to eco-friendly power generation and abundant availability. In upcoming years, these resources are expected to largely contribute to power generation and therefore leading to high penetration in the conventional grid. These resources can be integrated through stand-alone mode or grid-connected mode, as per the requirements for improved performance of the power system [6], [7]. However, the integration of these DGs in the transmission and distribution system poses a major challenge for protection issues of the overall integrated power network. However, the intermittent variations in wind speed and solar radiations in WPG and PV power generation may build operational issues and disturbances problems into the grid [7]. Thus, energy storing devices can be integrated along with conventional power-generating resources to maintain the quality and reliability of the power supply [6]-[7]. Such power generation sources have potentially harmful impacts and several problems with the DG linked to the power grid must be considered seriously and objectively [4], [8]. Consequently, the current industry exercises to find a simple and precise technique for the identification and classification of disturbances [7]-[8]. Such disturbances or faults can be identified by proper and effective relay coordination [9].

The advantages of the integration of DGs are emergency backup, improvement in system performance, increased reliability and flexibility, reduced loading of transmission and distribution, pollution-free power generation, and improved security etc. These advantages are very useful for accomplishing the energy demand in industries and household purposes. Several transmission and distribution networks are remarkably affected by DG's incorporation. With increased penetration of the DGs, numerous issues emerge that need to be taken care of to secure the network. Some major challenges are present in the integration of DGs, such as power quality (PQ), load-frequency regulation, unintentional islanding events, the transition from grid-connected to isolated mode and protection issues, etc. The traditional electric transmission and distribution network was established without including DG services in the power system [10], [11]. But, DGs penetration into the framework, significantly affects the control and protection strategies of different components.

2. Transmission and Distribution System

The power system is an interconnected network designed to generate electricity, transmit it efficiently, and deliver it to load centers for consumer use. For electricity generation and transmission to be effective and economical, the system is divided into three primary subsystems: generation, transmission, and distribution [11]. At generating stations, primary energy sources are transformed into electrical energy, and the generated voltage is increased to transmission levels using step-up transformers. The transmission system carries the power closer to load centers, forming part of the distribution network, where voltage is reduced to suitable levels. The distribution system delivers electricity to end-users, with voltage further

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stepped down for residential, commercial, or industrial applications. Figure 1 illustrates the block diagram of a traditional power system. Electricity is generated as a three-phase supply and is stepped up to high voltage at the power substation. This high-voltage energy is transmitted over long distances via transmission lines. At the distribution substation, the voltage is stepped down to a level suitable for consumption. Transformers facilitate the process of stepping up and stepping down the voltage, after which the electrical power is distributed to various consumers.

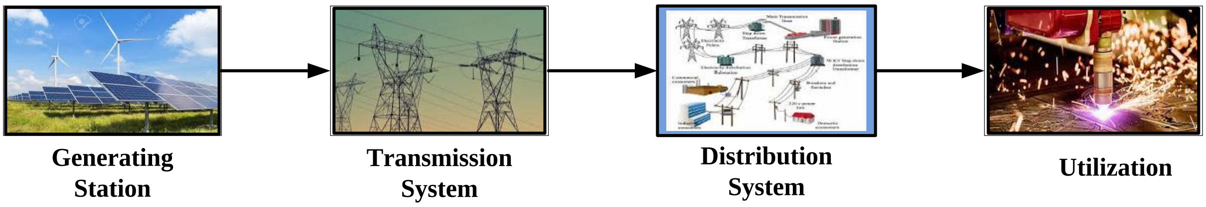

Figure 1. Block diagram of a power system

2.1 Detection of System Disturbance in Transmission and Distribution System

Disturbances in the power system can have a significant impact on certain transmission lines and distribution systems, while others may be less affected. Common issues include power quality (PQ) problems such as over-voltage, under-voltage, swells, sags, electrical notches, transients, flickers, harmonic distortions, electrical noise, and momentary interruptions caused by the operation of over-current protection devices. PQ disturbances are typically classified based on their magnitude and duration and are described differently across the literature [11]. These disturbances are broadly categorized into steady-state and transient-state phenomena. Steady-state disturbances, such as harmonic distortions, voltage flickers, and periodic notches, are characterized by their sustained presence. In contrast, transient phenomena, like impulses and oscillatory transients, are defined by their short duration. Voltage variations such as sags, swells, or interruptions exhibit distinct characteristics from other disturbances. To address the variability in defining these disturbances, it is crucial to classify them accurately based on their unique features. Detection of such disturbances is accomplished using active, passive, and hybrid methods [12].

Faults are usually caused by conductor breakdown or insulation failure. Certain causes of faults are mechanical failures, damages, unnecessary internal and external stress, etc. By enhancing system design, equipment efficiency, and servicing, the faults can be minimized [7]. The other abnormal conditions in the power system include voltage and current unbalance, over-voltage, under-frequency, reversal of power, temperature rise, power swings, power instability, etc.

Power System Technology
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2.2 Sympathetic Tripping

A trip unit is a component of a circuit breaker responsible for interrupting the circuit when a thermal overload, ground fault, or short circuit (SC) occurs. In an open circuit, current flow is halted by air or another insulating material within the loop. Power circuits use two types of trip units: electro-mechanical (also known as thermal magnetic) and electronic [11]. The electro-mechanical trip unit features moving parts and combines a current-sensitive mechanism with a thermal-sensitive system, which work together to mechanically open the circuit when necessary. In contrast, an electronic trip unit is a programmable device that monitors the current flowing through the circuit breaker and triggers a trip signal when required [12].

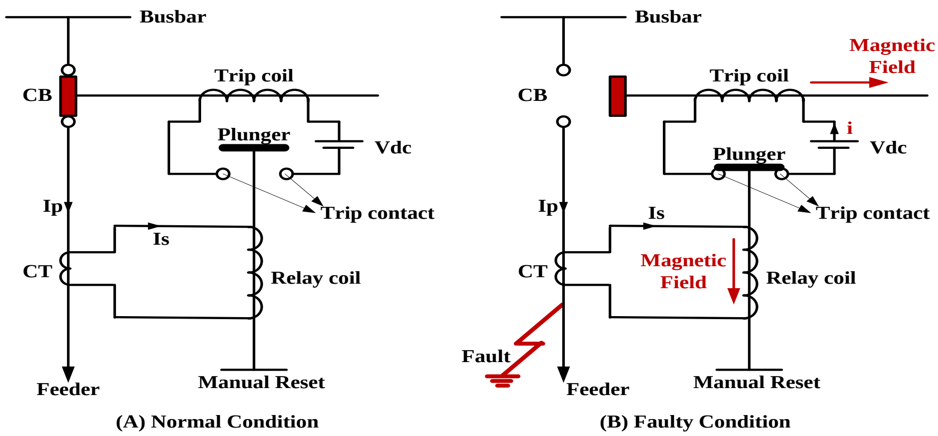

Figure 2. Mechanism of sympathetic tripping

Figure 2 depicts the two conditions; one is a normal condition and the other is a faulty condition. The trip circuit, which included a battery (VDC), trip coil, trip contacts, and relay coil, is shown in the above circuit. It will respond according to relay contacts or relay coil. A current transformer (CT) has its primary side connected to the power line for protection, while its secondary side is linked to the relay coil. In the event of a fault, the high current flowing through the circuit increases the secondary current (I_S) of the CT. This elevated current energizes the relay coil, creating a magnetic field that causes the trip contact in the CB to close. As a result, current flows from the battery, energizing the trip coil and generating a magnetic field that opens the CB contacts, halting the excessive current in the line. This process effectively isolates the faulty section from the rest of the system [13]. The described operation illustrates the concept of sympathetic tripping or testing of the CB.

2.3 Blinding of Protection

In recent years, new operating strategies have been implemented for power networks, and the amount of integrated DG is growing rapidly. The high rate of renewable energy resource incorporation has an immediate effect on the operation of existing power networks/ grids, and

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it also considerably affects the coordination of protective equipment. The involvement of DGs in distribution grids is initiating new challenges for protection problems, such as blinding feeder overcurrent protection, degradation of feeder overcurrent safety rating, recloser failure, recloser- miscoordination, etc., and causing failure of established protective devices [13]. In certain deployment cases blinding protection can become a serious issue. The blinding of relays also increases to some degree, when new DG systems are installed into the network. This can happen when simultaneous feeding of the fault is done by the DG unit and substation. The current flowing through the feeder relay is rising due to the SC impedances. Figure 3 shows the mechanism of blinding protection with the fault and DG penetration using an electrical switch (S_1).

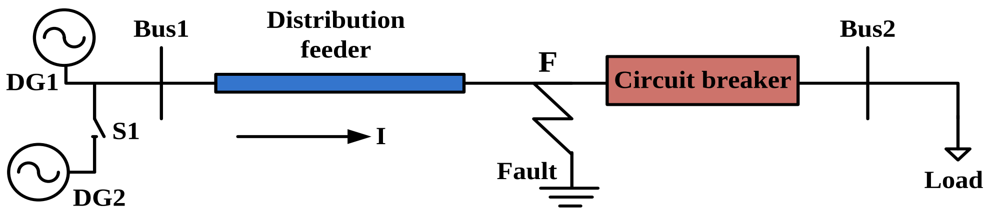

Figure 3. Mechanism of blinding protection

The integration of DG at the distribution level can significantly alter fault current levels. In a network with DG units, the fault current may exceed acceptable limits. Additionally, DG units can contribute fault currents to faults occurring on other feeders within the same substation or even at higher voltage levels, altering the direction of fault currents. A common protection issue in distribution systems is blinding, where relay coordination fails to operate correctly, particularly at the feeder ends with DG units [13]-[14]. Blinding of protection is more likely to occur in cases of double-line faults or faults involving high impedances.

2.4 Adaptive Zone Setting

The protection zone is identified as the part of the power network that is covered by the same protection scheme. If a fault occurs in any of the protective zones, only the concerned CBs contacts are opened within the particular zone [15]. Thus, it isolates only the faulty part without disrupting the rest of the power system network. The adaptive protection zone covers the whole power network and does not leave any portion of the network unprotected. The power system protective zone mostly depends on the machine's rating, its location, the possibility of faults, and the equipment's abnormal condition. Consider the two protection zones zone_1 and zone_2 that is overlapping each other. The F is the fault that occurs in zone_2, and due to this fault, the zone_2 CBs have tripped or opened along with the CB. Because of zone_2, zone_1 CB will also trip for other's fault in zone_2, which occurs to the right of the CB. Consequently, the unnecessary tripping of the breaker can only be tolerated in a particular region [16].

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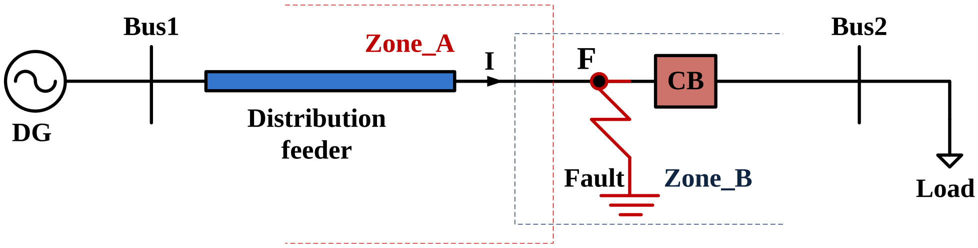

Figure 4. Overlapping zones of protection

Figure 4 shows a convinced amount of overlapping between the protective zones 1 and 2. The existence of some structural and operational changes in an integrated power network substantially modulates the current, voltage, and power and results in a substantial change in the measured impedance of a DR and the current of an OCR [15]-[16]. The mechanism that senses the fault of any of the units will have a higher sensitivity rate, and it will also have the ability to adapt to fast operating speed.

3. Protection Coordination or Relay Coordination

A protective relay is an electrical device positioned between the main circuit and the circuit breaker. It operates by detecting disturbances in the circuit and triggering the breaker to open, thereby isolating the faulty section if the disturbance is severe [17]. The relay assures the circuit equipment protection from any disruption that otherwise would be caused by the fault. All the relays' modules comprise of, most significant three fundamental units, i.e., sensing, comparing, and control unit [17]-[21]. The sensing unit, often also called the measuring unit, responds to the change in the actuating amount, in the case of OCR, the current in a secured system. The comparing unit serves to compare with a pre-selected relay setting and the action of the actuating quantity on the relay. The control unit on a relay pickup conducts a sudden change in the controlled quantity such as the active current circuit being closed.

All relays are used for SC safety work based on the current and voltage they receive from CTs or PTs [18], [19]. Failures in the power circuit are demonstrated by individual or proportional changes in current and voltage applied to the relaying protective equipment. There is some distinctive variation in these quantities for each type and location failure. Different types of protective relays are available, each designed to identify a specific variation and act as a response to it. The difference could be in terms of phase angle, magnitude, change of rate, frequency, harmonics or waveform, condition length, etc. Electromagnetic attraction or induction is the main principle employed in relay operation. In an electromagnetic attraction type relay, a plunger is strained into a solenoid or an armature is attracted to the poles of an electromagnet. In the case of electromagnetic induction relays, these relays can be controlled either by DC or AC [20]. The concept of induction motor is used, and electromagnetic induction produces the torque. Such relays are only powered by AC quantity.

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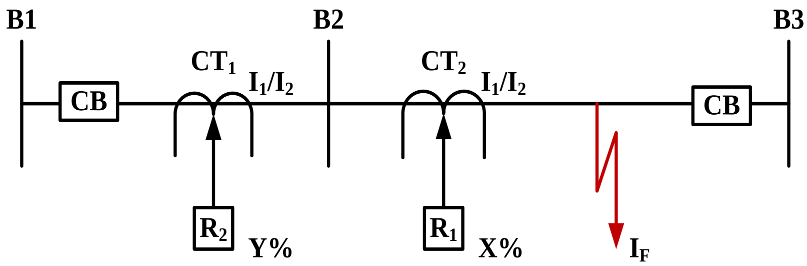

Figure 5. Representation of relay coordination

Figure 5 illustrates the fault current (I_F), with relay R_1 configured at X%, relay R_2 at Y%, and the CT ratio set to I_1/I_2. A time gradient margin of TS seconds, specified by the manufacturer, is maintained for discrimination between the relays. The operation time is determined by relay characteristics, the plug setting multiplier (PSM), and the time multiplier setting (TMS) or time dial setting (TDS), based on the standard operation time equation [20]-[21]. The fault current and CT ratio dictate the relays' current, with the current threshold predefined by the manufacturer. If the fault current surpasses this threshold, the relay issues a trip signal to the CB, causing its contacts to open due to the magnetic field generated in the trip coil.

In the event of a fault in the power network, the primary relay (PR) is the first to activate and isolate the affected section. If the PR fails to function, the secondary or backup relay (BR) intervenes promptly within the shortest possible time. This collaborative functioning of two relays is referred to as relay coordination in the protection system. The time difference between the operations of the primary and backup relays is known as the coordination time interval or margin (CTI) [16]-[21]. The operating time of the BR is always slightly longer than that of the PR. This process is collectively termed protection coordination.

Developing a robust and efficient power network with synchronized relays is a significant challenge for relay designers. To address this, various programming and optimization methods are widely employed to determine optimal relay settings for transmission and modern distribution systems. A suitable combination of primary and backup relays is established to prevent relay malfunctions and unnecessary power outages. Numerous optimization strategies have been utilized to achieve effective coordination among interconnected relays [19]. Researchers have introduced several specific optimization techniques, and there has been a growing interest in using artificial intelligence (AI) for relay coordination and management. Techniques such as simplex methods, graphical selection procedures, differential evolution (DE), genetic algorithms (GA), particle swarm optimization (PSO), grey wolf optimization (GWO), symbiotic organism search (SOS), teaching-learning-based optimization (TLBO), and ant colony optimization (ACO) have been explored. Additionally, hybrid approaches

Power System Technology
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combining these techniques with other linear and nonlinear programming methods have been proposed and shown varying levels of success [19]-[21].

For the protection of transmission lines and distribution systems in radial, meshed, and ring networks, directional relays (DRs) and directional overcurrent relays (DOCRs) are highly effective and cost-efficient solutions for isolating hazardous faults. Each protection system is designed to operate within its defined "protection zone" and avoids triggering actions outside this sensitive area. While many optimization techniques have been applied, further research is necessary to enhance relay coordination in complex power networks.

In this context, first of all, an objective function is obtained for the respective constraints. For the DOCRs settings, TDS/TMS, pickup current, and total operating time are optimized by several optimization techniques or algorithms [21]. Meanwhile, in the DR, protective zone settings and total operating time are optimized. Without optimization techniques or algorithms, proper relay settings are challenging to obtain. Therefore, optimization techniques or algorithms play an essential role in the protection zone and relay coordination objective in the power protection system.

4. Literature Review

This section provides an overview of the state-of-the-art techniques and relay coordination strategies for DOCRs and DRs, highlighting the challenges associated with integrating DG into power networks. It also reviews research efforts related to fault detection, classification, and relay coordination in meshed distribution and sub-transmission systems through simulation studies and evaluations. Since the performance of power system protection is highly sensitive within the network, it is explored in detail. The subsequent sections emphasize relay settings, relay characteristics, and relay coordination in sub-transmission or distribution systems with hybrid DG penetration.

4.1 Protection Challenges with Variable DG Penetration

In the power system restructuring, many challenges come in the protection field, mainly due to DGs integration and relay coordination challenges. Therefore, related research is being carried out by power protection engineers.DG resources are penetrated in the sub-transmission or distribution framework to provide connectivity on a broad scale as well as operational support for grid-connected operation [1], [22]. The introduction of power generation from DG sources has several advantages as mentioned in the earlier section. On the other hand, an increase in DG penetration into the traditional utility grid and its intermittency characteristics generate many operational, control, and security issues, increased safety threats and hazards of damage, which may also affect the power system output [23]. Among the various DG-related problems, relay coordination and power quality disturbances depict a major concern, which harms the power system apparatus and the DG itself. Hence, these challenges must be addressed and

Power System Technology
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isolated efficiently for the protection of the power system equipment. Also, these disturbances or SC need to be identified accurately through suitable classifiers to apply appropriate mitigation techniques [24]. Therefore, in this thesis work, the study of important issues related to relaying coordination has been considered. The following sections describe the review of works reported by different researchers, on the above-identified concerns. As a result of the increasing number of protection technologies, problems are resolved more quickly, enhancing safety through improved power system stability, and prolonging equipment life [25].

The high-level penetration of DGs is becoming a new problem for conventional power distribution networks. Increased DG penetration can be promoted by the use of soft open points (SOP) and network reconfiguration [25]. SOP is a power electronic device, which is deployed between adjacent distribution network feeders, which is capable of regulating active and reactive power flows via its connecting nodes. In [26], the researchers have presented an overview of the main problems surrounding the incorporation of distributed generation into electrical power networks that are of primary importance. The fundamental drives are behind the emphasis on DG integration, particularly of renewable energy-based, addressed in several countries all over the world [25]-[27]. It also analyzes the implications of transmission network operation and expansion that resulting from connecting large quantities of DGs of different energy conversion networks, that focusing on issues related to effects on stable state service, hazard analysis, safety management as well as dynamic behavior analysis [26]-[27].

As per the International Renewable Energy Agency (IRENA), the number of countries that have ratified the renewable energy requirements has increased to 180. These nations target to synchronize the DG to the grid, as well as small-scale wind power and PV plants [28]. However, voltage regulation in rural distribution networks is a major constraint in accommodating distributed generation. Here, a decentralized voltage control system has been introduced in which DG units switch between power factor control and voltage control to minimize voltage regulation problems [29]. In [30], the researcher explores the significant impact of integrating large-scale DG systems in the presence of non-linear loads. They examine how various DG integrations on the grid side influence the generation of current harmonics by downstream non-linear loads, leading to total demand distortion. While this adheres to IEEE standards, specific loading conditions may result in considerably elevated total harmonic distortion levels at the grid side. In [31]-[32], a new principle for phase selection based on waveform correlation is proposed for transient voltage, which is valid for the protection of intermittent wind or PV power plants. The 3-phase transient voltage waveforms of specific types of faults have distinctive correlation characteristics. The fault phase may be chosen within a short time span. This depends on the correlation capabilities [31].

4.2 DOCR-DOCR Coordination and Hybrid DOCR-DR Coordination

Power System Technology
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The integration of DG units into meshed distribution networks (MDN) increases the fault current levels, disrupting the existing CTI of overcurrent protection relays [33]. A practical approach to mitigating DG's adverse effects on protective element coordination is re-coordinating the relays by incorporating a unidirectional fault current limiter (UFCL) between the main grid and the microgrid [33]. In [34], the researcher proposed an optimal coordination of DOCRs in combined overhead and cable distribution systems using linear programming techniques. Their approach emphasized determining appropriate relay settings to minimize power flow interruptions and avoid miscoordination during relay operation [7], [13], [17]-[21], [34]. In [35], the researcher highlighted the synchronization of overcurrent relay directionality by considering faults at various locations within the power network. The objective function (OF) for relay coordination, introduced in 1988 [36], utilizes linear programming to optimize the total relay operating times for faults within their primary protection zones [36]. OCRs remain a cost-effective and straightforward option, widely employed as primary protection in distribution and sub-transmission systems and as backup protection for phase faults in transmission systems, despite advancements in protection schemes [37]. A novel approach to DG system protection coordination by utilizing inverse-time characteristics for directional overcurrent protection is introduced in [38]. The key challenge in protection coordination involves accurately determining all inverse-time characteristic parameters to ensure suitably short trip times and sufficiently long selectivity times [27], [38]."

The operating time of a DOCR primarily depends on two parameters: TMS and Ip [39]. Achieving coordination between relays in MDS and minimizing the total operating time requires selecting optimal TMS and pick-up settings for the overcurrent relays [22], [24], [39]. The integration of DG significantly affects the protection system, with the impact varying based on the nature of the distribution system (radial or meshed) and the type of DG. Protection systems linked to DG depend on the DG type and its connection at the point of common coupling (PCC) through an inverter [40].

Inverter-based DGs produce lower fault current levels compared to synchronous DGs, which substantially influences traditional protection systems [41]. Dual-setting DOCRs offer both primary and backup functionalities within a single unit, with separate settings programmed for forward and reverse directions. Each direction operates independently, utilizing distinct objective functions to optimize relay settings, thereby reducing overall operating time and enhancing performance [41], [42]. Relays with higher current settings should allow 110% of the rated current to flow during normal conditions. Microprocessor-based and electronic relays typically allow current setting adjustments in 5% increments [43]. In transmission networks, OCRs serve as backup protection, while in distribution networks, they act as primary protection, primarily safeguarding feeders. To protect various sections of a feeder, multiple OCRs may be required [4], [42], [44].

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Various optimization algorithms can be utilized to solve the objective function. GA is one such method that creates a population of mathematical objects, each with an associated fitness value, and evolves them into a new generation or population [44]. This process ensures proper relay coordination and reduces operating time by determining the optimal TMS values [44], [45]. By optimizing both the TMS and Ip settings, efficient relay coordination is achieved, minimizing the relays' operating time [45]. Load flow analysis is another essential tool, providing insights into line losses, voltage profiles, and the loading of lines and transformers. Relay pick-up values can also be derived from load flow calculations. Additionally, load flow analysis aids in power factor correction by determining the appropriate size and location for capacitors [46]. In radial systems, power flow is unidirectional, making them suitable for scenarios where substations are close to load centers and voltage levels are low. This configuration is straightforward and cost-effective. However, its main limitation is that a fault in a specific feeder impacts all connected consumers, regardless of the affected feeder. Radial systems are also only feasible for short distances, as voltage fluctuations become significant over longer distances [47].

An adaptive relaying algorithm with multiple relay group settings offers an effective solution for coordination protection. Studies in [18], [48] proposed approaches to address challenges arising from the large-scale integration of DERs into power networks. While relay organization in microgrids is typically designed for symmetrical faults, these systems can also experience phase or ground faults [49]. The impact of DG on relay coordination depends on the size, type, and location of the DG. Consequently, relay settings, such as TMS and Ip, must be adjusted [50]. Various optimization techniques have been employed to tackle relay coordination challenges, with non-linear algorithms proving effective in optimizing both TDS and PS. Sequential quadratic programming, random search methods, and gradient-based algorithms have been explored in this context [51].

In [52], the author proposed two strategies for adapting overcurrent protective device settings in radial distribution systems (RDS) with DG, leveraging smart meter data. The first is a planning-based approach that uses seasonal overcurrent pick-up settings for substation relays, while the second calculates peak demand over two 12-hour cycles based on prior-day data. Smart meters play a critical role in outage management, a priority for utilities in implementing future smart grid technologies [52]-[53]. However, in [53], the author suggested combining smart meters with voltage monitoring capabilities and impedance-based fault location methods to enhance fault detection and service restoration. Furthermore in [54], the researcher introduced the SOS algorithm, a reliable and efficient metaheuristic approach for solving numerical optimization and engineering design problems. The SOS algorithm simulates the symbiotic interactions among organisms in their environment. A key advantage of SOS is its ability to function without requiring algorithm-specific parameters, making it highly adaptable [55].

Power System Technology
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DOCRs are designed to send trip signals in one direction while preventing such signals in others. However, their performance in microgrid protection is limited by the need to adjust fault current magnitudes for different operating modes. DOCRs may serve as primary relays during faults and can function as gridlock relays in specific situations [56]. The minimum breakpoint set (MBPS) plays a critical role in achieving optimal synchronization of DOCRs, though identifying MBPS in large-scale power grids can be challenging and time-intensive [57].

Bidirectional power flows in MDS introduce complexity to protection schemes compared to the unidirectional flows in radial systems [41], [58]. This complexity increases with the network's size and scale [59]. Dual-setting DOCRs have recently emerged as an effective solution for these challenges. Coordination is achieved by optimizing parameters such as Ip and TDS. Relay characteristics are typically categorized as standard-inverse (SI), very inverse (VI), and extremely-inverse (EI) [60]. Optimization techniques like non-sorting GA have been applied to enhance coordination performance [61]. Despite advancements, miscoordination issues persist. Optimal relay settings are determined by modeling synchronization constraints for specific fault positions, such as near-end or far-end faults on the feeder. Maintaining proper relay configurations remains a critical challenge in power network protection [62]. Recent studies have extensively utilized optimization approaches to address protection coordination in interconnected networks [41], [58], [63]. These analyses often control DOCR tripping times using inverse time-current characteristics [63].

4.3 Impact of DG Penetration on Hybrid DOCR-DR Coordination

The presence of DG affects the magnitudes and directions of short-circuit currents, potentially disrupting the coordination between OCRs and DRs [64]. In MDSs, the inclusion of DG has made the protection system's operational cycle a critical issue, particularly to avoid unnecessary tripping of DG units. A novel time-current-voltage tripping characteristic for DOCRs is introduced in [65] to reduce overall relay operating times in meshed distribution networks. OCRs are vital for power network protection, and their integration with DRs enhances both reliability and security. However, it also introduces complexities in relay coordination [66]. Recently, advanced optimization techniques have been employed to compare mathematical models for their efficiency in solving nonlinear problems, improving speed, and eliminating complex calculations [67]. This research focuses on minimizing the operating time of OCRs and DRs while ensuring proper coordination. DRs typically serve as primary or backup relays in transmission networks, while OCRs act as backup relays (BRs) [68].

An innovative coordination optimization methods, in [70] presented a modern digital distance relaying method to protect against open conductor faults and ground faults occurring simultaneously on the same phase of a series-compensated double circuit line. Traditional

Power System Technology
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digital distance relays with series compensation systems often fail to provide adequate protection under such conditions [71]. Solutions have been suggested to address mutual coupling between double circuit lines and the impact of fault resistance [70], [71], though the influence of series compensation on relay coordination remains understudied [72]. For coordinating OCR-OCR and OCR-DR systems, identifying critical fault locations (CFLs) is essential. CFLs are fault points where the time difference between primary and backup relays is minimized. Coordination is established by deriving constraints based on time differences at CFLs.

In [73], the author explored the impact of offshore wind turbines connected to AC power grids via HVDC systems. SC fault in transmission lines connected to the HVDC network through PCC can influence DR performance on the AC grid. This is due to the rapid reactive power management response of HVDC grid-side converters in compensating for PCC bus voltage drops. A hybrid power system combining wind and photovoltaic (PV) modules as primary power sources, with battery storage and diesel generators as backups, has been analyzed using a multi-objective PSO–GWO optimization method. This approach minimizes total costs and CO2 emissions over a 20-year period [74]. A comparison of PSO–GWO against standalone PSO and GWO techniques highlights the benefits of combining these methods.

Research in [75] critiques traditional concepts in relay protection settings and configurations due to significant DG penetration. For instance, fault impedance coverage for three-phase faults can extend up to 300% of the positive-sequence impedance. This fault current can be reduced to 86.6% for phase-to-phase faults [75]. The implementation of distance-based protection schemes, using mho and quadrilateral components, is thoroughly analyzed in the literature for a future-proof roadmap [76].

Challenges in adaptive protection include designing efficient settings for artificial neural networks (ANNs) due to dynamic network configurations. For example, multilayer perceptron neural networks (MLPNNs) have been used for fault detection, though their speed and accuracy require further justification [77]. Distance protection strategies for radial distribution systems (RDSs) incorporating DG are gaining traction due to their benefits over overcurrent protection [78]. Issues such as intermediate sources (IS) and fault resistance (FR) have been identified as influencing factors [79]. A multi-zone distance protection approach for RDSs with DG is suggested in [80], addressing IS and relay coordination challenges.

In [81], the researcher examined interconnected wind power DG systems' performance in MDSs, highlighting their impact on power flow, voltage stability, and system reliability. Increased wind penetration necessitates interconnections and long lines, which may push systems closer to their limits unless costly upgrades are implemented [82]. Experiments using real-time digital simulators (RTDS) have analyzed relay performance under dynamic conditions, where transient fault currents pose additional synchronization challenges for

Power System Technology
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DOCRs and DRs [83]. Optimization approaches, including modified PSO techniques, address these issues by balancing population size and iteration requirements for objective functions [84].

In [85], the author proposed optimal coordination techniques for DRs and DOCRs by considering Ip as an optimization variable along with TMS and relay characteristics. GWO has been effectively applied for achieving optimal settings [86]. Coordination scenarios such as DR-DR, DOCR-DOCR, and DOCR-DR have been developed to minimize relay tripping times [87]. Extensive research addresses technical barriers in relay coordination, emphasizing fault location accuracy and maintaining proper backup configurations. Optimal relay synchronization ensures uninterrupted and reliable power network operations [88].

A novel oppositional Jaya (OJaya) algorithm with a distance-adaptive coefficient (DAC) is introduced in [89] to enhance DOCR coordination. This method minimizes primary relay (PR) operating times by optimizing decision variables such as TDS and Ip [90]. Future research focuses on applying OJaya to larger systems and microgrids. DOCR coordination challenges involve mixed-integer nonlinear programming (MINLP) techniques for discrete and continuous parameters [91]. Advanced methods like PSO compute Ip values for rapid data processing in smart grid applications [92].

In [93], the author examined DG impacts on SC capacity and load flow analysis, emphasizing their importance for effective protection systems. The rise of DG adoption is attributed to environmental awareness, technological advancements, and increasing electricity demand. However, high DG penetration introduces challenges such as incremental fault currents, influenced by DG size, type, and placement, as well as transformer configurations and grounding arrangements [94].

5. Conclusion

Overcurrent relay coordination plays a critical role in ensuring the reliability and safety of transmission and distribution systems. This review highlights the fundamental principles, methods, and advancements in relay coordination to achieve selective, dependable, and time-efficient fault isolation. Traditional time-current characteristic (TCC)-based methods have served as a foundation, but modern challenges, such as increased grid complexity, integration of renewable energy sources, and evolving load patterns, demand innovative approaches. Emerging techniques like adaptive relays, optimization algorithms, and machine learning offer promising solutions to enhance coordination, minimize fault-clearing times, and reduce cascading failures. Future research should focus on integrating these advanced methods with smart grid technologies to meet the demands of modern power systems while maintaining system stability and resilience.

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