Advancements in Protection Coordination of Microgrids: a Comprehensive Review of Protection Challenges and Mitigation Schemes for Grid Stability

Pratibha Singh, *Graduate Student Member*, *IEEE*, Uttam Kumar, Niraj Kumar Choudhary, *Senior Member*, *IEEE*, and Nitin Singh, *Senior Member*, *IEEE*

***Abstract*—The advancement accomplished in power systems over the last decade has enabled the extensive integration of renewable energy sources. It has resulted in enhanced efficiency and reliability of the system by meeting the load demand from small, local sources known as distributed generators (DGs). Consequently, this has led to the concept of microgrids (MGs). Nevertheless, there are operational challenges such as bidirectional power flow, fluctuations in fault current level, and protection issues such as blinding, false tripping, and unintentional islanding. Synchronous generator-based distributed generators (SGDGs) may experience a loss of synchronism across the generators due to undesirable events, such as abrupt changes in demand or faults. Similarly, voltage instability concerns may arise with inverter-based distributed generators (IDGs). This paper provides a thorough review of the concepts of critical clearing time (CCT) and grid code compliance in relation to SGDGs and IDGs, respectively. It provides a comprehensive analysis of the existing literature on several protection strategies used for reducing the adverse effects of DG integration. It highlights the characteristics, benefits, and constraints of these schemes. Finally, this paper presents the conclusion and outlines the potential areas for future study in the field of protective relaying methods, specifically addressing the issues posed by current power systems.**

***Index Terms*—Directional overcurrent relays, fault ride through, microgrid, protection coordination, transient stability, user-defined protection.**

Received: December 23, 2023
Accepted: July 12, 2024
Published Online: November 1, 2024
Pratibha Singh (corresponding author), Uttam Kumar, Niraj Kumar Choudhary, and Nitin Singh are with the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Prayagraj 211004, India (e-mail: pratibha.2021ree54@mnnit. ac.in; uttam.2022ps17@mnnit.ac.in; niraj@mnnit.ac.in; nitins@mnnit.ac.in).
DOI: 10.23919/PCMP.2023.000250

NOMENCLATURE

A. Abbreviations

CCA	critical clearing angle
CCT	critical clearing time
CB	circuit breaker
DFIG	doubly fed induction generator
DOCR	directional overcurrent relay
DG	distributed generator
DN	distribution network
DS	distribution system
FCL	fault current limiter
FRT	fault ride through
GA	genetic algorithm
GC	grid connected
GWO	grey wolf optimization
IDG	inverter based DG
ISL	islanded
MAS	multi-agent system
MG	microgrid
MINLP	mixed integer nonlinear programming
PCC	point of common coupling
PD	protection device
PS	power system
PSO	particle swarm optimization
PV	photovoltaic
RES	renewable energy sources
ROT	relay operating time
SCC	short-circuit current
SGDG	synchronous generator-based DG
UI	unintentional islanding
VSG	virtual synchronous generator

I. INTRODUCTION

Large-scale power generation from fossil fuels is associated with various issues, including greenhouse gas emissions, larger carbon footprints, and low energy efficiency. A decade-high surge in coal and gas prices due to recent conflict in Europe and around the world has raised the thermal power plant's operational costs since 2022. Renewable energy sources (RESs) such as wind, solar photovoltaic (PV), hydropower, and biofuel technologies are integrated into the modern distribution systems (DSs). This integration has many benefits, including enhanced overall efficiency, lower carbon footprints, conversion into smaller renewable energy source-based MGs, and reduced equipment expenses resulting from shorter transmission distances. Integrating distributed generators (DGs) into the systems offers supplementary benefits, including localized generation, continuous power supply, energy management, voltage support, and demand response [1].

In accordance with the United Nations' objective to achieve net-zero emissions by 2050, there has been a significant increase in dependency on wind and PV-based distributed generation systems. This trend has been particularly pronounced since the COVID-19 pandemic and the resulting shifts in world diplomacy. The implementation of environment-friendly technology, such as automobiles powered by liquid hydrogen fuel, offers a significant role in mitigating global warming and fostering international research collaborations, as shown in Fig. 1.

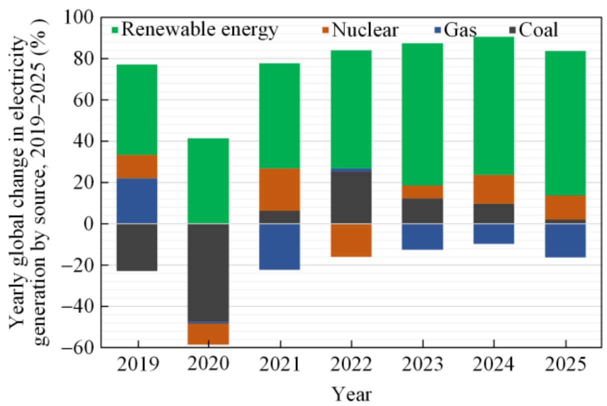

Fig. 1. Electricity generation and projections by different sources.

As of 2022, India's total installed generation capacity was 410 GW, including 236 GW fossil-fuel powered plants, 52 GW hydroelectric power plants, and 115 GW RESs such as solar PV and wind. India has planned to increase the 115 GW RESs to 500 GW by 2030 [2]. With the increasing population and climatic concerns, it is crucial to increase the use of DGs in the DSs.

Nevertheless, the increase in DG penetration creates new challenges, e.g., bi-directional power flow resulting in fluctuating current levels in transmission and distribution lines. It also leads to voltage sag/swell conditions [3], power quality degradation, loss of synchronism among synchronous generators (SGs) [4], and impacts on the sensitivity of protection devices (PDs) causing poor coordination [5]. Additionally, it presents various protection challenges such as unintentional islanding, blinding of protection, and false tripping [6].

Some of the key factors influencing the steady-state current and voltage levels are discussed in [7] and highlighted as follows:

1) Mode of operation of microgrids (MGs).
2) Type of DGs connected.
3) The size of the connected DGs.
4) The bus voltage at which DGs are to be connected.
5) Type of fault present in the system.
6) Short circuit level at the point of DG integration, and earthing conditions.

Figure 2 shows the integration of different types of DGs in a radial DS, classified as rotating machine-based and inverter-interfaced DGs.

Under undesirable events, such as a fault, the fault current and voltage levels vary depending on the type and location of DGs. SGDGs, offer a high short-circuit current (SCC) capacity of up to 5–6 times the nominal load current [8]. On the other hand, IDGs limit the SCC between 0.5–2 p.u. [9]. The high current contribution of SGDGs may disrupt the transient stability of the system, resulting in a loss of synchronization among the SGs. The loss of synchronism is a crucial issue for the generators, as it can lead to generator damage, frequent load shedding, and a shift in the operating mode of the MG from grid-connected (GC) to islanded (ISL) mode. Similarly, if the IDG integrated systems fail to meet the LVRT grid code criteria during a fault scenario, it may result in instability of voltage and frequency in the system [10].

References [11]–[14] specifically address the stability analysis and control of virtual synchronous generators (VSGs) in grid-forming operation. The studies use FACTs devices to improve stability in various MG configurations and present a virtual power calculation approach to facilitate a smooth transition from ISL to GC mode. Such transition is essential for maintaining the stability of the MG throughout different operating modes. References [15]–[17] address the stability issues in different types of wind generator-based systems, including LVRT challenges faced by the doubly-fed induction generators (DFIGs) and the decentralized hybrid systems consisting of wind-diesel-battery energy storages. The studies also delve into the methods for enhancing LVRT capabilities, such as using braking resistors. The stability issues in solar PV-based systems are discussed in [18], [19], where the transient voltage stability issue in low-voltage distribution networks (DNs) is analyzed using solid-state transformers during disturbances, and the effect of fault location on transient voltage stability is studied. The stability analysis of multiple parallel IDGs using VSG schemes with non-linear loads is discussed in [20], in which a small-signal model is derived for such systems.

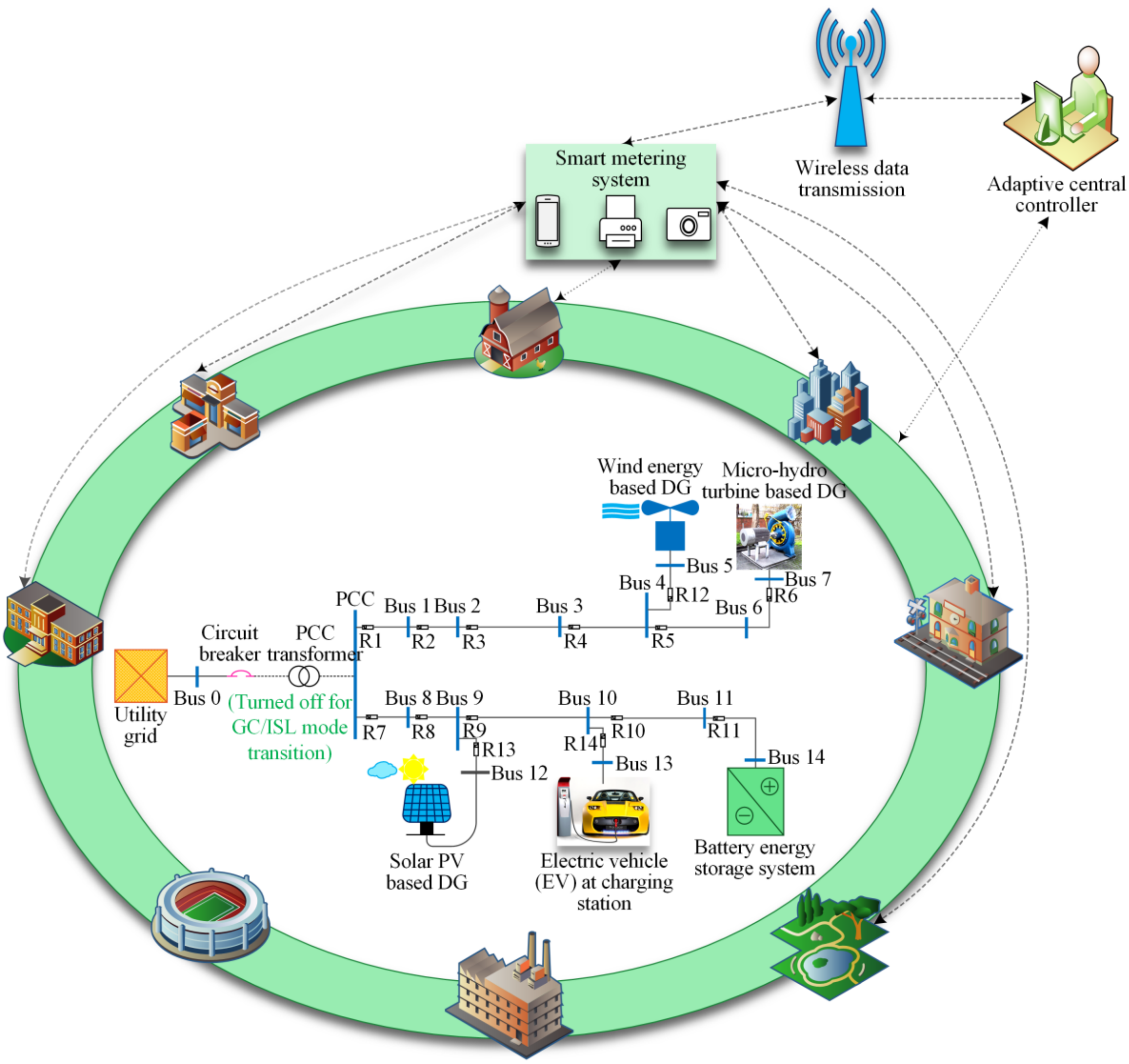

Fig. 2. DG integrated radial DS.

The current techniques available to address stability issues in DG-based systems are as follows:

1) Optimal size of the incoming DG.

2) Addition of an enhanced relaying system for proper coordination between PDs.

3) Employing additional PDs such as fault current limiters (FCLs), surge arresters, etc.

4) Implementing enhanced fault detection techniques.

5) Implementing voltage regulation and power factor control strategies in DG-based systems.

6) Utilizing advanced control systems and 5G communication protocols for coordinated DG operation.

7) Implementing proper grounding techniques for DG integration.

Furthermore, system stability is impacted by the type of load connected and the effectiveness of the control approach used for the DG interface. The control strategy of the IDGs has a significant impact on the stability of the MGs. In islanded MGs, control techniques such as droop and VSG control are often used to promote voltage and frequency stability. Droop control involves the adjustment of voltage and current sharing, while VSG control emulates the behavior of grid-forming inverters as voltage sources. Both control techniques aim to stabilize the power level of the MGs, especially in the presence of uncertainties and fluctuations caused by the DGs.

Most DGs inject active and reactive power into the grid. MGs need active energy management and effective control strategies to operate reliably and efficiently. These solutions are crucial since DGs have varying power outputs as compared to conventional power sources.

This review paper primarily focuses on the protection coordination strategies for minimizing stability issues in DG-based systems. Figure 3 illustrates a notable advancement in protective relaying systems, transitioning from traditional methods based on current, voltage, distance, and differential approaches to modern user-defined numerical relays.

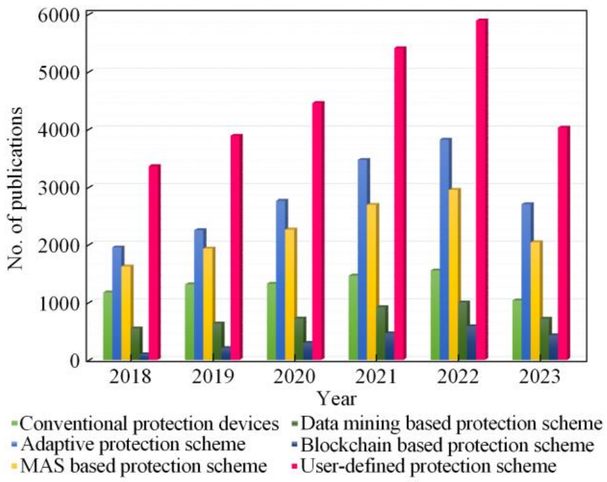

Fig. 3. Evolution of protection coordination schemes over the past five years.

Reference [21] suggests a cost-efficient method that involves disconnecting DGs during fault occurrences. This strategy relies on the optimal setting of relays to provide effective coordination among PDs. In [22], the deployment of various fault isolating devices, such as circuit breakers (CBs) and relays, is explored. The typical protection methods consist of overcurrent and overvoltage relays, fault current limiters (FCLs), directional overcurrent relays (DOCRs), fuses, and reclosers. Due to notable advancements in the architecture of PSs, researchers have proposed contemporary technologies such as blockchain [23] as a supervisory scheme to protect the system's security, prevent cyberattacks, and improve coordination among PDs.

Additionally, data mining technology is employed for efficient and real-time coordinated control. Reference [24] utilizes data mining technology to create an intelligent protection technique for various operational faults by combining the ideas of decision tree and wavelet transform. Multi-agent systems (MAS) technology is used to enhance the protection of MG by enabling the system to be autonomous, self-healed, and more resilient. Reference [25] presents a MAS architecture designed for grid protection, fault identification, isolation, and service restoration. In [26]–[28], several novel soft computing strategies used with traditional protection systems are explored, including user-defined protection coordination techniques that consider the particular attributes of DG-based systems to enhance the reliability and stability of the system. The primary objective of these advanced protection coordination schemes is to address the stability issues in DG-based systems by using state-of-the-art technologies and intelligent algorithms.

This paper highlights the significance of protection coordination schemes in DG-based systems for maintaining transient and voltage stability. This study is based on the thorough evaluation of 389 references. To identify papers relevant to this research, topic relevancy, assessment of abstracts, usage of methodology, test bus system (experimental or simulation-based), publication date within the previous ten years, and availability of full text are among the criteria considered. As shown in Fig. 4, 214 references are selected for further evaluation after rigorous screening. The main contributions of this research are as follows:

1) To assess the impact of DGs on the transient stability of the system to understand the dynamic behavior and stability margin under different fault scenarios and DG penetration levels.

2) To investigate the effects of IDGs on voltage stability and fault ride-through capability to address the issues of voltage regulation, reactive power compensation, and islanding detection.

3) To conduct a comparative analysis between conventional and modern technology-based protection schemes to evaluate the performance of relay characteristics, MG operational modes, methodologies, and optimization algorithms. It is beneficial to identify the advantages and limitations of different protection schemes, and to propose the best-suited scheme for any system configuration.

4) To present the comprehensive survey of protection schemes influenced by transient stability and voltage considerations, such as voltage sag and swell duration. It is beneficial to provide an overview of the existing literature, and highlight the research gaps and future scope of work.

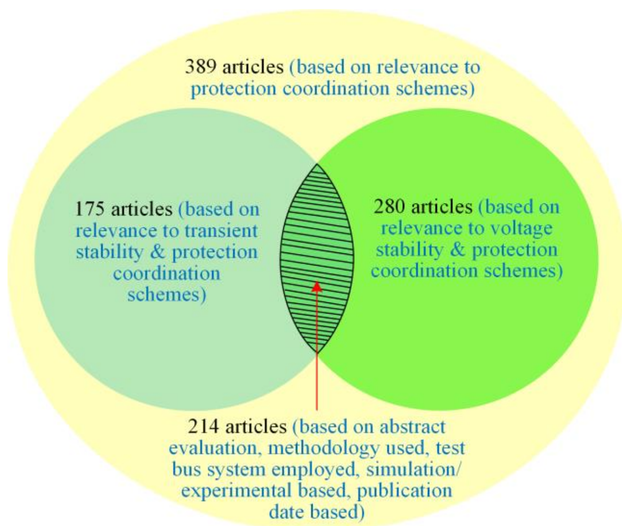

Fig. 4. Selection procedure of relevant articles for the literature survey.

The study also presents a critical analysis and comparison of different protection schemes, and identifies the key challenges and opportunities for future research. The subsequent sections of this article are outlined as follows. Section II presents the literature survey, emphasizing the adverse effects of DG integration on the stability of MGs. Section III overviews the protection challenges associated with modern PSs due to DG integration, while Section IV delivers an in-depth survey of diverse protection schemes to mitigate the adverse effects of DG integration. Finally, Section V presents concluding remarks and outlines future research prospects.

II. Effect of DG Integration on the Stability of the System

Incorporating DGs into MGs raises several stability issues that must be addressed to ensure reliable and secure operation. This research aims to comprehensively analyze these challenges and provide efficient techniques to alleviate them effectively.

A. Transient Stability

A key aspect of this study is to analyze the impact of DGs on the transient stability of the system. Transient stability, also known as rotor angle stability, pertains to the ability of a power system to retain synchronized operation of SGs following a disturbance. Figure 5(a) illustrates that in a system integrated with SGDGs, the transients occurring under the fault events may cause a loss of synchronism among the SGs.

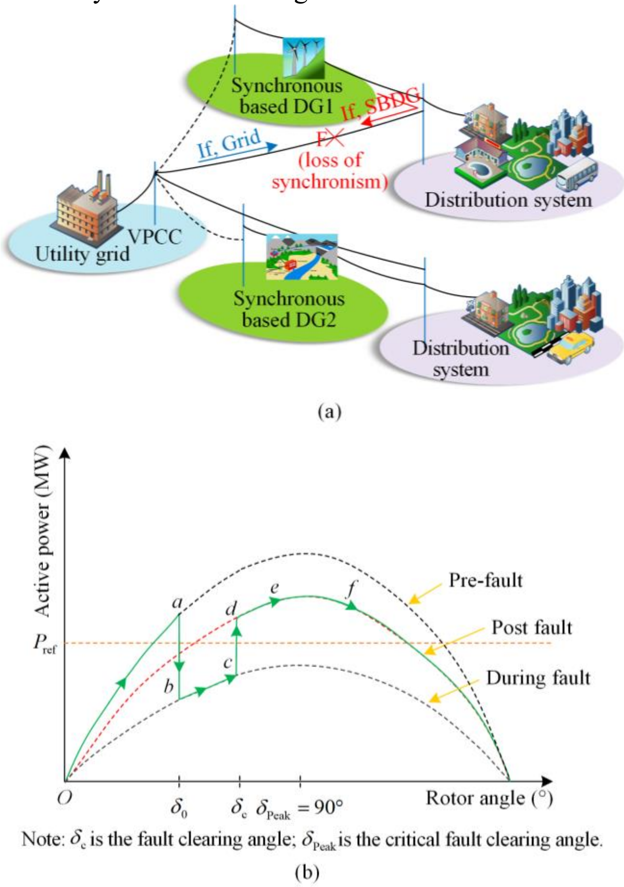

Fig. 5. Transient stability influenced by DG and different power angle curves. (a) Impact of DG integration on the transient stability of the system. (b) Power-angle curve under fault condition.

The stability under this condition is upheld by the inertia of the SGs. A higher amount of rotational mass possessed by an SG result in reduced responsiveness of its rotor, leading to acceleration or deceleration. Therefore, due to the substantial rotating mass within interconnected PSs, it is desirable for these systems to remain stable following a disturbance. However, in the case of a critical fault, such as a three-phase fault, the change in the power-rotor angle curve is shown in Fig. 5(b). As seen, the state of active power before, during, and after the fault occurrence clearly shows that the system operates at reduced power (curve *d-e-f*) if the fault is not cleared before the critical fault clearing time. The transients continuously persist in the system and degrade the power quality.

The integration of IDGs into the grid, as explained in [29], follows similar principles and considerations for maintaining overall system stability. However, power generations of by DGs such as solar PVs, and fuel cells, do not contribute additional inertia to the system. Furthermore, power electronic interfaces also separate the frequency of rotating machine-based DGs from the grid's frequency, effectively hiding the inertia contribution from such DGs behind the interface. Examples include wind turbines equipped with either a DFIG or a direct-drive SG. Figure 6 shows a radial system comprising two SGs, i.e., SG1 and SG2. The fault location is denoted by F at the mid-point of line 2.

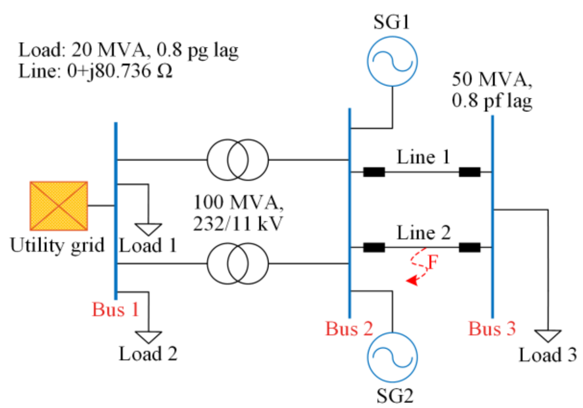

Fig. 6. Single line diagram of a DS integrated with SGDGs.

In this scenario, SG1 and SG2 oscillate and may become unsynchronized, resulting in the inability to satisfy the required load demands. This results in the absorption or injection of real power, causing the production of substantial current and torque [30]. Consequently, it becomes necessary to isolate the unstable SGs, and therefore, an effective protection scheme is extremely crucial. Figure 7(b) illustrates the impact of an effective protection system, noting a synchronized operation of SGDGs and maintaining the transient stability of the system. The protective relaying schemes measure the transient stability margin in terms of critical clearing time (CCT) and critical clearing angle (CCA) under contingency conditions.

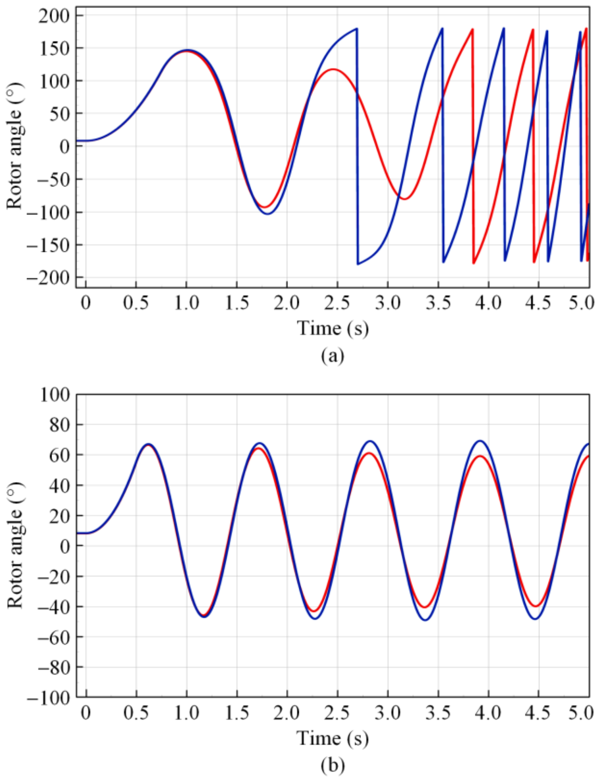

Fig. 7. Rotor angle trajectory depicting. (a) Transient instability. (b) Transient stability in SGDG-based systems.

1) Importance of CCT Evaluation

CCT refers to the maximum duration for which a disturbance can affect the system without compromising its ability to return to a stable operation. Mathematically, CCT is represented by T_{CCT} as:

$$T_{\mathrm{CCT}}=\sqrt{\frac{2H}{P_{m0}\pi f}(\delta_{\mathrm{cr}}-\delta_0)} \tag{1}$$

where H is the inertia constant; P_{m0} is the mechanical power; and f is the frequency of operation.

Similarly, the rotor angle corresponding to the T_{CCT} is expressed as θ_{CCA} as:

$$\theta_{\mathrm{CCA}}=\cos^{-1}\left[(\pi-2\delta_0)\sin\delta_0-\cos\delta_0\right] \tag{2}$$

The trajectory sensitivity analysis method is used in [31] to calculate the CCT in a three-level protection strategy. In this strategy, the relay characteristics are adjusted based on stability constraints. On the other hand, reference [32] demonstrates the implementation of the single-machine equivalent method for transient stability analysis using support vector machines, whereas [33]–[35] are based on phasor measurement unit methods, widely used for detecting loss of synchronism. A summary of various methods of CCT evaluation is shown in Table I. As the operating conditions of PSs constantly change in real time, there is a significant variation in stability and corresponding T_{CCT} values. To ensure satisfactory operation, it is necessary to periodically update the offline computed T_{CCT} values for the online operational environment of modern PSs. In [36], the concept of equal active power loading of all generators is used to enhance the transient stability and the protection coordination of DS by considering the transient constraints, shown as:

$$t_{\mathrm{prim}}<T_{\mathrm{CCT}}-t_{\mathrm{CB}} \tag{3}$$

$$T_{\mathrm{CCT}}=\min\left\{T_{\mathrm{CCT}_{\mathrm{DG1}}},T_{\mathrm{CCT}_{\mathrm{DG2}}},\cdots,T_{\mathrm{CCT}_{\mathrm{DG}n}}\right\} \tag{4}$$

TABLE I
VARIOUS METHOD FOR THE EVALUATION OF CCT

CCT evaluation method	Citation	Advantages	Limitations
Critical trajectory method	[37]	The computational time on a CPU is less than 0.01 s.	4th order Runge–Kutta method is used for numerical integration with a time step of 0.001. Thus, more time is required for the computation of minima.
Neural network method and extreme learning machine	[38]–[40]	The system is trained against undesirable events. Makes the system robust and reliable.	Data management and storage. Large computation of data is done using the Newton-Raphson method.
AI-based method	[41]–[44]	Higher accuracy; easy prediction.	Risk of cyberattacks.
Power synchronization control method	[45]	Possesses a self-restoration property.	Theoretical examination based on nonlinear differential equations can be challenging.
Lyapunov's direct method	[46]	The effect of reactive power control on rotor angle stability is illustrated through the P-δ curve.	Involves large computation due to the inclusion of state variables and state estimation.
Damping energy visualization and geometry approximation	[47]	The damping energy method is used; It is an enhanced version of the equal area criterion method where the damping energy area before, during, and after the fault is taken and critical damping energy is computed.	An extension of the classical Lyapunov method is used for computation, and an additional linear function of damping energy is taken. Large and complex calculations for multi-machine systems.

B. Voltage Stability

DG integration impacts not only the voltage stability and LVRT capabilities but also the transient stability of modern PSs. Voltage stability is a critical issue in DG-integrated modern PSs. The effect of DG integration can be observed on the voltage at the point of common coupling (PCC), i.e., V_{PCC} as depicted in Fig. 8(a). During faults, the DGs must remain connected to the grid for a specific time duration, depending on the magnitude of V_{PCC}. This time delay is determined according to the flowchart shown in Fig. 8(b).

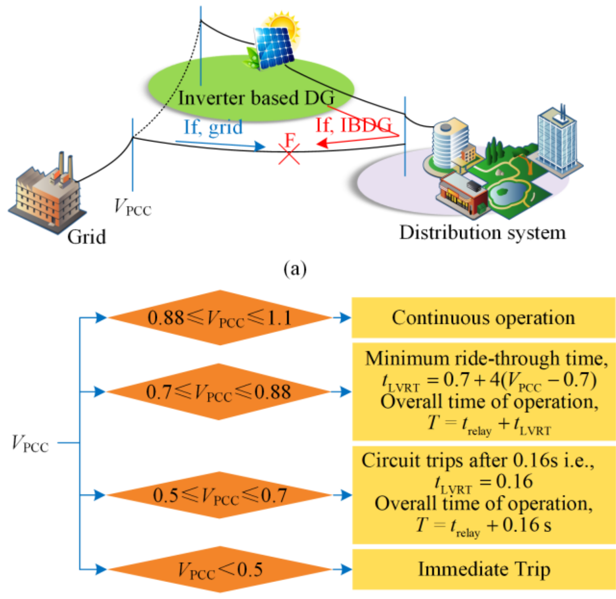

Fig. 8. PCC and LVRT. (a) Fault current contribution by an IDG-based system connected at PCC. (b) Flowchart of LVRT requirements in IDG-based systems.

According to the IEEE Std. 1547, 2018, the faulty section is disconnected from the system if V_{PCC} is below 0.5 p.u. The transition from GC to ISL mode causes the steady-state current and voltage to change and may lead to voltage instability. It is a crucial challenge as the penetration of DG is increasing globally.

Let us consider a three-phase, near-end fault occurring at $t = 0$ s at line 2, as previously shown in Fig. 5. The voltage magnitudes before, during, and after the fault are shown in Fig. 9. Under normal conditions, the steady-state voltage ranges between 0.8–1.1 p.u. In Fig. 9, $V_{PCC} = 0.5$ p.u., while the voltage sags for about 0.8 s. Therefore, to comply with the LVRT grid code, the CB must trip after 160 ms for voltage recovery. During voltage recovery, DGs must stay connected to the grid [48]. However, if V_{PCC} is less than 0.5 p.u. during a fault, CBs trip immediately to isolate the faulty section. For V_{PCC} between 0.7–0.88 p.u., the grid remains connected for a specified time, meeting voltage and frequency dip conditions as per regional grid codes.

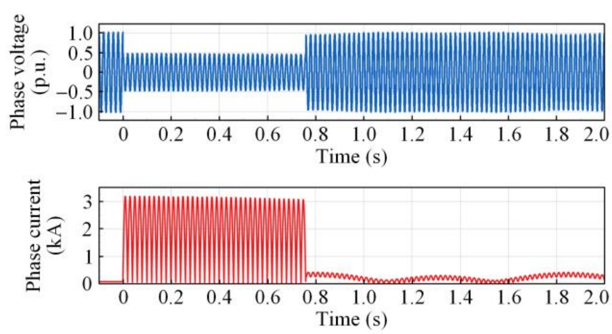

Fig. 9. Voltage sag under a three-phase short circuit.

1) Significance of Grid Code Compliance

Grid codes are the rules and regulations defined by the regulatory bodies to integrate generators into the grid effectively. Since the structure of PS is rapidly changing, the use of grid codes helps increase transparency in the operation of the PS and enhance the grid interoperability and safety of the grid operators, as these rules remain the same for all technologies. These standards are designed in anticipation that decentralized IDG-based systems will be the dominant sources in the network.

In European countries such as Spain, the voltage sag condition due to disturbances can be tackled by the grid for 200–500 ms, while the grid configuration of the system does not change. Similarly, the Central Electricity Authority controls the grid codes in India. In the case of IDG integrated systems, the grid configuration can be maintained for up to 300 ms after the fault event to recover the voltage and maintain grid stability. However, in the case of a voltage swell condition in South Africa, there is no disconnection of DG units for a larger time interval of 2000 ms. Table II shows the LVRT and HVRT requirements of different countries [49], [50].

TABLE II
FAULT RIDE THROUGH (FRT) REQUIREMENTS ACCORDING TO VARIOUS COUNTRY GRID CODES

Country	Voltage under LVRT condition (p.u.)	Time of normal operation (ms)	Voltage under HVRT condition (p.u.)	Time of normal operation (ms)
South Africa	0	150	⩾1.2	2000
Spain	0.2	500	1.2–1.3	250
Italy	0	200	1.1–1.3	100
Japan	0.3	1000		
Germany	0	150	⩾1.2	100–200
US	0.15	625	⩾1.2	1000
UK	0.15	140		
Australia	0	450	1.3	1000
New Zealand	0	140		
Canada	0	150		
China	0	150	1.2–1.3	500
Taiwan	0	625		
Norway	0.15	400		
India	0.15	300		

If the system is not restored to its normal state, then the disturbance is considered a permanent fault leading to a voltage sag, also known as a brownout condition. The regulatory bodies have an easy-to-access pathway for end-users with the implementation of standardized and certified equipment at a subsidized cost. Grid code compliance also includes communication peripherals to monitor and control the smart grids. However, the existing grid codes are also linked to challenges such as being less effective in regulating frequency due to the increased level of variable RESs integration and others, as discussed in [51].

C. Existing Protection Schemes with Stability Considerations

SGDGs in the system may cause transient stability issues, whereas IDGs may affect the voltage stability and LVRT conditions under fault events. These stability concerns can be handled by implementing an efficient protection system. The most widely used protection schemes can be categorized as conventional DOCRs and user-defined DOCRs from the perspective of modern PSs.

1) Conventional DOCRs

The advancements in PSs have facilitated the introduction of more sophisticated and efficient DOCRs. However, these modern DOCRs retain functional similarity to conventional relays. This section conducts a literature survey on various protection schemes addressing stability concerns in DG-integrated systems. As per IEC 60255-3 Std. [52], the operating time of conventional DOCRs is defined as:

$$t = \frac{A \times TMS}{\left(\frac{I_\text{f}}{I_\text{p}}\right)^B - 1} \tag{5}$$

where A and B are the relay coefficients; I_p is the pickup current; I_f is the fault current magnitude; and TMS is the time multiplier settings of the DOCRs.

The values of relay coefficients A and B vary for standard inverse, very inverse, and extremely inverse relay characteristics, and the inverse time-current characteristics of these relays are shown in Fig. 10. Reference [53] discusses the selectivity problem amongst relays in IDG-based systems and its mitigation using adaptive protection scheme. To signify the sensitivity of the relays, the term CTI is introduced, which refers to the gap between the operation of primary and backup relays and is expressed as:

$$t_\text{b} - t_\text{p} \geqslant CTI \tag{6}$$

where t_p and t_b are the operating times of the primary and backup relays, respectively. The typical value of CTI ranges between 0.2–0.5 s, and the minimum operating time of relays is assumed to be 0.05 s.

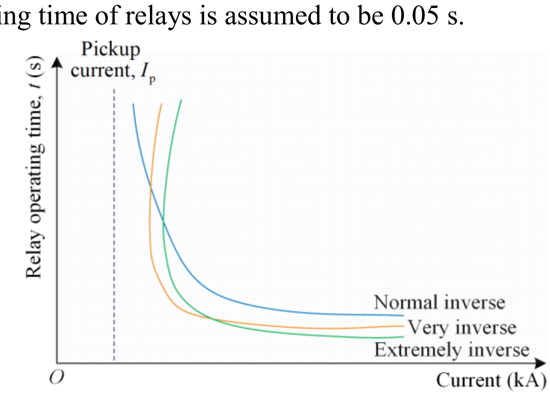

Fig. 10. Inverse time-current characteristics for different types of conventional DOCRs.

Depending on the linear or mixed integer nonlinear programming (MINLP) approach for finding the optimal relay settings, the DOCRs must satisfy the following constraints:

$$TMS_\text{min} \leqslant TMS \leqslant TMS_\text{max} \tag{7}$$

$$I_\text{p,min} \leqslant I_\text{p} \leqslant I_\text{p,max} \tag{8}$$

$$t_\text{min} \geqslant 0.05 \tag{9}$$

2) User-defined DOCRs

Reference [54] introduces an innovative protection scheme based on dual settings of DOCRs for forward (F) as well as reverse (R) directions of the flow of fault current. The dual-setting DOCRS (DS-DOCRs) proposes a different set of relay settings for forward and reverse modes (TDS_F, $I_\text{p,F}$, TDS_R, and $I_\text{p,R}$) since the relays operate in a bi-directional mode due to the integration of DGs in the system (see Fig. 11). Such relays are ideal for DG-based systems, and can be implemented in both SGDGs and IDGs-based systems. Reference [55] proposes a DS-DOCR-based protection scheme for the IEEE 30-bus system under the conditions: (a) with DG integration; and (b) without DG integration. The MATLAB in-built optimization tool "*fmincon*" is implemented to obtain the optimal relay settings in both the GC and ISL modes with the objective function, defined as:

$$\text{minimise } T = \sum_{c=1}^{C}\sum_{i=1}^{N}\sum_{j=1}^{M}\left(t_{\text{F},ij}^{\text{p}} + \sum_{k=1}^{K} t_{\text{R},cij}^{bk}\right) \tag{10}$$

where c is the configuration identifier; i is the relay identifier; j is the fault location identifier; p is the primary relay; and b is the backup relay.

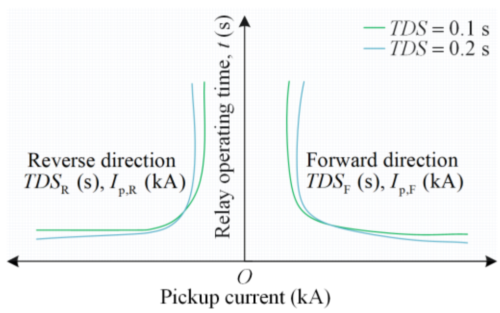

Fig. 11. Inverse time-current characteristics of DS-DOCRs for TMS = 0.1 and 0.2 s.

Reference [56] shows the implementation of a double inverse type DOCR (DI-DOCR). In this relay type, a combination of the primary relay and the first backup relay is considered for satisfying the CTI constraints, and the combination of the primary relay and second backup relay is considered for meeting the T_CCT constraints. An additional high-set relay is used to signify the type of relay characteristics. Similarly, reference [57] highlights the operating conflicts and voltage regulation issues that often arise when DGs are integrated into the system. In [58], an improvement in voltage stability is proposed by coordinating the reactive power output of the DG system with its real power output. This coordination method helps in regulating the PCC voltage and improving grid stability.

TABLE III
LITERATURE SURVEY OF THE PROTECTION SCHEMES TO MITIGATE DGS IMPACT ON THE SYSTEM STABILITY

System dynamics	Features/operation	Research gaps found
Transient stability	• Modified IEEE 14-bus meshed system and IEEE 33-bus systems are taken. • The simplex optimization algorithm is used to evaluate the optimal TDS settings [67].	• Instability conditions still exist due to other DGs in the system. • Only two types of relay characteristics are considered: standard inverse and very inverse. • Only the modified IEEE 14-bus mesh system is considered as the test system.
	• IEEE 33-bus system with SGDG integration is taken into consideration. • A hybrid communication-assisted protection scheme is implemented. • The ROT depends on the position of the CCT curve for each relay. • A communication channel is used to detect the fault condition. • The definite time (DT) stage is advantageous in reducing the ROT [68].	• An additional definite time relay is used whose tripping times have to be evaluated. • Increased computation time. • Prone to cyberattacks due to the presence of communication links.
	• Communication assisted DS-DOCRs are used. • User-defined relay characteristics are used. • Seeker algorithm optimization tool [69]. • An adaptive auto reclosing scheme is used to preserve network stability. • Fault location is determined by discrete wavelet transform [70].	• Transient stability constraints are considered only for the primary relays. • Sensitivity problem for far-end faults. • Relay operation in fault isolation is not taken. • Protection coordination study has not been performed.
Voltage stability/FRT capability	• Ring bus structure; SGDG and PV-based IDGs are taken with standard inverse characteristic relays. • OPAL-RT 5600 industrial PC; Python API is used to validate the settings obtained for different fault types and possible locations [71].	• Only the islanded mode is considered. • Restrictions in utilizing the ride-through capabilities as it can function only when phase-locked loop (PLL) is in sync with positive sequence voltage.
	• Modified superconducting FCL (SFCL) (Z_{FCL}) is used; SGDGs and IDGs integrated system with FRT operation of IDGs [72], [73].	• Voltage and current are assumed to be balanced. • The effect on the CCT in the case of the SGDGs is not considered.
PCI	• The crow search algorithm is used to evaluate optimal relay settings; less standard deviation from the optimal value; DS-DOCRs are considered. • Suitable for both GC and ISL modes of operation. • Optimal sizing of FCL is done; energy management in terms of optimal power flow and load shedding costs are taken to evaluate the I_{PC} value [74].	• Bus voltages before fault occurrence are taken. • LVRT conditions are not taken into account. • Effect of the size of energy storage systems is not considered. • Only considers a single MG in both operating modes. Other scenarios, such as multi-MG, networked MG, and hybrid MGs, could be explored for optimal protection coordination.
	• Both modes of operation are considered; genetic algorithm (GA) is taken to evaluate the optimal size of DGs • X_{FCL} constraints are taken to obtain minimum operating time, t_{op} [75].	• Initial values of X_{FCL} is not considered. • Does not consider the impact of different types of DGs, such as wind turbines, PV, and fuel cells, on the protection coordination. • Does not compare the performance of GA with other optimization methods, such as particle swarm optimization (PSO), market-based optimal power flow (OPF), and mixed-integer linear programming (MILP).
	• The capacity of DG installation at other locations affects the maximum DG penetration at a specific location. • Optimal sizing and allocation of FCLs is taken for maximum DG penetration and consequently PCI. FCL increases the feeder's impedance, influencing the steady state voltage level. [76]. $t_{ij}(S_{\mathrm{DG}},X_{\mathrm{FCL}})=TDS_j\left(\frac{A}{\left(\frac{I_{\mathrm{SC}j}(S_{\mathrm{DG}},X_{\mathrm{FCL}})}{I_{\mathrm{p}j}}\right)^B-1}\right)$	• A higher rating DG cannot be installed at an existing DG location because the I_{PC} values decrease. • A smaller step size should be taken for more precise optimization; 20% step size is assumed. • Violation of grid code limits due to the presence of FCL. • Additional voltage constraints have to be taken into consideration leading to increased complexity.
	• DS-(*t*-*I*-*V*)-based characteristics of DOCRs is considered; studies the effect of DS-user defined DOCRs on PCI. • IEEE 14-bus and 30-bus meshed and multi-source test systems. • Comparison of the results obtained by GA and grey wolf optimization (GWO) algorithm [77].	• Requires careful selection of initial states to obtain a better convergence rate. • Increased complexity for the system with a higher number of relay pairs.
	• 39-bus and 119-bus DN with SGDGs. • Hybrid sine cosine algorithm and GWO algorithm [78].	• Uncertainties in the load parameters and DGs are not considered. • The impedance of the series transformer of SGDGs is assumed as 0.0027 p.u.
	• IEEE 30-bus ring and IEEE 69-bus radial DNs with SGDGs are used as test systems. • Hybrid PSO-crow search algorithm; voltage security index has been considered as constraints [79].	• Precise selection of the initial conditions, number of decision variables and Lagrange's multipliers are required to obtain a global optimal solution with better convergence characteristics. • Does not validate the scheme on real-world DNs with more complex topologies, load profiles, and protection schemes.

To obtain voltage stability in MGs, reference [59] proposes a protection strategy to reduce the fault clearing time, *T*, and thus the voltage sag lost energy index (VSLEI). VSLEI is defined as the index that gives the lost energy to the loads during the voltage sag events, denoted by *W*, as:

$$W = \left(1 - \frac{V}{V_{\text{nom}}}\right)^{3.14} \times T \tag{11}$$

where *V* is the phase voltage in p.u.; V_{nom} is the nominal voltage during a sag event; and *T* is the voltage sag duration in ms.

Reference [60] proposes a protection coordination scheme in a system deeply penetrated by six different types of DGs. The optimal relay setting of such a system is obtained by implementing a stochastic fractal search algorithm. Reference [61] proposes a protection coordination scheme suitable for both GC and ISL operational modes based on the symbiotic organism search algorithm by taking additional LVRT considerations. The implemented control scheme uses an intelligent central controller system, thus requiring a communication channel.

Apart from the coordination schemes, an important parameter, the protection coordination index (PCI), is introduced in [62], [63]. The term PCI is used to determine the size of incoming and installed DGs into the system that would not hamper the sensitivity and selectivity of the PDs. PCI is denoted by I_{PC} in the expression below as:

$$I_{\text{PC}} = \frac{-\Delta P}{\Delta CTI} \tag{12}$$

where ΔP is the change in the penetration level, and ΔCTI is the change in the *CTI*.

The analysis in [64] shows that the maximum DG penetration at a given location is influenced by the installed capacity of the DGs at other locations. The higher is the value of the I_{PC}, the lesser will be the effect of DG penetration on the sensitivity of the PDs.

Reference [65] considers the protection coordination scheme as a two-phase nonlinear programming optimization problem in the IEEE 30-bus system. In phase I, the conventional coordination constraints are developed, while phase II involves maximizing the penetration level of DGs. The two-step proposed strategy gives the optimal relay settings for the minimum overall relay operating time (ROT). In [66], an adaptive central controller-based system integrated with the DGs is considered. This system combines two-stage FCL and DOCRs to protect against undesirable events, while the optimal settings of the DOCRs are evaluated using the differential evolution algorithm.

III. PROTECTION COORDINATION CHALLENGES IN DG INTEGRATED SYSTEMS

The integration of DGs introduces challenges to protection schemes. Proper selection and placement of PDs such as relays, fuses, breakers, and reclosers, can mitigate DGs' adverse effects. This section outlines the protection challenges in DG-integrated systems. The performance of PDs may deteriorate due to DG connection [80]. Therefore, it is crucial that the PDs exhibit properties such as selectivity, sensitivity, reliability, fast operation, easy installation, and cost-effectiveness for fault detection, isolation, and service restoration.

A. Protection Challenges

The key protection challenges in DG-integrated systems are illustrated in Fig. 12 and are described as follows.

1) Change in the SCC Level

The presence of DGs can change the magnitude and direction of the fault current. The variation in the current magnitude depends on the operating mode, size and type of DGs installed, point of DG integration, power converter ratings, etc.

Assuming a 3-bus system with DG integration at bus 2, as shown in Fig. 12(a), the fault occurs at point F between buses 2 and 3. It causes a variation in the fault current magnitude and, hence, disturbs the operation of the protection system. Reference [81] shows the implementation of various AI techniques for optimal sizing and placement of DGs. Since the fault current magnitude differs for a system operating in ISL mode, reference [82] discusses the fault current contribution by the DGs alone and relevant protection coordination schemes.

2) Blinding of Protection

Figure 12(b) illustrates the concept of blinding of protection in a 3-bus system with DG connection at bus 2.

Assuming that a fault occurs at point F in the system. The protection blinding occurs due to the contribution of DG impedance to the overall impedance of the system. The increased impedance value causes the fault current to decrease, and thus decreases the pickup current of DOCRs. It causes the reach of the relay R1 to decrease. The reduced reach of R1 with respect to the location of DGs and fault location fails to sense the fault and trip the circuit breaker. In [83], the protection blinding issue in the case of a real DN is addressed and a neural network-based fault detection technique is utilized to overcome its adverse effects.

3) False / Nuisance Tripping

A 4-bus system is considered, as shown in Fig. 12(c). With no DG integration, the utility grid provides current to loads 1 and 2. In the case of a fault event occurring at location F, the primary relays R2 and R3 operate and isolate the faulty section. However, this process is affected by the presence of DG in the system. The fault current level of DOCR, R1, increases depending on the size of the DG. Hence, its pickup current value increases, leading the section between buses 1 and 3 to trip immediately. This false tripping eliminates a healthy grid portion, and seriously damage the PDs and other components. It also affects the system's reliability, decreases power quality, and increases the maintenance cost [84].

4) Unintentional Islanding Condition

Islanding is a condition where MGs connected to the loads are isolated from the grid under abnormal conditions. An islanding event leads to a deficiency of active and reactive power. This power is compensated through reactive power injection, which allows the SGs to maintain the voltage and frequency of the system and produce real power to fulfill the load demands.

Islanding can be categorized as intentional and unintentional (UI). Intentional islanding mainly occurs during a system outage. Under such circumstances, selected islands are formed, each comprising a DG such that there is a minimal mismatch between the demand and the generation. Figure 12(d) shows a 3-bus system with a high penetration of SGDG and IDG at bus 2, and induction-based DGs at bus 3. For a fault occurring in the section between buses 1 and 2, R1 and R2 act as the primary relays, thus isolating the DGs from the utility grid. In this islanding condition, the DGs continue to serve the loads. However, the system faces problems with abnormal voltage and frequency outside of grid code compliance during the resynchronization of SGs during the transition from ISL to GC mode at the load end [85]. Reference [86] illustrates the droop control method for controlling the transient power of an IDG-based DS under the UI condition.

5) Auto Recloser Issues

Reclosers, a specialized type of CB, swiftly detect and isolate transient faults through rapid open and close operations. Unlike regular CBs, reclosers assess fault nature (transient, semi-permanent, or permanent) and respond accordingly. Auto reclosers, comprising relays, automatically operate the recloser for swift system restoration after fault clearance. In Fig. 12(e), a single-machine infinite bus system with integrated DG is depicted, assuming a fault at point F. Without a DG connection, the auto recloser attempts multiple cycles to clear the fault. If unsuccessful, it remains permanently open, potentially making a transient fault permanent.

6) Proper Selection of PDs

The selection of the PDs is based on the severity of the fault, the type of DGs integrated, the characteristics of the PDs, and their availability. The higher the magnitude of the SCC, the shorter the operating time of the PDs. The switching speed of the PDs depends on the magnitude and direction of the current along with the voltage parameter. Reference [87] discusses a centralized PS in which the settings of the PDs depend on the real-time magnitude of current, voltage, phasor angle, and impedance. The integration of DGs into the system has enabled the researchers to develop different types of non-standard relays, as discussed in the next section.

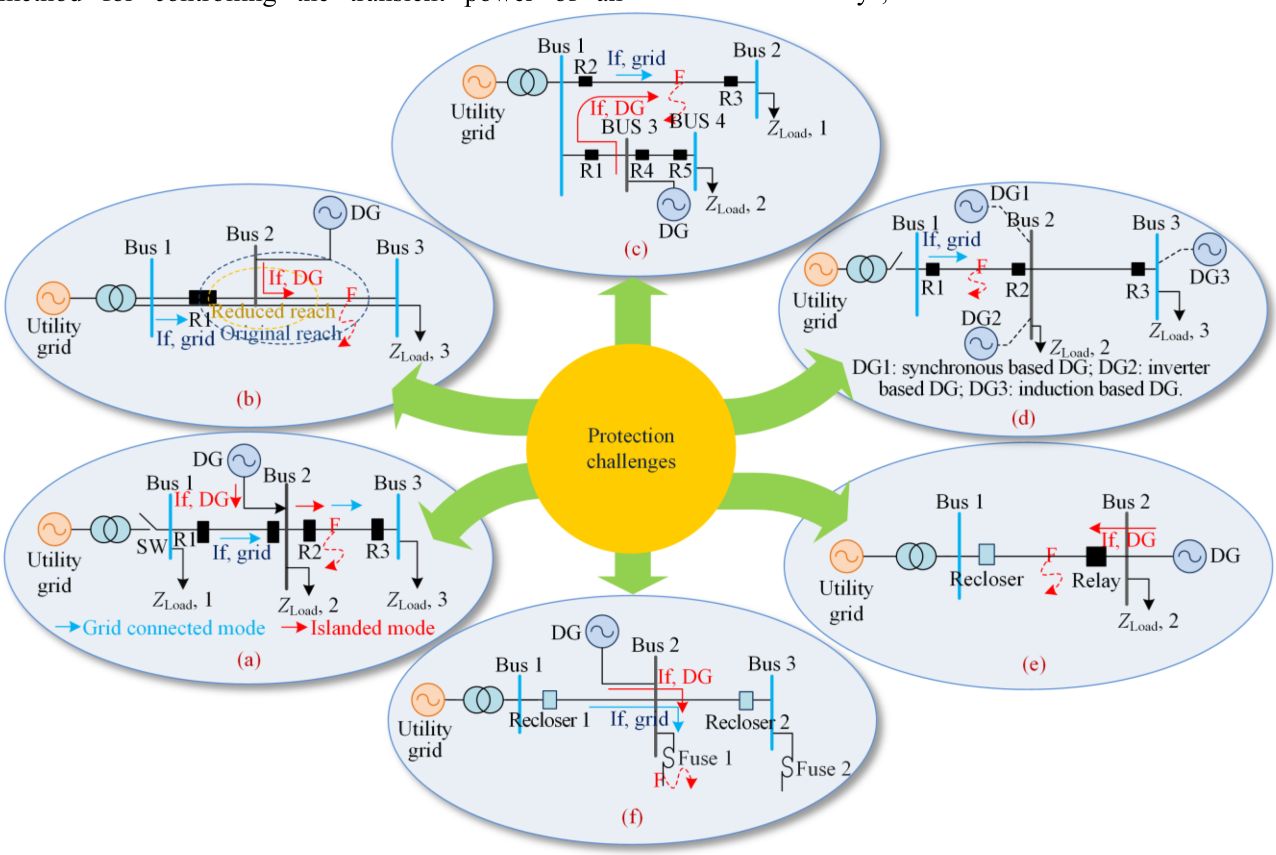

Fig. 12. Protection challenges in DG integrated systems. (a) SCC in different operating modes of MG. (b) Blinding of protection. (c) False tripping. (d) Unintentional islanding. (e) Auto-recloser problem with DG. (f) Effect of DG on fuse-recloser coordination integration.

IV. Available Solutions for Mitigation of Protection Challenges in MGs

This section critically analyzes the different types of protection schemes to tackle the aforementioned protection challenges. These schemes are designed to detect and isolate faults in the system, thereby preventing further damage and maintaining overall stability. The categorization is performed using conventional and modern-day technology-based schemes.

A. Conventional Protection Schemes

The conventional protection schemes immediately disconnect the DGs in the case of single-setting DOCRs in a GC operational system. Such relays are unsuitable for stability and safety reasons in the ISL mode of MGs. The conventional approaches for system protection are surveyed and presented in Table IV.

TABLE IV
CONVENTIONAL PROTECTION SCHEMES TO MITIGATE THE IMPACT OF DG INTEGRATED SYSTEMS

Features and operations	Merits	Challenges
Current-based: • MINLP is used to obtain common optimized values of relay parameters for both modes. Different combinations of relays taken (all very inverse (VI), extremely inverse (EI), normal inverse (NI), and VI-EI-NI mix-up); GA optimization tool [93]. • DOCRs with wind turbine-based DGs and SGDGs are used; GA optimization tool is used to obtain optimal relay settings; ROT is considered as a function of voltage; Co-ordination of fuse and relays is done for additional protection [94].	• Efficient and economical. • Current harmonics are not considered as their magnitude is non-substantial. • Computation and monitoring of current are easier compared to a voltage-based or any other protection scheme.	• MG operation may be severely affected if no effective protection is present for the bidirectional flow of fault currents. • The sensitivity of the OCRs may be compromised. • Unwanted power outage. • In the case of non-linear loads, total harmonic distortion has to be taken into account.
Voltage-based: • SGDG and IDGs-based system is taken. • Pre-fault and post-fault voltages are considered in the case of an SGDG, whereas only post-fault voltage and current are taken for IDGs. • OCRs and voltage-restrained frequency relays are used [95]. • Bus voltages are compared to the synchronous machine reference and this difference is taken for generating a tripping signal for the PDs [96].	• In the case of IDGs, the fault current is limited to 2–3 times the line current, so it is not easily detectable. Therefore, bus voltages are used to detect faults. • Easy computation. • Less complex.	• Additional cost of controllers is generated. • Compensators may be installed to achieve stable voltage levels and reduce harmonics. • Maloperation of the voltage-based relays can result in a voltage drop within the MG.
Distance-based: • Measured values of currents and voltages are used to calculate impedance/admittance. • Based on the impedance/admittance, the FL is identified. • Inverse time-admittance characteristics-based relays are used to protect the MG. • The fault impedance before and after the fault occurrence is evaluated, and the zone of protection is identified [97]. • Distance protection in a STATCOM enhanced system gives better voltage stability [98].	• Mainly used for line segment protection. • High sensitivity to change in current. • They are inherently directional. • Enhanced performance, accuracy, and sensitivity.	• The design and implementation of distance relay schemes can be complex, particularly for large PSs with multiple protection zones and coordination requirements. • Disturbances may cause stable or unstable power swings in the system, which can affect the apparent impedance measured by the relay and, hence, may cause their maloperation. • It may be unreliable in the case of DG-based systems. • May severely faces the problem of under and over-reach. • Errors may be caused by fault resistance and admittance during computations.
Differential-based: The current at the two ends of the feeder is retrieved to obtain differential energy. • A threshold-based protection scheme using time-frequency transform with Hilbert transform [99]. • Differential energy is computed using S-transform for MG protection [100]. • Differential frequency protection scheme for protection of islanded IDGs [101]. • Use of optical fiber-based current differential protection scheme in MGs [102].	• Sensitivity to noise is reduced. • Reduces the aliasing effect. • High speed and sensitivity • Suitable for primary protection in transmission systems, where a fast response is critical to prevent cascading failures and widespread blackouts.	• High computation time and complexity. • Transient during the switching of DGs may cause problems. • Additional wiring, communication channels, and testing equipment are needed to ensure proper operation and maintenance. • Any errors or mismatches in the current or voltage transformers can affect the sensitivity and security of the differential relay.

1) Current and Voltage-based Relays

Conventional current-based protection schemes in MGs rely on the measurement of current at different points in the system to detect abnormal conditions or faults. This information is then used to activate PDs, such as relays or CBs, to isolate the faulted section from the rest of the MG. By monitoring the current levels, these protection schemes can quickly identify and respond to faults, minimizing the impact on the system and preventing widespread disruptions.

Similarly, voltage-based protection schemes measure the voltages at various points in the MG to ensure that the voltages remain within acceptable limits. If a fault or abnormal condition is detected, such as a voltage sag or swell, the PDs are triggered to isolate the affected area and prevent further damage to the system. However, these conventional protection schemes have limitations in terms of their ability to accurately detect and mitigate certain types of faults or attacks in MGs.

2) Distance-based Protection Relays

Distance-based protection relays are widely used in PSs to detect and locate faults in transmission lines. Most importantly, power utilities are concerned about the increased proliferation of intermittent DGs in the distribution system, which may threaten its stability and reliability [88]. Distance-based protection relays are commonly employed in PS to address these concerns, and play a crucial role in fault detection, fault clearance, and minimizing disruption to the system. However, it is important to note that the assumption of constant pickup values for these protective relays may not hold true in dynamic PSs, especially following a large-scale disturbance. It is thus particularly relevant when considering the integration of intermittent DGs, such as solar PV and wind power, into the grid. In dynamic system conditions, the performance of distance relays can be compromised due to the dynamic behavior of wind power plants and the decoupling of mechanical and electrical parameters in DGs [89]. Therefore, it is crucial to decouple the mechanical rotor speed of the SGDGs with the electrical frequency of the grid through power electronic interfaces to ensure accurate and reliable operation of distance-based protection relays. In conclusion, constant advancements and improvements in distance relays have contributed to enhanced performance, accuracy, and sensitivity.

3) Differential-based Protection Relays

Differential-based protection relays are another type of relay commonly used in PSs to detect and locate faults. These relays operate based on comparing the currents entering and leaving a protected area, such as a generator, motor, or transformer. These relays can quickly detect any imbalance or fault within the protected area by continuously monitoring the difference between the currents. With the increasing penetration of DGs on DNs, the traditional protection schemes must be updated by incorporating differential and distance-based relays with new protection algorithms specifically designed for these PSs [90].

Overall, differential-based protection relays and technological advancements, such as digital relays and optical fiber communication systems, have revolutionized the field of fault detection and location in PSs. These fiber-based systems offer numerous advantages, including improved accuracy and faster response times, compared to conventional distance-based protection methods. With the proliferation of differential relays in transmission lines and the advancements in communication technologies, current differential protection has become widely used to protect SGs and transformers [91]. However, one limitation of current differential protection is its sensitivity to load current, fault resistance, and distributed capacitive current [92].

B. Modern Technology-based Protection Schemes

Modern-day technology-based protection coordination schemes have been developed for MGs to overcome the abovementioned limitations. These schemes utilize advanced communication and control systems to enhance the overall reliability and security of the grid. One such scheme uses intelligent electronic devices (IEDs) that are capable of monitoring and analyzing various grid parameters in real time. These devices can quickly detect and classify faults, including those caused by cyberattacks or malicious intrusions. By integrating communication networks, IEDs can exchange information with each other and with the central control system, allowing for coordinated protection actions across the MG.

A literature survey of modern day protection schemes is shown in Table V. Various modern-technology-based protection schemes are categorized as follows.

TABLE V
MODERN TECHNOLOGY-BASED PROTECTION SCHEMES FOR DG-BASED SYSTEMS

Protection scheme and its features	Operation	Merits and limitations
Adaptive protection *Communication Assisted:* • Centralized adaptive MG protection is done using microgrid central controller (MCC), which communicates with each relay and fuse. • MCC observes the dynamic nature of the system and updates its relay settings and numbers.	• A new bat algorithm with a fuzzy interference system; additional feature of self-adaptive characteristics using the concept of setting groups [116]. • MCC reconfiguration algorithm is used to reconfigure the system when a fault occurs, and the fault bus is isolated to form sub-MGs [117]. • Both GC and ISL modes are considered; common optimized relay settings for both modes are obtained; VI relay characteristics are taken for primary protection and NI relay for backup protection [118]. • Fuzzy logic-based settings of the DOCRs with a reduction in ROT while ensuring a stable system operation; teleprotection is used to send a “trip” signal to CB when t=t_{op} and for setting the CTI [119]. • ANN is used for fault detection and fault location; protection settings are modified by the data concentrator in PLC SCADA [120].	Merits: • Requires no need for the initial parameters of the DOCRs. • Improves the reliability, selectivity, and sensitivity of the protection system by adapting to the dynamic nature of MGs. • Reduce the number of false trips and mal-operations by using real-time data and communication. • Prevent data theft and sabotage, contain a threat when it occurs instantly, and lessen the dwell time of threats by using adaptive security. Limitations: • The protection may be affected by the communication delay. • No communication amongst relays is taken. • Prone to cyber-attacks. • The cost related to the installation of communication channels is higher. • It may fail during high-impedance faults. • Not a reliable protection solution.

Protection scheme and its features	Operation	Merits and limitations
Non-communication assisted*:* • Communication structure is not used making it less complex. • The operating delay of the communication channel is reduced; faster and more reliable operation is achievable.	• Predefined specific harmonics are injected into the system and superimposed with the output current only under the fault condition; harmonics are assumed as 10% of fault current [121]. • The dual-settings of relays common for both GC and ISL mode are evaluated and the direction of fault current is assumed to be forward only [122]. • Natural logarithmic (*t-I-V*) function-based relay characteristics for obtaining common settings for GC and ISL mode of operation under different fault conditions in IEEE 30-bus system and Iranian radial DS [123].	Merits: • No risk factors related to communication failure and cyber-attacks. • Reduce the cost and complexity of installing and maintaining communication channels and devices. Limitations: • Real-time data is not accessed due to the absence of a communication channel. • Due to the absence of a communication channel, reconfiguration of relay settings has to be done for any change in the topology of the MG or for increased DG penetration.
MAS-based • MG agents are present in the three layers (system, substation, and equipment layer). • MAS contains an intelligent controller, interconnected equipment, and DGs.	• MG agents are located in the distribution lines to measure the phase angle difference of the current at buses [124]. • The hybrid protection scheme is adaptive and MAS-based for MG. For single-event faults, equipment layer agents calculate the system parameters, and relay settings are updated. For multi-event faults, online calculations are done at the substation layers [125]. • Adaptive protection-based MAS control for the protection of MGs using communication structure [126].	Merits: • The inter-operating feature of MAS affects the performance of one agent due to other agents. • Automatic adaptability to the changes in PS. • Real-time integration of an expert system with SCADA; this expert system divides the power grid into different protection zones. • Robust and reliable. Limitations: • Higher complexity. • The decrease of fault current in ISL mode is due to the topology change, bidirectional current, and telecommunication, which are the most critical issues. • Lack of reliability of the central adaptive protection schemes.
Soft computing techniques-based Most recent techniques: Includes techniques such as artificial bee colony, biogeography, bat, gravitational search, firefly, differential, harmonic search algorithms and artificial neural network Most successful techniques: Includes techniques such as GA, PSO, GWO, cuckoo algorithm, and hybrid cuckoo algorithm-linear programming.	• Ant colony optimization algorithm-based linear optimization to find optimal values of relay parameters [127]. • Artificial neural network-based linear optimization to find optimal values of relay parameters [128]. • Cuckoo-based linear optimization algorithm for optimal relay operating time [129]. • Gorilla troops optimization algorithm is used to improve the convolution neural network for measuring current and voltage for fault detection and isolation [130]. • PSO-based linear optimization to find optimal values of relay settings [131]. • GA-based linear optimization and nonlinear optimization to find optimal values of relay settings [132].	Merits: • It is a predictive method that can predict the nature and status of the PDs for any change in current/voltage under different conditions of the MGs. • Gives unbiased results. Limitations: • It requires multiple relay settings that may increase complexity. • Separate relay settings for both the operation modes of MG. • Convergence time may be high for some AI techniques. • A large amount of data is required to train the system in the case of ANN/CNN.
Data mining-based A large volume of current, voltage, and power data is collected and utilized to identify the pattern of the MG under different scenarios, such as different types of faults, the effect of fault resistance, FL, and type of topology.	• A deep neural network-based method is used for fault detection and computation of the relay settings [133]. • Discrete fourier transform-based data mining technique for protection of MGs [134]. • A dual-tree complex wavelet transform is used for fault detection and classification [135].	Merits: • Improves the accuracy, reliability, and speed of fault diagnosis using ML algorithms that can learn from historical and real-time data. • Handles the complexity, uncertainty, and nonlinearity the MG by using soft computing techniques. • Increases the security and privacy of the data exchange among the MG protection relays by using encryption and anonymization techniques. • Enhances the decision-making process and the coordination of the PDs to discover the hidden patterns and rules in the data. Limitations: • A large size of data is required for higher efficiency. • Additional computer peripherals are required for data storage and processing. • Increased cost and risk of cyberattacks.
Blockchain and machine learning-based It is a data-driven method of training the system for different states of the MGs.	• The rate of change of bus current is calculated for evaluating the zone of protection and fault isolation using blockchain and machine intelligence [136].	Merits: • Fault identification and protection of MG improves. • Additional features of fault prediction may be added since the technology is purely data-driven. Limitations: • The data extracted by the user may contain human errors. • Requires additional structure for processing, storing, and accessing data. • Scalability and performance may be affected by the large amount of data and transactions involved in the MG operation. • The accuracy and robustness of the ML models may be influenced by the uncertain and dynamic elements in the MG environments. • Concerns related to data privacy and interoperability.

1) Adaptive Protection

Adaptive protection schemes in DG-based systems take the concept of current differential protection further by introducing advanced features that address the challenges associated with DG integration. These schemes adapt to changing system conditions, and ensure coordinated and reliable protection for DG systems. This approach allows for accurate fault detection and location in DG systems, ensuring prompt and efficient response to faults.

Furthermore, this scheme utilizes optical fiber-based communication systems to achieve high-speed and reliable communication between the relays. Moreover, multi-zone-based backup protection has been proposed to enhance the reliability and efficiency of the protection system [103]. These schemes minimize outage areas and prevent delays by employing communication and cooperation between IEDs, enabling them to coordinate and implement adaptive protection strategies [104]. Despite several drawbacks of communication-assisted protection schemes, such as increased complexity, high costs, and susceptibility to interference from low-communication bandwidth signals and the transmission channels, their widespread use is documented in [105]–[108]. Reference [109] updates the operating current of the PDs and sets appropriate time delay between relays for effective fault isolation by continuously monitoring the status of all the components via central controller and communicating through IEC 61850's GOOSE protocol. Recent advancements in this scheme include integrating wireless networks with optical fiber communication systems, offering lower costs and faster response times.

2) MAS-based Protection Schemes

These schemes utilize multi-agent technology, where multiple intelligent agents with specialized functions work together to achieve a common goal. In the context of the protection system, a MAS involves the coordination and cooperation between multiple protection relays, each acting as an intelligent agent. These relays communicate and exchange information in real time, enabling them to respond to faults and disturbances in the PS collectively. This approach allows for the adaptive and dynamic adjustment of protection settings based on system conditions, ensuring efficient and accurate fault detection and isolation. References [110], [111] explain the MAS-based adaptive protection scheme at several layers of a PS, such as equipment, substation, and system layers, for single and multi-event fault events. With the rapid development of 5G communications technology in the past few years, its use in the field of PS protection is of particular importance as it enables the grid operator to fast fault detection and restoration. In [112], the importance of 5G network end-to-end communication in system restoration after a fault occurrence is discussed, and its concepts are utilized in conjunction with multi-agent technology.

3) Data Mining and Big Data-based Protection Schemes

Another notable development in PS protection utilizes the concepts of data mining and big data to develop enhanced protection schemes. These schemes use the vast amount of data generated by power systems to improve fault detection, prediction, and restoration processes. For example, data mining techniques such as clustering and classification algorithms can identify patterns and anomalies in power system data, allowing for early detection of potential faults and prompt mitigating actions. Furthermore, big data analytics can handle and process large volumes of data in real time, enabling faster and more accurate decision-making in protection relays. One example of the application of data mining and big data-based protection schemes is the work conducted in [113], where a powerful machine learning algorithm is developed based on a big data support platform. This algorithm utilizes large amounts of power data to train a machine-learning model that can accurately predict faults in the power system and provide effective relay protection. These techniques analyze massive datasets to identify patterns, trends, and anomalies that can quickly and accurately indicate potential faults or vulnerabilities in the PS.

4) Blockchain Technology-based Protection Schemes

Blockchain technology is employed in the protection strategy to securely store events and incidents in PSs. Originally developed for cryptocurrency, blockchain ensures secure and transparent recording and validation of information. Reference [114] proposes the steps to detect the outliers using an unsupervised learning algorithm. Although ML focuses on PS cybersecurity, reference [115] highlights research gaps in applying ML to protective relays, necessitating further exploration. Blockchain technology offers several advantages, including:

1) Ensuring the integrity and traceability of data and enhancing the security and reliability of the grid.

2) Serving as a decentralized and transparent platform for storing and sharing data related to PS events and incidents.

3) Analyzing large amounts of data and identifying patterns or anomalies that may indicate a cyberattack or other malicious activities.

4) Ensuring the integrity and authenticity of the data by system operators, making it tamper-proof and resistant to unauthorized modifications.

5) Facilitating secure and efficient communication among different entities in the PS ecosystem.

Using ML, big data, MAS, and blockchain enables the protective relays to boost fault diagnosis decision accuracy, data security, and speed for MG protection. The ML algorithms can choose relay parameters from sample data of normal and emergency states, which helps prevent cyberattacks on the systems.

5) Soft Computing Techniques-based Protection Schemes

AI-based protection schemes utilize techniques such as ML and data fusion to enhance the accuracy and efficiency of relays. These schemes utilize advanced algorithms to identify patterns and anomalies in large amount of data from various sources, including sensors and communication systems, to make intelligent decisions for faster and more accurate fault diagnosis and restoration. The optimization algorithms aim to improve the efficiency and performance of protection schemes by optimizing various parameters and decision-making processes. For example, evolutionary algorithms such as genetic algorithms (GA) and particle swarm optimization (PSO) have been used to optimize the coordination of DOCRs in DG-based systems. These algorithms help to find optimal settings for relays, such as the time delays and thresholds for fault detection and isolation. Overall, the advancements in signal processing and AI techniques have greatly improved digital protection relaying [137].

Table VI gives an elaborate literature survey of various optimization algorithms implemented in the DG-based systems. The compilation of different algorithms used in the last five years, i.e., 2018–2023, is shown in the table. The trends in Table VI show that the focus of the researches has shifted from conventional metaheuristic-based algorithms such as GA and PSO to nature-inspired evolutionary algorithms such as cuckoo search algorithms, whale algorithms, firefly algorithms, ant colony algorithms, and hybrid technologies such as GA-ANN, GA-Fuzzy, etc. In recent years, significant research and development have been conducted on applying AI techniques in PS protection.

6) User-defined Protective Relaying Schemes

Previously, faults were addressed based solely on current. However, advancements in DOCRs also integrate voltages for specific faulty component diagnosis. In recent developments, the negative-sequence components of both current and voltage are incorporated to obtain the relay settings of DOCRs. While some researchers suggest to include a voltage parameter in the standard relay characteristics to accommodate DG connections and MG configurations, others propose to utilize admittance-based characteristics while maintaining the inverse time characteristic. This section reviews different types of relay characteristics using various combinations of measured current and voltage, as detailed in Table VII. The benefits of such characteristics, including enhanced efficiency, sensitivity, and selectivity, and reduced ROT drive researchers to optimize relay settings for stability and reliability in DG-based systems. References [189], [190] represent the (*t*-*I*-*V*) characteristics of DOCRs in an IDG-based 9-bus Canadian system. The third harmonic voltage introduced by the IDGs during the fault events is used, and the relay characteristics are designed as an exponential function of voltage alongside the standard characteristics per IEC 60255-3 Std., represented as:

$$t=\left(\frac{1}{e^{\left(1-V_{\mathrm{p}}^{\mathrm{h}}\right)}}\right)^{K}\times\frac{A\times TMS}{\left(\frac{I_{\mathrm{f}}}{I_{\mathrm{p}}}\right)^{B}-1} \tag{13}$$

$$t_{\mathrm{recloser}}=\left(\frac{V_{\mathrm{f}}}{e^{(K\times V_{\mathrm{f}})}}\right)\times\frac{A\times TMS}{\left(\frac{I_{\mathrm{f}}}{I_{\mathrm{p}}}\right)^{B}-1} \tag{14}$$

where V_{f} is the fault voltage across the relay, and K is a decision variable defining the contribution of V_{f}.

References [191] and [192] show DOCR characteristics as a logarithmic function of fault voltage, represented as:

$$t=\left(\frac{1}{1-\log v_{\mathrm{p}}^{a}}\right)^{Z}\times\frac{A\times TMS}{\left(\frac{I_{\mathrm{f}}}{I_{\mathrm{p}}}\right)^{B}-1} \tag{15}$$

$$t=\frac{1}{\left(1-\log\left(\frac{v_{\mathrm{f}}}{v_{\mathrm{p}}}\right)^{a}\right)^{K}}\times\frac{A\times TMS}{\left(\frac{I_{\mathrm{f}}}{I_{\mathrm{p}}}\right)^{B}-1} \tag{16}$$

where v_{p} is the pickup voltage across the relay. By incorporating these characteristics, the relays enhance their performance in weak fault systems and obtain a faster response. The simulation study is conducted on an IEEE 14-bus test system using the differential evolution algorithm.

Reference [193] proposes the relay characteristics to be a logarithmic function of plug setting under the conditions that $\Delta V > 1$ and $\Delta V < 1$ as represented in (17). The paper corresponds to a MINLP problem, and the ROT is a function of TMS, PSM, and standard characteristic curves. Four optimization algorithms are implemented to obtain the optimal relay settings of all relay pairs in an IEEE 30-bus system.

$$t=\begin{cases}\left(5.8-1.35\times\Delta V\log_{\mathrm{e}}\left(\frac{I_{\mathrm{f}}}{I_{\mathrm{p}}}\right)\right)\times TMS;\ \Delta V>1\\ \left(5.8-1.35\times\log_{\mathrm{e}}\left(\frac{I_{\mathrm{f}}}{I_{\mathrm{p}}}\right)\right)\Delta V\times TMS;\ \Delta V<1\end{cases} \tag{17}$$

In [194], the optimal relay settings of DS-DOCRs are obtained as a function of fault voltage. The MINLP solver determines the optimal relay parameters of an IEEE 33-bus test system integrated with squirrel cage induction generator-based DGs and PV-based DGs. Another non-standard expression of ROT [195] is shown in (18) for the voltage-constrained OCRs, whose operating times are inversely dependent on the fault voltage and current. Conventional DOCRs and voltage-constrained OCRs are coordinated using a hybrid-harmony search algorithm.

$$t=\frac{A\times TMS}{\left(\frac{1-V_{\mathrm{f}}}{1-V_{\mathrm{p}}}\right)^{D}\left(\frac{I_{\mathrm{f}}}{I_{\mathrm{p}}}\right)-1} \tag{18}$$

Reference [196] shows the modified version of (19) for obtaining optimal recloser-fuse coordination. In [197], the time of operation of the recloser is proposed as an exponential function of fault voltage in p.u.

$$t_{\mathrm{recloser}}=\frac{28.2}{\left(\frac{I_{\mathrm{f}}}{I_{\mathrm{p}}}\right)\left(\frac{1}{e^{(1-V_{\mathrm{f}})}}\right)^{2}}+0.1217\times(V_{\mathrm{f}}\times(1-V_{\mathrm{f}}))\times TMS \tag{19}$$

Where t_{recloser} is the recloser operating time.

TABLE VI
LITERATURE SURVEY OF SOFT COMPUTING TECHNIQUES IMPLEMENTED IN DG-BASED SYSTEMS

Year of publication	Citation	Optimization algorithm	Test bus	Protection strategy
2018	[138]	Improvised grey wolf optimizer	IEEE 15-bus system	DOCRs
	[139]	GA	11 kV Egyptian distribution feeder	ANN-PI controllers with adaptive protection
	[140]	Ant lion optimizer	IEEE 30-bus and practical 11-bus Egyptian west delta distribution utility	DOCRs
	[141]	Continuous PSO	Multi-loop distribution system	DOCRs
	[142]	Invasive weed optimizer	IEEE 9-bus system	DOCRs
	[143]	Gravitational search optimizer	IEEE 30-bus system	DOCRs
	[144]	Mixed-integer linear programming optimizer	IEEE 14 and 30-bus systems	DOCRs
	[145]	Hybrid GA and linear programming	20 kV DN of Sirjan city in Iran	DOCRs
	[146]	GA, PSO, and teaching-learning-based optimizer	IEEE 6-bus system	DOCRs
	[147]	Simulated annealing and Brute force optimizers	Radial network	DOCRs
2019	[148]	Water cycle algorithm optimizer	IEC MG benchmark	DOCRs
	[149]	Improved firefly algorithm optimizer	IEEE 6, 9, and 30-bus systems	Numerical DOCRs
	[150]	Modified water cycle algorithm	IEEE 8, 9, 15, and 30-bus systems	DOCRs
	[151]	Hybridized whale algorithm	IEEE 8, 9, 15, and 30-bus systems	DOCRs
	[152]	Bio-inspired rooted tree algorithm	IEEE 14 and 30-bus systems	DOCRs
	[153]	Crow search algorithm	Single mesh distribution system	OCRs
	[154]	Oppositional Jaya algorithm	IEEE 3, 8, 9, and 15-bus systems	Distance relays adaptive protection
	[155]	Hybrid BBO/DE algorithm	IEEE 6-bus, 15-bus, and 42-bus test systems	DOCRs
	[172]	MINLP solver of general algebraic modeling systems software	IEEE 33-bus radial DN and a local 40-bus system with multiple SCIG and PV-based DGs	(*t-I-V*)-based DS-DOCRs
2022	[173]	Aggrandized class topper optimization algorithm	IEEE 3, 4, and 8-bus networks	DOCRs
	[174]	Improved seagull optimization algorithm	IEEE 8 and 14-bus test systems	Distance relays and DOCRs
	[175]	Modified PSO, teaching learning, grey wolf and moth-flame optimization algorithms	IEC MG and IEEE 9-bus systems	Non-standard DOCRs
	[176]	Hybrid gravity search algorithm and sequential quadratic programming	9-bus and 39-bus test systems	(*t-I-V*)-based DOCRs
	[177]	Hybrid grey wolf optimizer and rule-based fuzzy logic controller scheme	Real-time using field-programmable gate array DE2-115 board equipped with Cyclone IV-E device	OCRs
	[178]	GA and hybrid gravitational search algorithm-sequential quadratic programming algorithm	IEEE 9-bus, IEC radial MG system benchmark, and IEEE 30-bus meshed system	OCRs
	[179]	Fuzzy logic and GA	Radial 3-bus system with DG	DOCRs
2023	[180]	Wild horse optimizer and nonlinear programming	15-bus MG	Non-standard DOCRs
	[181]	Modified African vulture's optimization algorithm	8-bus, IEEE 30-bus, and IEEE 39-bus networks	Non-standard DOCRs
	[182]	Dragonfly algorithm	6-bus and IEEE 14-bus test systems	Adaptive DOCRs
	[183]	General algebraic modeling system (GAMS) optimization	Canadian urban DN	(*t-I-V*)-based DOCRs
	[184]	PSO and GWO	Modified 14-bus and 39-bus test systems	DS-DOCRs
	[185]	PSO, water cycle algorithm (WCA), whale optimization, crow search, evaporation rate WCA and Archimedes algorithm	IEC MG benchmark	DOCRs
	[186]	Elite marine predators' algorithm	3, 8, 9, and 15-bus test systems	DOCRs
	[187]	Hybrid GSA-SQP	IEEE 9 and 39-bus test systems	Distance relays and (*t-I-V*)-based DOCRs
	[188]	Fmincon optimizer	IEEE 9-bus test system	DS-ROCOV-based relays

TABLE VII
VARIOUS TYPES OF USER-DEFINED PROTECTIVE RELAYING SCHEMES

Type of characteristics	Features
User-defined current-based	• Two level user-defined protection relay is used where both primary and backup relays are user-defined with variables [198]. • Various coordination strategies for different grid-connected MGs for different contingencies under near-end and far-end faults [199]. • A hybrid GA-NLP approach is used to find the relay settings for near-end and far-end faults. This method also investigates the impact of DGs on the protection of MG [200]. • A chaotic Cuckoo search algorithm is used, and performance with and without DG is evaluated [201]. • Non-standard characteristic features not described in IEC and IEEE are considered; maximum value of PSM is taken as a decision variable and not as a parameter; comparative analysis of various optimization algorithms is done [202]. • A combination of integer linear programming and PSO is employed to determine the optimal setting group activation for each relay during non-sequential tripping [203]. • GA, PSO, and teaching-learning-based optimization (TLBO) algorithms are used to obtain the optimal relay settings of the non-standard relays in the IEEE 30-bus system [204]. • Different load conditions (critical, semi-critical, and non-critical) are considered, salp-swarm algorithm and linear programming are used to obtain the optimal relay settings under pre- and post-contingency conditions [205].
Dual setting DOCR	• Networked MGs are taken; LVRT is taken; interior point method is used for optimization; conventional and dual setting DOCRs are taken [206]. • IEEE 30-bus test system; GA optimization tool; communication aided protection [207]. • The covering zone of each backup relay has increased [208]. • DS-DOCRs, non-standard characteristics; SGDG-based system [209]. • Automated DNs are taken to allow flexible control of DSs; α and β are additional decision variables alongside TMS and PS in the optimization problem; the PSO optimization algorithm is used [210]. • User-defined dual setting DOCRs with hybrid (t-I-V) characteristics-based protection coordination for active DN, optimized using MINLP in GA solver [211].
User-defined voltage-based	• ROT expression depends on the local voltage at the relay location in place of the line current. (t-V) curve is drawn, and GA-based non-linear optimization is performed in [212]. This study is extended to different types of faults and fault resistance values. • The protection scheme develops a VI index based on minimizing the energy-not-supplied concept; the IDG-based system is considered in two modes (slow and fast) [213]. • Piece-wise linear characteristics are implemented to obtain the relay settings in an online system that helps reduce the overall ROT, and they automatically maintain the CTI [214].
Rate-of-change-of-voltage (ROCOV)-based:	• Robust against the change in short-circuit level or change in network operating conditions. • (t-I-V)-based DS-directional overcurrent protection [215], [216]. • A third harmonic voltage generated by the IDG controller during short-circuit faults is proposed for overcurrent protection and (t-I-V) characteristics taken [217]. • A comparative study of conventional with dual setting and non-standard DS-DOCRs-based on (t-I-V) characteristics with common relay settings for GC and ISL mode of operation [218]. • The concept of ROCOV is developed and implemented to obtain optimal relay settings of DOCRs in a modified IEEE 14-bus meshed network with SGDG and IDGs for both GC and ISL modes [219].
User-defined (*t-I-V*)-based:	• User-defined characteristic curves. ROT is a function of current as well as bus voltage. Additional features of a duration of voltage sag/ swell may be used for the optimization of overall ROT. • A minimum CTI margin is obtained in the case of a system consisting of a combination of distance and user-defined relays such that the robustness of the system is increased [220]. • Parametric variation of the pair of relays is taken into consideration, and an invasive weed optimization algorithm is implemented to obtain proper coordination among the relay pairs and their minimum operating times [221]. • The exponential function of current and voltage is taken [222]. GA, hybrid GA-linear programming, GA-PSO, and GA-fuzzy techniques are used to obtain optimal relay settings.

V. CONCLUSION

This review paper explores the intricate world of MG protection, addressing critical challenges and exploring various protective relaying schemes. The investigations sheds light on the following key aspects:

1) Stability issues: stability is of paramount importance in MGs. Transient and voltage stability during GC to ISL transitions, faults and load variations are examined. Emphasizing the crucial role of CCT, various techniques for CCT assessment are explored to ascertain the stability of DG-integrated systems. Additionally, the voltage sag/swell under undesirable conditions are discussed. The significance of adhering to grid code compliance and its role in augmenting the stability of DG-integrated systems is also highlighted.

2) Protection challenges: an extensive survey on the operational challenges faced by different types of PDs, such as FCLs, fuse, CBs, relays, and reclosers in the DG integrated systems, is being carried out. A literature survey is conducted in MGs during GC to ISL mode transitioning, fault events, and load variations. The analysis underscores the need for adaptive protection schemes and non-standard characteristics of the PDs to achieve a stable and well-protected system.

3) Protective relaying schemes: a wide array of protective relaying schemes is encompassed in this review

paper. These includes conventional and modern-day-based protection schemes. This review paper recommends the adaption of modern-day technology-based protection schemes due to the dynamic nature of DG-based systems.

4) The development of different types of user-defined protection relaying schemes is examined, such as dual-setting DOCRs, ROCOV-based DOCRs, (*t-I-V*) relay characteristics, due to their customizable nature according to the MG configuration. This paper presents the ability of these relaying schemes to enhance the stability of the DG-integrated systems.

5) Implementing soft computing techniques, such as neural networks and AI techniques, to obtain PD settings, is discussed. This paper recommends the implementation of various nature-inspired evolutionary algorithms to obtain the optimal setting of the PDs to achieve better protection coordination and make the system more self-healed and self-reliant.

VI. Scope for Future Work

This section outlines several promising directions for future research within the ambit of this study, primarily emphasizing on the development of diverse protection schemes to ensure a stable and reliable power system, particularly in the context of challenges posed by DG integration. The following recommendations are put forth:

1) Development of real-time fast operating relaying schemes: Future research endeavors should prioritize the development of multi-objective protective relays that seamlessly integrate stability constraints. This approach seeks to enhance relay operation, improve overall system stability, and elevate selectivity and sensitivity during load variations or fault events.

2) Dynamic stability assessment for high DG penetration: a critical focus should be placed on advancing dynamic stability assessment tools tailored to address the unique challenges posed by high levels of DG penetration. It involves a comprehensive exploration of the influence of intermittent RESs on system dynamics, coupled with the proposal of innovative techniques to enhance overall system stability.

3) Integration of energy storage systems (ESS): Integrating ESSs with DGs emerges as a promising avenue for fortifying system stability. Future research could delve into implementing advanced AI techniques for optimal sizing, placement, and control of ESS. This initiative aims to mitigate DG variability and enhance the overall resilience of the system.

4) Decentralized control strategies: Investigating decentralized control strategies for DG units is a significant avenue to contribute to a more resilient and adaptive power system. Future efforts may explore self-healing capabilities with advanced power electronics-based controller strategies and protection coordination mechanisms among DGs.

5) Cybersecurity in DG Systems: With the growing reliance on communication-assisted protection schemes, future research should address the crucial aspect of cybersecurity in DG systems. Developing robust cybersecurity measures becomes imperative to ensure the integrity and secure operation of protection relays and communication networks.

6) Resilience assessment and enhancement: Future research can delve into assessing and enhancing the overall resilience of power systems with integrated DGs. It includes exploring methodologies to quantify and improve resilience in the face of various disruptions, such as extreme weather events or cyber-attacks.

7) Human-centric approaches: incorporating human-centric approaches into the design of protective relaying schemes could be an additional area of exploration. It involves studying user interactions, usability, and decision-making processes to enhance the overall effectiveness and reliability of protection systems.

In conclusion, the future research landscape in DG integration is multifaceted, requiring concerted efforts to address evolving challenges. It includes developing advanced stability assessment tools, improved cybersecurity measures, and innovative protective relaying schemes. The collaborative pursuit of these research directions is essential for fostering a sustainable, secure, and resilient power infrastructure amid evolving energy paradigms.

Acknowledgment

Not applicable.

Authors' Contributions

Pratibha Singh and Uttam Kumar: conceptualized research objectives, and methodology, data collection and analysis, full-text writing and the construction of the paper framework. Niraj Kumar Choudhary: conceptualization, supervision, review and editing the manuscript. Nitin Singh: review and editing the manuscript. All authors read and approved the final manuscript.

Funding

Not applicable.

Availability of Data and Materials

Not applicable.

Declarations

Competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

AUTHORS' INFORMATION

Pratibha Singh received her M. Tech degree in power electronics and drives in 2016 from the Department of Electrical Engineering, National Institute of Technology, Kurukshetra, India. She is currently working toward the Ph.D. degree in the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Prayagraj, India and is a visiting research scholar at the University of British Columbia, Vancouver, Canada. Her research interests include protection in distribution networks, smart grids, and microgrids.

Uttam Kumar is a M. Tech graduate from the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Prayagraj, India. His research interests include power system protection.

Niraj Kumar Choudhary received the Ph. D. degree from the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Prayagraj, India and M.E. degree from IIEST Shibpur, West Bengal, India. He is currently an assistant professor in the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Prayagraj, India. His research interests include renewable energy and distribution generation-based power systems, and protection of power system, microgrids, and smart grids.

Nitin Singh received the Ph. D. degree from the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Prayagraj, India. He is current an associate professor in the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Prayagraj, India. His research interests include power system planning, electricity markets, artificial intelligence, implementation of optimization algorithms and machine learning techniques in power system.

REFERENCES

[1] A. Latif, M. Paul, and D. C. Das *et al.*, "Price based demand response for optimal frequency stabilization in ORC solar thermal based isolated hybrid microgrid under salp swarm technique," *Electronics (Basel)*, vol. 9, no. 12, Dec. 2020.

[2] S. N. V. B. Rao, Y. V. Pavan Kumar, and M. Amir *et al.*, "An adaptive neuro-fuzzy control strategy for improved power quality in multi-microgrid clusters," *IEEE Access*, vol. 10, pp. 128007-128021, Dec. 2022.

[3] F. Lin, J. Liao, and C. Chen *et al.*, "Voltage restoration control for microgrid with recurrent wavelet Petri fuzzy neural network," *IEEE Access*, vol. 10, pp. 12510-12529, Dec. 2022.

[4] T. S. Tran, D. T. Nguyen, and G. Fujita, "The improvement of an islanding detection method based on the perturbation signal in case of a multi-photovoltaic operation," *Applied Sciences*, vol. 9, no. 19, Sep. 2019.

[5] S. D. Saldarriaga-Zuluaga, J. M. López-Lezama, and N. Muñoz-Galeano, "Optimal coordination of over-current relays in microgrids using unsupervised learning techniques," *Applied Sciences*, vol. 11, no. 3, Jan. 2021.

[6] W. M. Hamanah, M. I. Hossain, and M. Shafiullah *et al.*, "AC microgrid protection schemes: a comprehensive review," *IEEE Access*, vol. 11, pp. 76842-76868, Jul. 2023.

[7] M. Sarwar, N. A. Warsi, and A. S. Siddiqui *et al.*, "Optimal selection of renewable energy-based microgrid for sustainable energy supply," *International Journal of Energy Research*, vol. 46, no. 5, pp. 5828-5846, Apr. 2022.

[8] J. Li, X. Song, and J. Ma, "A novel adaptive distance protection principle for distribution system with distributed generators," in *2015 International Power, Electronics and Materials Engineering Conference (IPEMEC 2015)*, Dalian, China, May 2015, pp. 346-351.

[9] L. G. R. Tonini, R. S. F. Ferraz, and O. E. Batista, "Load flow and short-circuit methods for grids dominated by inverter-based distributed generation," *Energies (Basel)*, vol. 15, no. 13, Jun. 2022.

[10] A. Gencer, "Analysis and control of low-voltage ride-through capability improvement for PMSG based on an NPC converter using an interval type-2 fuzzy logic system," *Elektronika ir Elektrotechnika*, vol. 25, no. 3, pp. 63-70, Jun. 2019.

[11] A. Rupesh Kumar and Z. Hussain, "Investigation of stability analysis and control of synchronous generator connected infinite bus system under fault condition," *IOP Conference Series: Materials Science and Engineering*, vol. 1228, no. 1, Mar. 2022.

[12] C. Liu, X. Cai, and R. Li *et al.*, "Optimal short-circuit current control of the grid-forming converter during grid fault condition," *IET Renewable Power Generation*, vol. 15, no. 10, pp. 2185-2194, Jul. 2021.

[13] Y. Zhao, J. Chai, and S. Wang *et al.*, "Instantaneous power calculation based on intrinsic frequency of single-phase virtual synchronous generator," *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 6, pp. 970-978, Nov. 2017.

[14] A. Abdelrahim, M. Smailes, and K. H. Ahmed *et al.*, "New fault detection algorithm for an improved dual VSM control structure with FRT capability," *IEEE Access*, vol. 9, pp. 125134-125150, Aug. 2021.

[15] J. Teh, C. Lai, and Y. Cheng, "Improving the penetration of wind power with dynamic thermal rating system, static VAR compensator and multi-objective genetic algorithm," *Energies (Basel)*, vol. 11, no. 4, Apr. 2018.

[16] J. Huang, L. Zhang, and S. Sang *et al.*, "Optimized series dynamic braking resistor for LVRT of doubly-fed induction generator with uncertain fault scenarios," *IEEE Access*, vol. 10, pp. 22533-22546, Feb. 2022.

[17] H. Ibrahim, M. Ghandour, and G. El-Jamal, "Feasibility study of hybrid wind-diesel-battery power generating systems: parametric and sensitivity analysis," in *MATEC Web of Conferences*, vol. 171, Jun. 2018.

[18] S. Li, Z. Zhou, and Q. Shan *et al.*, "Analysis of transient voltage stability in a low voltage distribution network using SST for the integration of distributed generations," *Journal of Electrical and Computer Engineering*, vol. 2018, pp. 1-9, Jun. 2018.

[19] W. Wang, N. Cai, and B. Song *et al.*, “Research on distributed photovoltaic grid-connected mode based on PSASP,” *Journal of Physics: Conference Series*, vol. 2488, no. 1, May 2023.

[20] B. Zhang, X. Yan, and D. Li *et al.*, “Stable operation and small-signal analysis of multiple parallel DG inverters based on a virtual synchronous generator scheme,” *Energies (Basel)*, vol. 11, no. 1, Jan. 2018.

[21] A. Reda, M. Farahat, and A. F. Abdelgawad *et al.*, “Investigation of the DGs effect on the coordination between protective elements in distribution network,” *International Journal of Educational Research and Innovation*, vol. 7, no. 4, pp. 227-237, Apr. 2019.

[22] N. Bayati, H. R. Baghaee, and A. Hajizadeh *et al.*, “A fuse saving scheme for DC microgrids with high penetration of renewable energy resources,” *IEEE Access*, vol. 8, no. 2169-3536, pp. 137407-137417, Jul. 2020.

[23] K. Fu, L. Wang, and W. Shao *et al.*, “Supervisory scheme for blockchain privacy protection technique based on group signature,” in *Proceedings of the 2021 ACM International Conference on Intelligent Computing and its Emerging Applications*, New York, USA, Dec. 2021, pp. 223-228.

[24] S. Samantaray, D. Mishra, and G. Joos, “A combined wavelet and data-mining based intelligent protection scheme for microgrid,” in *2018 IEEE Power & Energy Society General Meeting (PESGM)*, Portland, USA, Aug. 2018.

[25] A. A. Shobole and M. Wadi, “Multiagent systems application for the smart grid protection,” *Renewable and Sustainable Energy Reviews*, vol. 149, Oct. 2021.

[26] N. Kumar, Ch. Sanjay, and M. Chakravarthy, “Mamdani fuzzy expert system based directional relaying approach for six-phase transmission line,” *International Journal of Interactive Multimedia and Artificial Intelligence*, vol. 6, no. 1, Jan. 2020.

[27] R. Trivedi and S. Khadem, “Implementation of artificial intelligence techniques in microgrid control environment: Current progress and future scopes,” *Energy and AI*, vol. 8, May 2022.

[28] S. M. E. Ghadiri and K. Mazlumi, “Adaptive protection scheme for microgrids based on SOM clustering technique,” *Applied Soft Computing*, vol. 88, Mar. 2020.

[29] G. Grdenic, M. Delimar, and J. Beerten, “Comparative analysis on small-signal stability of multi-infeed VSC HVDC system with different reactive power control strategies,” *IEEE Access*, vol. 7, pp. 151724-151732, Oct. 2019.

[30] S. Saravanasundaram, S. Muthukrishnan, and G. Murugananth, “Performance analysis of double boost converter powered FSTPI fed induction motor,” *Circuits and Systems*, vol. 7, no. 11, pp. 3448-3455, Sep. 2016.

[31] S. Sharma, S. Pushpak, and V. Chinde *et al.*, “Sensitivity of transient stability critical clearing time,” *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6476-6486, Nov. 2018.

[32] J. D. E. Echeverria, C. J. C. Cepeda, and D. G. Colome, “Real-time transient stability assessment of electric power systems using predictive-SIME based on machine learning,” in *2017 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, Quito, Ecuador, Sep. 2017, pp. 1-6.

[33] D. E. Echeverria, J. L. Rueda, and J. C. Cepeda *et al.*, “Comprehensive approach for prediction and assessment of power system transient stability in real-time,” in *IEEE PES ISGT Europe 2013*, Lyngby, Denmark, Oct. 2013, pp. 1-5.

[34] J. C. Cepeda, J. L. Rueda, and D. G. Colomé *et al.*, “Real-time transient stability assessment based on centre-of-inertia estimation from phasor measurement unit records,” *IET Generation*, *Transmission & Distribution*, vol. 8, no. 8, pp. 1363-1376, Aug. 2014.

[35] J. C. Cepeda, J. L. Rueda, and D. G. Colomé *et al.*, “Data-mining-based approach for predicting the power system post-contingency dynamic vulnerability status,” *International Transactions on Electrical Energy Systems*, vol. 25, no. 10, pp. 2515-2546, Oct. 2015.

[36] S. Gupta and R. K. Tripathi, “Transient stability enhancement of multimachine power system using robust and novel controller based CSC-STATCOM,” *Advances in Power Electronics*, vol. 2015, pp. 1-12, Feb. 2015.

[37] N. Yorino, A. Priyadi, and H. Kakui *et al.*, “A new method for obtaining critical clearing time for transient stability,” *IEEE Transactions on Power Systems*, vol. 25, no. 3, pp. 1620-1626, Aug. 2010.

[38] I. B. Sulistiawati, A. Priyadi, and O. A. Qudsi *et al.*, “Critical clearing time prediction within various loads for transient stability assessment by means of the extreme learning machine method,” *International Journal of Electrical Power & Energy Systems*, vol. 77, pp. 345-352, May 2016.

[39] A. L. Bettiol, A. Souza, and J. L. Todesco *et al.*, “Estimation of critical clearing times using neural networks,” in *2003 IEEE Bologna Power Tech Conference Proceedings,* Bologna, Italy, Jun. 2003, pp. 543-548.

[40] G. Huang, Q. Zhu, and C. Siew, “Extreme learning machine: Theory and applications,” *Neurocomputing*, vol. 70, no. 1-3, pp. 489-501, Dec. 2006.

[41] N. Yorino, A. Priyadi, and R. A. Mutalib *et al.*, “Direct computation of critical clearing time for transient stability analysis,” in *17th Power Systems Computation Conference*, *PSCC 2011*, Sweden, Stockholm, Aug. 2011.

[42] Y. Lin, “Explaining critical clearing time with the rules extracted from a multilayer perceptron artificial neural network,” *International Journal of Electrical Power & Energy Systems*, vol. 32, no. 8, pp. 873-878, Oct. 2010.

[43] A. Karami, “Power system transient stability margin estimation using neural networks,” *International Journal of Electrical Power & Energy Systems*, vol. 33, no. 4, pp. 983-991, May 2011.

[44] G. Huang, Q. Zhu, and C. Siew, “Extreme learning machine: a new learning scheme of feedforward neural networks,” in *2004 IEEE International Joint Conference on Neural Networks (IEEE Cat. No.04CH37541)*, Budapest, Hungary, Jul. 2004, pp. 985-990.

[45] H. Wu and X. Wang, “Design-oriented transient stability analysis of grid-connected converters with power synchronization control,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 6473-6482, Aug. 2019.

[46] Z. Shuai, C. Shen, and X. Liu *et al.*, “Transient angle stability of virtual synchronous generators using Lyapunov’s direct method,” *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 4648-4661, Jul. 2019.

[47] J. Lei, X. Xiang, and B. Liu *et al.*, "Transient stability analysis of grid forming converters based on damping energy visualization and geometry approximation," *IEEE Transactions on Industrial Electronics*, vol. 71, no. 3, pp. 2510-2521, Mar. 2024.

[48] B. B. Adetokun, J. O. Ojo, and C. M. Muriithi, "Reactive power-voltage-based voltage instability sensitivity indices for power grid with increasing renewable energy penetration," *IEEE Access*, vol. 8, pp. 85401-85410, 2020.

[49] Z. Din, J. Zhang, and Z. Xu *et al.*, "Low voltage and high voltage ride-through technologies for doubly fed induction generator system: comprehensive review and future trends," *IET Renewable Power Generation*, vol. 15, no. 3, pp. 614-630, Feb. 2021.

[50] E. Buraimoh and I. E. Davidson, "Overview of fault ride-through requirements for photovoltaic grid integration, design and grid code compliance," in *2020 9th International Conference on Renewable Energy Research and Application (ICRERA)*, Glasgow, UK, Sep. 2020, pp. 332-336.

[51] A. Murdan, I. Jahmeerbacus, and S. Z. Sayed Hassen, "Challenges of existing grid codes and the call for enhanced standards," *Clean Technologies and Recycling*, vol. 3, no. 4, pp. 241-256.

[52] "Electrical relays-part 3: single input energizing quantity measuring relays with dependent or independent time," *IEC Standard* 60255-3, 1989.

[53] J. Y. R. Wong, C. Tan, and A. H. A. Bakar *et al.*, "Selectivity problem in adaptive overcurrent protection for microgrid with inverter-based distributed generators (IBDG): theoretical investigation and HIL verification," *IEEE Transactions on Power Delivery*, vol. 37, no. 4, pp. 3313-3324, Aug. 2022.

[54] R. Tiwari, R. K. Singh and N. K. Choudhary, "Coordination of dual setting overcurrent relays in microgrid with optimally determined relay characteristics for dual operating modes," *Protection and Control of Modern Power Systems*, vol. 7, no. 1, pp. 1-17, Jan. 2022.

[55] H. M. Sharaf, H. H. Zeineldin, and E. El-Saadany, "Protection coordination for microgrids with grid-connected and islanded capabilities using communication assisted dual setting directional overcurrent relays," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 143-151, Jan. 2018.

[56] T. Soleymani Aghdam, H. Kazemi Karegar, and H. H. Zeineldin, "Optimal coordination of double-inverse overcurrent relays for stable operation of DGs," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 1, pp. 183-192, Jan. 2019.

[57] R. C. Dugan and T. E. McDermott, "Operating conflicts for distributed generation on distribution systems," in *2001 Rural Electric Power Conference*, Little Rock, AR, USA, 2001, pp. 1-6.

[58] H. Fedayi, M. Ahmadi, and A. Basir Faiq *et al.*, "BESS based voltage stability improvement enhancing the optimal control of real and reactive power compensation," *AIMS Energy*, vol. 10, no. 3, pp. 535-552, Mar. 2022.

[59] K. H. Oon, C. Tan, and A. H. A. Bakar *et al.*, "Establishment of fault current characteristics for solar photovoltaic generator considering low voltage ride through and reactive current injection requirement," *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 478-488, Sep. 2018.

[60] A. A. El-Fergany and H. M. Hasanien, "Optimized settings of directional overcurrent relays in meshed power networks using stochastic fractal search algorithm," *International Transactions on Electrical Energy Systems*, vol. 27, no. 11, Nov. 2017.

[61] M. Farzinfar and M. Jazaeri, "Coordinated protection and control scheme for smooth transition from grid-connected to islanded mode of microgrids," *Iranian Journal of Science and Technology*, *Transactions of Electrical Engineering*, vol. 44, no. 2, pp. 911-926, Jun. 2020.

[62] Y. Liang, Y. Ren, and J. Yu *et al.*, "Current trajectory image-based protection algorithm for transmission lines connected to MMC-HVDC stations using CA-CNN," *Protection and Control of Modern Power Systems*, vol. 8, no. 1, pp. 1-14, Jan. 2023.

[63] J. Elizondo and J. L. Kirtley, "Effect of inverter-based DG penetration and control in hybrid microgrid dynamics and stability," in *2014 Power and Energy Conference at Illinois (PECI)*, Champaign, IL, USA, Feb. 2014, pp. 1-6.

[64] H. Zeineldin, E. El-Saadany, and L. Huchel, "Protection coordination index enhancement considering multiple DG locations using FCL," in *2017 IEEE Power & Energy Society General Meeting*, Chicago, IL, USA, Jul. 2017.

[65] H. H. Zeineldin, Y. A. R. I. Mohamed, and V. Khadkikar *et al.*, "A protection coordination index for evaluating distributed generation impacts on protection for meshed distribution systems," *IEEE Transactions on Smart Grid*, vol. 4, no. 3, pp. 1523-1532, Sep. 2013.

[66] M. Y. Shih, A. Conde, and C. Ángeles-Camacho *et al.*, "A two stage fault current limiter and directional overcurrent relay optimization for adaptive protection resetting using differential evolution multi-objective algorithm in presence of distributed generation," *Electric Power Systems Research*, vol. 190, Jan. 2021.

[67] Shahabuddin Khan and Ananta Adhikari, "Coordination of over-current relays in power distribution networks with DG considering transient stability constraint," in *IOE Graduate Conference*, *2019 Winter*, IOE Graduate Conference, Dec. 2019, pp. 79-83.

[68] T. S. Aghdam, H. K. Karegar, and H. H. Zeineldin, "Transient stability constrained protection coordination for distribution systems with DG," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 5733-5741, Nov. 2018.

[69] A. Yazdaninejadi, D. Nazarpour, and V. Talavat, "Optimal coordination of dual-setting directional over-current relays in multi-source meshed active distribution networks considering transient stability," *IET Generation*, *Transmission & Distribution*, vol. 13, no. 2, pp. 157-170, Jan. 2019.

[70] M. Yousaf, K. M. Muttaqi, and D. Sutanto, "Improvement of transient stability of the power networks by an intelligent autoreclosing scheme in the presence of synchronous-based DGs," *IEEE Transactions on Industrial Application*, vol. 58, no. 2, pp. 1783-1796, Mar. 2022.

[71] M. Vygoder, F. Banihashemi, and J. Gudex *et al.*, "Coordination of protection and ride-through settings for islanded facility microgrids," in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Vancouver, BC, Canada, Oct. 2021, pp. 1095-1102.

[72] H. He, L. Chen, and T. Yin *et al.*, "Application of a SFCL for fault ride-through capability enhancement of DG in a microgrid system and relay protection coordination," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 7, pp. 1-8, Oct. 2016.

[73] J. Tucker, D. Martin, R. Mersenski *et al.*, "Fault protection and ride-through scheme for MVDC power distribution systems utilizing a supervisory controller," in *2011 IEEE Electric Ship Technologies Symposium*, Alexandria, VA, USA, Apr. 2011, pp. 319-325.

[74] S. A. F. Asl, M. Gandomkar, and J. Nikoukar, "Optimal protection coordination in the micro-grid including inverter-based distributed generations and energy storage system with considering grid-connected and islanded modes," *Electric Power Systems Research*, vol. 184, Jul. 2020.

[75] W. K. A. Najy, H. H. Zeineldin, and W. L. Woon, "Optimal protection coordination for microgrids with grid-connected and islanded capability," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1668-1677, Apr. 2013.

[76] H. Hua, T. Liu, X. Liu *et al.*, "Optimal allocation and sizing of fault current limiters considering transmission switching with an explicit short circuit current formulation," *IEEE Transactions on Power Systems*, vol. 38, no. 2, pp. 1322-1335, Mar. 2023.

[77] S. Dadfar and M. Gandomkar, "Augmenting protection coordination index in interconnected distribution electrical grids: optimal dual characteristic using numerical relays," *International Journal of Electrical Power & Energy Systems*, vol. 131, Oct. 2021.

[78] S. M. Sadeghi, M. Daryalal, and M. Abasi, "Two-stage planning of synchronous distributed generations in distribution network considering protection coordination index and optimal operation situation," *IET Renewable Power Generation*, vol. 16, no. 11, pp. 2338-2356, Aug. 2022.

[79] H. Shad, M. Gandomkar, and J. Nikoukar, "Analysis the securable operation and protection coordination indices on multi-objective sitting and sizing of synchronous distributed generations on distribution networks," *IET Generation*, *Transmission* & *Distribution*, vol. 17, no. 9, pp. 2169-2181, May 2023.

[80] M. W. Altaf, M. T. Arif, and S. N. Islam *et al.*, "Microgrid protection challenges and mitigation approaches–a comprehensive review," *IEEE Access*, vol. 10, pp. 38895-38922, Apr. 2022.

[81] C. Yammani, S. Maheswarapu, and S. K. Matam, "Optimal placement and sizing of distributed generations using shuffled bat algorithm with future load enhancement," *International Transactions on Electrical Energy Systems*, vol. 26, no. 2, pp. 274-292, Feb. 2016.

[82] L. Hong, M. Rizwan, and M. Wasif *et al*., "User-defined dual setting directional overcurrent relays with hybrid time current-voltage characteristics-based protection coordination for active distribution network," *IEEE Access*, vol. 9, pp. 62752–62769, Apr. 2021.

[83] Ö. Çelik, J. S. Farkhani, and A. Lashab *et al*., "A deep GMDH neural-network-based robust fault detection method for active distribution networks," *Energies (Basel)*, vol. 16, no. 19, Sep. 2023.

[84] A. Pandey, S. Kumar, and S. Mohire *et al*., "Dynamic modeling and cascade failure analysis of the Mumbai grid incident of October 12, 2020," *IEEE Access*, vol. 10, pp. 43598-43610, Mar. 2022.

[85] M. A. Khan, A. Haque, and F. Blaabjerg *et al*., "Intelligent transition control between grid-connected and standalone modes of three-phase grid-integrated distributed generation systems," *Energies (Basel)*, vol. 14, no. 13, Jul. 2021.

[86] Y. Xia, Y. Dai, and W. Yan *et al*., "Adaptive-observer-based data driven voltage control in islanded-mode of distributed energy resource systems," *Energies (Basel)*, vol. 11, no. 12, Nov. 2018.

[87] R. Jain, Y. N. Velaga, and K. Prabakar *et al*., "Modern trends in power system protection for distribution grid with high DER penetration," *e-Prime-Advances in Electrical Engineering*, *Electronics and Energy*, vol. 2, 2022.

[88] Y. Chen, M. Wen, and X. Yin *et al*., "Distance protection for transmission lines of DFIG-based wind power integration system," *International Journal of Electrical Power & Energy Systems*, vol. 100, pp. 438-448, Sep. 2018.

[89] E. Vázquez, M. A. Zamora-Mendez, and M. R. Arrieta Paternina *et al*., "Dynamic phasor-driven digital distance relays protection," *Electric Power Systems Research*, vol. 184, Jul. 2020.

[90] A. A. Prada Hurtado, E. Martinez Carrasco, and M. T. Villén Martínez *et al*., "Application of IIA method and virtual bus theory for backup protection of a zone using PMU data in a WAMPAC system," *Energies (Basel)*, vol. 15, no. 9, May 2022.

[91] M. Abasi, A. T. Farsani, and A. Rohani *et al*., "A novel fuzzy theory-based differential protection scheme for transmission lines," *International Journal of Integrated Engineering*, vol. 12, no. 8, Aug. 2020.

[92] L. Zang, G. Zou, and C. Zhou *et al*., "A *d*-axis based current differential protection scheme for an active distribution network," *Protection and Control of Modern Power Systems*, vol. 7, no. 2, pp. 1-10, Apr. 2022.

[93] M. N. Alam, "Overcurrent protection of AC microgrids using mixed characteristic curves of relays," *Computers & Electrical Engineering*, vol. 74, pp. 74-88, Mar. 2019.

[94] C. Reiz and J. B. Leite, "Optimal coordination of protection devices in distribution networks with distributed energy resources and microgrids," *IEEE Access*, vol. 10, pp. 99584-99594, Sep. 2022.

[95] M. Saad, F. Alasali, and N. El Naily *et al*., "Coordination of mixed overcurrent and voltage-restrained overcurrent relays to avoid miscoordination problems considering IEC time-current curve limitations," in *2021 12th International Renewable Energy Congress (IREC)*, Hammamet, Tunisia, Oct. 2021, pp. 1-6.

[96] P. Singh and A. K. Pradhan, "A local measurement based protection technique for distribution system with photovoltaic plants," *IET Renewable Power Generation*, vol. 14, no. 6, pp. 996-1003, Apr. 2020.

[97] Y. Liang, Z. Lu, and W. Li *et al*., "A novel fault impedance calculation method for distance protection against fault resistance," *IEEE Transactions on Power Delivery*, vol. 35, no. 1, pp. 396-407, Feb. 2020.

[98] A. Nasser and S. Arkan, "Enhancement effects of the STATCOM on the distance relay protection," *Interna-*

tional Journal of Computer Application, vol. 182, no. 40, pp. 10-14, Feb. 2019.

[99] L. Tang, O. P. Mahela, and B. Khan *et al*., "Current- and voltage-actuated transmission line protection scheme using a hybrid combination of signal processing techniques," *Sustainability*, vol. 15, no. 7, Mar. 2023.

[100] S. Kar and S. R. Samantaray, "Time-frequency transform-based differential scheme for microgrid protection," *IET Generation, Transmission & Distribution*, vol. 8, no. 2, pp. 310-320, Feb. 2014.

[101] A. Soleimanisardoo, H. Kazemi Karegar, and H. H. Zeineldin, "Differential frequency protection scheme based on off-nominal frequency injections for inverter-based islanded microgrids," *IEEE Transactions on Smart Grid*, vol. 10, no. 2, pp. 2107-2114, Mar. 2019.

[102] S. Sheng, K. K. Li, and X. Zeng, "Distribute coordinated wide area current differential protection based on IEC61850," in *TENCON 2006 - 2006 IEEE Region 10 Conference*, 2006, pp. 1-4.

[103] V. C. Nikolaidis, G. Michaloudis, and A. M. Tsimtsios *et al*., "A multi-zone differential protection scheme for MV distribution systems with distributed generation," in *15th International Conference on Developments in Power System Protection (DPSP 2020)*, Institution of Engineering and Technology, 2020, pp. 1-6.

[104] M. A. Dawoud, D. K. Ibrahim, and M. I. Gilany *et al*., "Robust coordination scheme for microgrids protection based on the rate of change of voltage," *IEEE Access*, vol. 9, pp. 156283-156296, Nov. 2021.

[105] H. Beder, B. Mohandes, and M. S. El Moursi *et al*., "A new communication-free dual setting protection coordination of microgrid," *IEEE Transactions on Power Delivery*, vol. 36, no. 4, pp. 2446-2458, Aug. 2021.

[106] A. E. C. Momesso, W. M. S. Bernardes, and E. N. Asada, "Adaptive directional overcurrent protection considering stability constraint," *Electric Power Systems Research*, vol. 181, Apr. 2020.

[107] H. Lin, J. M. Guerrero, and C. Jia *et al*., "Adaptive overcurrent protection for microgrids in extensive distribution systems," in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, Florence, Italy, Oct. 2016, pp. 4042-4047.

[108] H. Aghaei and H. Hashemi-Dezaki, "Optimal communication-aided protection of meshed smart grids considering stability constraints of distributed generations incorporating optimal selection of relay characteristics," *IET Renewable Power Generation*, vol. 16, no. 11, pp. 2313-2337, Aug. 2022.

[109] M. A. U. Khan, Q. Hong, and A. Egea-Àlvarez *et al*., "A communication-free active unit protection scheme for inverter dominated islanded microgrids," *International Journal of Electrical Power & Energy Systems*, vol. 142, Nov. 2022.

[110] M. H. Sadeghi, A. Dastfan, and Y. Damchi, "Optimal distributed generation penetration considering relay coordination and power quality requirements," *IET Generation, Transmission & Distribution*, vol. 16, no. 12, pp. 2466-2475, Jun. 2022.

[111] J. J. G. Ledesma, L. R. de Araujo, and D. R. R. Penido, "A method for evaluation of overcurrent protection in unbalanced distribution systems," *International Transactions on Electrical Energy Systems*, vol. 26, no. 2, pp. 412-428, Feb. 2016.

[112] L. F. F. De Almeida, J. R. Dos Santos, and L. A. M. Pereira *et al*., "Control networks and smart grid teleprotection: key aspects, technologies, protocols, and case-studies," *IEEE Access*, vol. 8, pp. 174049-174079, Sep. 2020.

[113] W. Purwanto, Y. He, and J. Ossom *et al.*, "DeapSECURE computational training for cybersecurity students: improvements, mid-stage evaluation, and lessons learned," *The Journal of Computational Science Education*, vol. 12, no. 2, pp. 3-10, Feb. 2021.

[114] Y. Cao, Y. Wang, and Y. Ding *et al*., "Blockchain-empowered security and privacy protection technologies for smart grid," *Comput Stand Interfaces*, vol. 85, Apr. 2023.

[115] Y. M. Khaw, A. Abiri Jahromi, and M. F. M. Arani *et al*., "A deep learning-based cyberattack detection system for transmission protective relays," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 2554-2565, May 2021.

[116] J. Perez, F. Valdez, and O. Castillo, "Modification of the bat algorithm using fuzzy logic for dynamical parameter adaptation," in *2015 IEEE Congress on Evolutionary Computation (CEC)*, May 2015, pp. 464-471.

[117] B. J. Brearley, R. Raja Prabu, and K. Regin Bose *et al*., "Adaptive relay co-ordination scheme for radial microgrid," *International Journal of Ambient Energy*, vol. 43, no. 1, pp. 2180-2193, Dec. 2022.

[118] H. Beder, B. Mohandes, and M. S. El Moursi *et al*., "A new communication-free dual setting protection coordination of microgrid," *IEEE Transactions on Power Delivery*, vol. 36, no. 4, pp. 2446-2458, Aug. 2021.

[119] A. E. C. Momesso, W. M. S. Bernardes, and E. N. Asada, "Adaptive directional overcurrent protection considering stability constraint," *Electric Power Systems Research*, vol. 181, Apr. 2020.

[120] H. Lin, J. M. Guerrero, and C. Jia *et al*., "Adaptive overcurrent protection for microgrids in extensive distribution systems," in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, IEEE, Oct. 2016, pp. 4042-4047.

[121] A. Moradi, J. Yaghoobi, and A. Alduraibi *et al*., "Modelling and prediction of current harmonics generated by power converters in distribution networks," *IET Generation, Transmission & Distribution*, vol. 15, no. 15, pp. 2191-2202, Aug. 2021.

[122] P. Niranjan, P. K. Gupta, and P. Ahmad *et al*., "Protection coordination scheme in microgrid with common optimal settings of user-defined dual-setting overcurrent relays," in *2023 5th International Conference on Energy, Power and Environment*: *Towards Flexible Green Energy Technologies (ICEPE)*, IEEE, Jun. 2023, pp. 1-5.

[123] S. Jamali and H. Borhani-Bahabadi, "Non-communication protection method for meshed and radial distribution networks with synchronous-based DG," *International Journal of Electrical Power & Energy Systems*, vol. 93, pp. 468-478, Dec. 2017.

[124] F. A. S. Dizioli, P. H. A. Barra, and T. S. Menezes *et al*., "Multi-agent system-based microgrid protection using angular variation: an embedded approach," *Electric Power Systems Research*, vol. 220, Jul. 2023.

[125]R. Aazami, S. Esmaeilbeigi, and M. Valizadeh *et al*., "Novel intelligent multi-agents system for hybrid adaptive protection of micro-grid," *Sustainable Energy, Grids and Networks*, vol. 30, Jun. 2022.

[126]G. Kaur, A. Prakash, and K. U. Rao, "A critical review of microgrid adaptive protection techniques with distributed generation," *Renewable Energy Focus*, vol. 39, pp. 99-109, Dec. 2021.

[127]A. E. Labrador Rivas, L. A. Gallego Pareja, and T. Abrão, "Coordination of distance and directional overcurrent relays using an extended continuous domain ACO algorithm and an hybrid ACO algorithm," *Electric Power Systems Research*, vol. 170, pp. 259-272, May 2019.

[128]Q. Li, Z. Cui, and Y. Cai *et al*., "Multi-objective operation of solar-based microgrids incorporating artificial neural network and grey wolf optimizer in digital twin," *Solar Energy*, vol. 262, Sep. 2023.

[129]Z. S. Rahmania, L. Syafa'ah, and I. Pakaya *et al*., "Optimization of overcurrent relay coordination using cuckoo search algorithm in electronic induction systems," *IOP Conference Series*: *Materials Science and Engineering*, vol. 674, no. 1, Nov. 2019.

[130]A. Y. Hatata, M. A. Essa, and B. E. Sedhom, "Adaptive protection scheme for freedm microgrid based on convolutional neural network and gorilla troops optimization technique," *IEEE Access*, vol. 10, pp. 55583-55601, May 2022.

[131]A. Elmitwally, M. F. Kotb, and E. Gouda *et al*., "A coordination scheme for a combined protection system considering dynamic behavior and wind DGs fault ride-through constraints," *Electric Power Systems Research*, vol. 213, Dec. 2022.

[132]P. Singh, P. Niranjan, and A. Anand *et al*., "A logarithmic function based relay characteristics for optimal protection coordination in distributed generation systems," in *2023 IEEE IAS Global Conference on Emerging Technologies (GlobConET)*, London, USA, May 2023, pp. 1-6.

[133]J. J. Q. Yu, Y. Hou, and A. Y. S. Lam *et al*., "Intelligent fault detection scheme for microgrids with wavelet-based deep neural networks," *IEEE Transactions on Smart Grid*, vol. 10, no. 2, pp. 1694-1703, Mar. 2019.

[134]O. A. Gashteroodkhani, M. Majidi, and M. Etezadi-Amoli, "A combined deep belief network and time-time transform based intelligent protection scheme for microgrids," *Electric Power Systems Research*, vol. 182, May 2020.

[135]S. Ranjbar, A. R. Farsa, and S. Jamali, "Voltage-based protection of microgrids using decision tree algorithms," *International Transactions on Electrical Energy Systems*, vol. 30, no. 4, Apr. 2020.

[136]E. Fantin Irudaya Raj, K. Manimala, and M. Appadurai, "Differential protection scheme along with backup blockchain system for DC microgrid," in *Smart and Power Grid Systems - Design Challenges and Paradigms*, 2022.

[137]S. Authafa, "Short circuit faults identification and localization in IEEE 34 nodes distribution feeder based on the theory of wavelets," *Iraqi Journal for Electrical and Electronic Engineering*, vol. 14, no. 1, pp. 65-79, Jun. 2018.

[138]N. Z. Jamal, M. Herwan, and O. Aliman *et al*., "Optimal overcurrent relays coordination using an improved grey wolf optimizer," *International Journal of Advanced Computer Science and Applications*, vol. 9, no. 11, 2018.

[139]M. I. Mosaad, N. I. Elkalashy, and M. G. Ashmawy, "Integrating adaptive control of renewable distributed Switched Reluctance Generation and feeder protection coordination," *Electric Power Systems Research*, vol. 154, pp. 452-462, Jan. 2018.

[140]A. Y. Hatata and A. Lafi, "Ant lion optimizer for optimal coordination of DOC relays in distribution systems containing DGs," *IEEE Access*, vol. 6, pp. 72241-72252, 2018.

[141]A. Wadood, C. Kim, and T. Khurshiad *et al*., "Application of a continuous particle swarm optimization (CPSO) for the optimal coordination of overcurrent relays considering a penalty method," *Energies (Basel)*, vol. 11, no. 4, Apr. 2018.

[142]S. T. P. Srinivas and K. S. Swarup, "Optimal protection coordination for microgrid considering DG and line outages using IWO-ILP technique," in *2018 IEEE 20th National Power Systems Conference (NPSC)*, Dec. 2018, pp. 1-6.

[143]A. Chawla, B. R. Bhalja, and B. K. Panigrahi *et al*., "Gravitational search based algorithm for optimal coordination of directional overcurrent relays using user defined characteristic," *Electric Power Components and Systems*, vol. 46, no. 1, pp. 43-55, Jan. 2018.

[144]Y. Damchi, M. Dolatabadi, and H. R. Mashhadi *et al*., "MILP approach for optimal coordination of directional overcurrent relays in interconnected power systems," *Electric Power Systems Research*, vol. 158, pp. 267-274, May 2018.

[145]R. M. Chabanloo, M. G. Maleki, and S. M. Mousavi Agah *et al*., "Comprehensive coordination of radial distribution network protection in the presence of synchronous distributed generation using fault current limiter," *International Journal of Electrical Power & Energy Systems*, vol. 99, pp. 214-224, Jul. 2018.

[146]S. Roy, P. S. Babu, and N. V. P. Babu, "Intelligent overcurrent and distance relays coordination: a comparative analysis using GA, PSO and TLBO," *International Journal on Electrical Engineering and Informatics*, vol. 10, no. 4, pp. 162-167, Dec. 2018.

[147]H. Verma, S. Mahapatra, and S. P. Anwaya *et al*., "Optimal coordination of overcurrent relays using simulated annealing and brute force algorithms," in *2018 International Conference on Power*, *Control*, *Signals and Instrumentation Engineering (ICPCSI)*, Chennai, India, Dec. 2018, pp. 177-183.

[148]N. El Naily, S. M. Saad, and M. M. El Misslati *et al*., "Optimal protection coordination for IEC microgrid benchmark using water cycle algorithm," in *2019 10th International Renewable Energy Congress (IREC)*, Sousse, Tunisia, 2019, pp. 1-6.

[149]T. Khurshaid, A. Wadood, and S. G. Farkoush *et al*., "Improved firefly algorithm for the optimal coordination of directional overcurrent relays," *IEEE Access*, vol. 7, pp. 78503-78514, Jun. 2019.

[150]A. Korashy, S. Kamel, and A. R. Youssef *et al*., "Modified water cycle algorithm for optimal direction over-

current relays coordination," *Applied Soft Computing*, vol. 74, pp. 10-25, Jan. 2019.

[151] T. Khurshaid, A. Wadood, and S. Gholami Farkoush *et al.*, "An improved optimal solution for the directional overcurrent relays coordination using hybridized whale optimization algorithm in complex power systems," *IEEE Access*, vol. 7, pp. 90418-90435, Jul. 2019.

[152] A. Wadood, T. Khurshaid, and S. G. Farkoush *et al.*, "A bio-inspired rooted tree algorithm for optimal coordination of overcurrent relays," in *International Conference on Electrical Engineering*, Gyeongsan, Korea, 2019, pp. 188-201.

[153] D. Sarkar, S. Kudkelwar, and D. Saha, "Optimal coordination of overcurrent relay using crow search algorithm," *Smart Science*, vol. 7, no. 4, pp. 282-297, Oct. 2019.

[154] J. Yu, C. H. Kim, and S. B. Rhee, "Oppositional Jaya algorithm with distance-adaptive coefficient in solving directional over current relays coordination problem," *IEEE Access*, vol. 7, pp. 150729-150742, Oct. 2019.

[155] A. R. Al-Roomi and M. E. El-Hawary, "Optimal coordination of double primary directional overcurrent relays using a new combinational BBO/DE algorithm," *Canadian Journal of Electrical and Computer Engineering*, vol. 42, no. 3, pp. 135-147, Jul. 2019.

[156] K. Sarwagya, P. K. Nayak, and S. Ranjan, "Optimal coordination of directional overcurrent relays in complex distribution networks using sine cosine algorithm," *Electric Power Systems Research*, vol. 187, Oct. 2020.

[157] D. Sarkar and S. Kudkelwar, "Optimal over current relay coordination in microgrid using a novel hybrid water cycle-moth flame algorithm," *International Journal of System Assurance Engineering and Management*, vol. 12, no. 3, pp. 553-564, Jun. 2021.

[158] K. H. Khan, K. B. Thapa, and N. R. Karki, "Optimal coordination of directional overcurrent relays using enhanced L-SHADE Algorithm," in *2020 IEEE International Conference on Power Systems Technology (POWERCON)*, Sep. 2020, pp. 1-6.

[159] K. Cheng, A. Priyadi, and M. Pujiantara *et al.*, "The coordination of dual setting DOCR for ring system using adaptive modified firefly algorithm," in *2020 IEEE International Seminar on Intelligent Technology and Its Applications (ISITIA)*, Jul. 2020, pp. 44-50.

[160] J. Yu, C. H. Kim, and S. B. Rhee, "The comparison of lately proposed harris hawks optimization and jaya optimization in solving directional overcurrent relays coordination problem," *Complexity*, vol. 2020, pp. 1-22, Jan. 2020.

[161] A. Hatata, S. Kaddah, and H. Abdraboh *et al.*, "Optimal directional overcurrent relay coordination using artificial immune algorithm. (Dept. E.)," *Bulletin of the Faculty of Engineering*, *Mansoura University*, vol. 39, no. 4, pp. 9-18, Jul. 2020.

[162] G. J. Meyer, T. Lorz, and R. Wehner *et al.*, "Hybrid fuzzy evaluation algorithm for power system protection security assessment," *Electric Power Systems Research*, vol. 189, Dec. 2020.

[163] S. M. Saad, N. El Naily, and A. Elhaffar *et al.*, "Time-current-voltage overcurrent scheme for reliable microgrids protection considering arc flash incident energy," in *2020 11th International Renewable Energy Congress (IREC)*, Hammamet, Tunisia, Oct. 2020, pp. 1-6.

[164] K. Srikumar, "A control strategy for optimal coordination of interconnected distribution system using dual setting directional over current relays (DSDOR)," in *Emerging Trends in Electrical*, *Communications, and Information Technologies. Lecture Notes in Electrical Engineering*, vol. 569, Singapore: Springer, 2020, pp. 199-212.

[165] M. Irfan, A. Wadood, and T. Khurshaid *et al.*, "An optimized adaptive protection scheme for numerical and directional overcurrent relay coordination using Harris hawk optimization," *Energies (Basel)*, vol. 14, no. 18, Sep. 2021.

[166] R. M. Rizk-Allah and A. A. El-Fergany, "Effective coordination settings for directional overcurrent relay using hybrid Gradient-based optimizer," *Applied Soft Computing*, vol. 112, Nov. 2021.

[167] A. Narimani and H. Hashemi-Dezaki, "Optimal stability-oriented protection coordination of smart grid's directional overcurrent relays based on optimized tripping characteristics in double-inverse model using high-set relay," *International Journal of Electrical Power & Energy Systems*, vol. 133, Dec. 2021.

[168] F. Alasali, N. El-Naily, and E. Zarour *et al.*, "Highly sensitive and fast microgrid protection using optimal coordination scheme and nonstandard tripping characteristics," *International Journal of Electrical Power & Energy Systems*, vol. 128, Jun. 2021.

[169] S. K. ElSayed and E. E. Elattar, "Hybrid Harris hawks optimization with sequential quadratic programming for optimal coordination of directional overcurrent relays incorporating distributed generation," *Alexandria Engineering Journal*, vol. 60, no. 2, pp. 2421-2433, Apr. 2021.

[170] P. K. Choudhary and D. K. Das, "Optimal coordination of over-current relay in a power distribution network using opposition based learning fractional order class topper optimization (OBL-FOCTO) algorithm," *Applied Soft Computing*, vol. 113, Dec. 2021.

[171] A. Draz, M. M. Elkholy, and A. A. El-Fergany, "Slime mould algorithm constrained by the relay operating time for optimal coordination of directional overcurrent relays using multiple standardized tripping curves," *Neural Computing & Applications*, vol. 33, no. 18, pp. 11875-11887, Sep. 2021.

[172] L. Hong, M. Rizwan, and M. Wasif *et al.*, "User-defined dual setting directional overcurrent relays with hybrid time current-voltage characteristics-based protection coordination for active distribution network," *IEEE Access*, vol. 9, pp. 62752-62769, Apr. 2021.

[173] P. K. Choudhary and D. K. Das, "Optimal coordination of over-current relay in a power distribution network using aggrandized class topper optimization (A-CTO) algorithm," *Journal of Supercomputing*, vol. 78, no. 17, pp. 19296-19321, Nov. 2022.

[174] M. Abdelhamid, E. H. Houssein, and M. A. Mahdy *et al.*, "An improved seagull optimization algorithm for optimal coordination of distance and directional over-current relays," *Expert Systems with Applications*, vol. 200, Aug. 2022.

[175]F. Alasali, E. Zarour, and W. Holderbaum *et al*., "Highly fast innovative overcurrent protection scheme for microgrid using metaheuristic optimization algorithms and nonstandard tripping characteristics," *IEEE Access*, vol. 10, pp. 42208-42231, Apr. 2022.

[176]A. Assouak, R. Benabid, and A. A. Ladjici, "Optimal coordination of directional overcurrent relays with non-standard multi-characteristics for power systems transient instability protection," *Electrical Engineering*, vol. 104, no. 5, pp. 3697-3715, Oct. 2022.

[177]M. Uddin, N. Rezaei, and O. Emmanuel Olufemi, "Adaptive and optimal overcurrent protection of wind farms with improved reliability," *IEEE Transactions on Industry Applications*, vol. 58, no. 3, pp. 3342-3352, May 2022.

[178]S. Abeid, Y. Hu, F. Alasali, and N. El-Naily, "Innovative optimal nonstandard tripping protection scheme for radial and meshed microgrid systems," *Energies (Basel)*, vol. 15, no. 14, Jul. 2022.

[179]L. R. Chandran, A. Parvathy, and M. G. Nair, "Adaptive over current relay protection in a pv penetrated radial distribution system with fuzzy GA optimisation," in *2022 IEEE 19th India Council International Conference (INDICON)*, Nov. 2022, pp. 1-7.

[180]S. Biswal and S. R. Samantaray, "An effective protection coordination scheme for networked microgrids based on nonstandard tripping characteristics of DOCRs," *IEEE System Journal*, pp. 1-12, 2023.

[181]A. Korashy, S. Kamel, and F. Jurado *et al*., "Optimal coordination of distance relays and non-standard characteristics for directional overcurrent relays using a modified African vultures optimization algorithm," *IET Generation, Transmission & Distribution*, vol. 17, no. 11, pp. 2497-2522, Jun. 2023.

[182]K. Sarwagya, P. K. Nayak, and S. Ranjan, "Adaptive coordination of directional overcurrent relays for meshed distribution networks with distributed generations using dragonfly algorithm," *Electrical Engineering*, Jun. 2023.

[183]Y. H. El Gohary, T. E. Sati, and A. H. Osman *et al*., "Optimal protection coordination for inverter-based islanded microgrids utilizing an optimized time-current-voltage characteristic," in *2023 3rd International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*, IEEE, Jul. 2023, pp. 1-6.

[184]D. K. Singh, S. Sarangi, and A. K. Singh *et al*., "Coordination of dual-setting overcurrent and distance relays for meshed distribution networks with distributed generations and dynamic voltage restorer," *Smart Science*, vol. 11, no. 1, pp. 135-153, Jan. 2023.

[185]S. B. Kudkelwar, B. B. Sinha, and S. K. Gunturi, "An archimedes metaheuristic algorithm based optimum relay coordination in microgrid and combined overhead/cable distribution network," *Journal of Supercomputing*, Jun. 2023.

[186]O. Merabet, M. Bouchahdane, and H. Belmadani *et al*., "Optimal coordination of directional overcurrent relays in complex networks using the Elite marine predators algorithm," *Electric Power Systems Research*, vol. 221, Aug. 2023.

[187]A. Assouak and R. Benabid, "A new coordination scheme of directional overcurrent and distance protection relays considering time-voltage-current characteristics," *International Journal of Electrical Power & Energy Systems*, vol. 150, Aug. 2023.

[188]P. K. Gupta, P. Niranjan, and N. K. Choudhary *et al*., "A novel protection coordination scheme based on dual-setting rate of change of voltage based relays," in *2023 IEEE 5th International Conference on Energy, Power and Environment: Towards Flexible Green Energy Technologies (ICEPE)*, Jun. 2023, pp. 1-6.

[189]W. T. El-Sayed, M. A. Azzouz, and H. H. Zeineldin *et al*., "A harmonic time-current-voltage directional relay for optimal protection coordination of inverter-based islanded microgrids," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 1904-1917, May 2021.

[190]K. A. Saleh, H. H. Zeineldin, and A. Al-Hinai *et al*., "Optimal coordination of directional overcurrent relays using a new time-current-voltage characteristic," *IEEE Transactions on Power Delivery*, vol. 30, no. 2, pp. 537-544, Apr. 2015.

[191]M. V. Tejeswini and B. C. Sujatha, "Optimal protection coordination of voltage-current time based inverse relay for PV based distribution system," in *2017 IEEE Second International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, Feb. 2017, pp. 1-7.

[192]M. Singh and A. Agrawal, "Voltage-current-time inverse-based protection coordination of photovoltaic power systems," *IET Generation*, *Transmission & Distribution*, vol. 13, no. 6, pp. 794-804, Mar. 2019.

[193]E. Zarour, F. Alasali, and O. Alsmadi *et al*., "A new adaptive protection approach for overcurrent relays using novel nonstandard current-voltage characteristics," *Electric Power Systems Research*, vol. 216, Mar. 2023.

[194]L. Hong, M. Rizwan, and M. Wasif *et al*., "User-defined dual setting directional overcurrent relays with hybrid time current-voltage characteristics-based protection coordination for active distribution network," *IEEE Access*, vol. 9, pp. 62752-62769, Apr. 2021.

[195]V. N. Rajput, K. S. Pandya, and J. Hong *et al*., "A novel protection scheme for solar photovoltaic generator connected networks using hybrid harmony search algorithm-Bollinger bands approach," *Energies (Basel)*, vol. 13, no. 10, May 2020.

[196]S. Jamali and H. Borhani-Bahabadi, "Self-adaptive relaying scheme of reclosers for fuse saving in distribution networks with DG," *International Journal of Power and Energy Research*, vol. 1, no. 1, Apr. 2017.

[197]S. Jamali and H. Borhani-Bahabadi, "Recloser time-current-voltage characteristic for fuse saving in distribution networks with DG," *IET Generation, Transmission & Distribution*, vol. 11, no. 1, pp. 272-279, Jan. 2017.

[198]A. B. Fayoud, H. M. Sharaf, and D. K. Ibrahim, "Optimal coordination of DOCRs in interconnected networks using shifted user-defined two-level characteristics," *International Journal of Electrical Power & Energy Systems*, vol. 142, Nov. 2022.

[199]A. Ataee-Kachoee, H. Hashemi-Dezaki, and A. Ketabi, "Optimized adaptive protection coordination of microgrids by dual-setting directional overcurrent relays

considering different topologies based on limited independent relays' setting groups," *Electric Power Systems Research*, vol. 214, Jan. 2023.

[200] J. M. Tripathi and S. K. Mallik, "An adaptive protection coordination strategy utilizing user-defined characteristics of DOCRs in a microgrid," *Electric Power Systems Research*, vol. 214, Jan. 2023.

[201] S. Biswal and S. R. Samantaray, "A user defined characteristics based optimal coordination of directional overcurrent relay for microgrids," in *2021 National Power Electronics Conference (NPEC)*, IEEE, Dec. 2021, pp. 1-6.

[202] A. Samadi and R. M. Chabanloo, "Adaptive coordination of overcurrent relays in active distribution networks based on independent change of relays' setting groups," *International Journal of Electrical Power & Energy Systems*, vol. 120, Sep. 2020.

[203] A. Darabi, M. Bagheri, and G. B. Gharehpetian, "Highly sensitive microgrid protection using overcurrent relays with a novel relay characteristic," *IET Renewable Power Generation*, vol. 14, no. 7, pp. 1201-1209, May 2020.

[204] S. D. Saldarriaga-Zuluaga, J. M. López-Lezama, and N. Muñoz-Galeano, "Optimal coordination of over-current relays in microgrids considering multiple characteristic curves," *Alexandria Engineering Journal*, vol. 60, no. 2, pp. 2093-2113, Apr. 2021.

[205] M. Usama, M. Moghavvemi, and H. Mokhlis *et al.*, "Optimal protection coordination scheme for radial distribution network considering on/off-grid," *IEEE Access*, vol. 9, pp. 34921-34937, Jan. 2021.

[206] M. N. Alam, R. Gokaraju, and S. Chakrabarti, "Protection coordination for networked microgrids using single and dual setting overcurrent relays," *IET Generation, Transmission & Distribution*, vol. 14, no. 14, pp. 2818-2828, Jul. 2020.

[207] M. Aghaei-Fatideh, H. Hashemi-Dezaki, and A. H. Niasar, "Optimal protection of smart grids using communication-based dual-setting directional overcurrent relays considering different grid configurations," in *2022 IEEE International Conference on Protection and Automation of Power Systems (IPAPS)*, Jan. 2022, pp. 1-6.

[208] A. Yazdaninejadi, D. Nazarpour, and S. Golshannavaz, "Dual-setting directional over-current relays: an optimal coordination in multiple source meshed distribution networks," *International Journal of Electrical Power & Energy Systems*, vol. 86, pp. 163-176, Mar. 2017.

[209] A. H. Ataee-Kachoee, H. Hashemi-Dezaki, and A. Ketabi, "Optimal protection coordination of dual-setting directional overcurrent relays based on three-point coordination strategy," in *2021 11th Smart Grid Conference (SGC)*, Tehran, Iran, Dec. 2021, pp. 1-6.

[210] A. Yazdaninejadi, S. Golshannavaz, and D. Nazarpour *et al.*, "Dual-setting directional overcurrent relays for protecting automated distribution networks," *IEEE Transaction on Industrial Informatics*, vol. 15, no. 2, pp. 730-740, Feb. 2019.

[211] L. Hong, M. Rizwan, and M. Wasif *et al.*, "User-defined dual setting directional overcurrent relays with hybrid time current-voltage characteristics-based protection coordination for active distribution network," *IEEE Access*, vol. 9, pp. 62752-62769, Nov. 2021.

[212] C. Reiz and J. B. Leite, "Protection devices coordination in distribution systems with microgrids powered by renewable distributed generation," *SSRN Electronic Journal*, 2022.

[213] H. Ebrahimi, A. Yazdaninejadi, and S. Golshannavaz *et al.*, "An ENS-oriented voltage protection scheme for inverter-based generators in active distribution networks," *IEEE Transactions on Smart Grid*, vol. 13, no. 4, pp. 2639-2649, Jul. 2022.

[214] M. Azari, K. Mazlumi, and M. Ojaghi, "Efficient non-standard tripping characteristic-based coordination method for overcurrent relays in meshed power networks," *Electrical Engineering*, vol. 104, no. 4, pp. 2061-2078, Aug. 2022.

[215] A. A. Balyith, H. M. Sharaf, and M. Shaaban *et al.*, "Non-communication based time-current-voltage dual setting directional overcurrent protection for radial distribution systems with DG," *IEEE Access*, vol. 8, pp. 190572-190581, Oct. 2020.

[216] N. El-Naily, S. M. Saad, and T. Hussein *et al.*, "A novel constraint and non-standard characteristics for optimal over-current relays coordination to enhance microgrid protection scheme," *IET Generation, Transmission & Distribution*, vol. 13, no. 6, pp. 780-793, Mar. 2019.

[217] W. T. El-Sayed, M. A. Azzouz, and H. H. Zeineldin *et al.*, "A harmonic time-current-voltage directional relay for optimal protection coordination of inverter-based islanded microgrids," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 1904-1917, May 2021.

[218] A. Yazdaninejadi, D. Nazarpour, and V. Talavat, "Optimal coordination of dual-setting directional over-current relays in multi-source meshed active distribution networks considering transient stability," *IET Generation, Transmission & Distribution*, vol. 13, no. 2, pp. 157-170, Jan. 2019.

[219] M. A. Dawoud, D. K. Ibrahim, and M. I. Gilany *et al.*, "Robust coordination scheme for microgrids protection based on the rate of change of voltage," *IEEE Access*, vol. 9, pp. 156283-156296, Nov. 2021.

[220] M. Singh, V. Telukunta, and S. G. Srivani, "Enhanced real time coordination of distance and user defined over current relays," *International Journal of Electrical Power & Energy Systems*, vol. 98, pp. 430-441, Jun. 2018.

[221] R. Hemmati and H. Mehrjerdi, "Non-standard characteristic of overcurrent relay for minimum operating time and maximum protection level," *Simulation Modeling Practice and Theory*, vol. 97, Dec. 2019.

[222] S. D. Saldarriaga-Zuluaga, J. M. López-Lezama, and N. Muñoz-Galeano, "Adaptive protection coordination scheme in microgrids using directional over-current relays with non-standard characteristics," *Heliyon*, vol. 7, no. 4, Apr. 2021.