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REVIEW

The recent development of protection coordination schemes based on inverse of AC microgrid: A review

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Abstract

Integration of distributed generation systems and diversity of microgrid operations led to a change in the structure of the power system. Due to this conversion, new challenges have arisen when employing traditional overcurrent protection schemes. As a consequence, non-classical protection schemes have attracted significant attention in the last few years. Engineers and scholars have proposed different non-standard methods to increase the power protection system and ensure the highly selectivity performance. Although the non-standard characteristics and their requirements, in general, have been outlined and analyzed in the available literature, protection coordination based on voltage current–time inverse, as a branch of non-standard optimization methods, has not yet been thoroughly discussed, compared, or debated in detail. To close this gap, this review introduces a broad overview of recent research and developments of the voltage current–time inverse based protection coordination. Focuses on assessing the potential advantages and disadvantages of related studies and provide a classification and analysis of these studies. The future trends and some recommendations have been included in this review for improving fault detection sensitivity and coordination reliability.

1 | INTRODUCTION

1.1 | Motivation and background

The need for power has grown with time, where the increased demand for electricity requires the installation of a new power station to meet this demand. Traditional power stations have numerous difficulties, including power losses, high prices, system inefficiency, and environmental pollution [1, 2]. The distribution network (DN) uses a number of scaled-down generators and distributed generators (DGs), rather than a single huge power source. Due to the utilization of sustainable renewable energy sources such as solar, wind, and other sources, these micro-sources are discontinuous in their availability. The use of this grouping of micro-sources and loads to controllably supply electricity to the area around them results in the concept of a MG [3]. A MG is typically described as a group of DGs and local loads with a specific electrical zone under control and protection systems in comparison to conventional systems employing long transmission lines, it is a local power system that is efficient, reasonably priced, and robust that uses DGs to supply electricity to local loads with very little loss. MG is an independent part of the power system that, from the utility's perspective, can be dispatched simultaneously with local loads without the need for a transmission system. On the contrary, from the customer's point of view, it is a carefully built system that provides an effective, trustworthy, aiding the protection system, and stable power [4]. MGs typically operate in two operational modes, connected mode and island mode. In the grid connected mode, the MG acquires power from both the utility grid and DGs, but DGs are the primary source of power for the microgrid [5]. Also, the utility is mainly responsible for supplying the extra loads, which are microgrid demand, and providing a stable voltage frequency and reliable MG operations on island mode, the utility is out of service, and the DGs are the main and only supplying source based on energy analysis management which is responsible for managing load demand during peak and off-peak load times. In peak time, the power balance is achieved by supplying energy to the critical loads only, and outside peak hours, the excess energy is stored in the local storage. Microgrids develop many benefits such power factor correction, voltage and frequency regulation and also improve power quality in case of using a proper control strategy; in addition, microgrid faces operation and technical challenges, including system stability, voltage/frequency regulation, protection issues, and power quality [6]. These characteristics present questions about the applicability of existing concepts of protection system, stability, power flow management, and so on, this should be examined in terms of how well they are able to portray and take into account these benefits.

Overcurrent relays (OCRs) are the most common type of protective equipment used in distribution systems. OCRs monitor the flow of current and determine whether or not to send a trip signal to open the connected circuit breaker [7]. Although there are many various types of relays, such as distance relays and directional relays, inverse-time OCR protection relays are the most widely used type in distribution systems [8]. The protection issue imposed by the variation in load and fault currents is one of the preliminary challenges experienced by the components studied as a result of the changing topologies. Under changing topologies, the traditional approaches to power system protection, which, mainly depending on presented load and fault currents, is no longer applicable. Because of that, distribution networks have many different branches that may be equipped with various types of protective devices and are subject to topologies changes, including the integration of DG or microgrid operations. Conventional protection systems are likely to fail in distribution system applications. Consequently, enquiries were raised regarding the efficacy of protective mechanisms, specifically in relation to distribution networks [9, 10].

1.2 | Literature review

In the literature, several review studies highlighted the challenges in the developments in the field of protection for the distribution power network and the microgrid system. The review paper proposed in [11] examines the coordination strategies for microgrid protection to address these challenges. The existing microgrid protection limitations and advantages are argued by [11]. However, the research did not touch the non-classical strategies as a solution to the microgrid protection scheme. A comprehensive review presented in [12] of the proposed protection modes for distribution system with integration of the DGs. The fault current characteristics in the DC and AC distribution systems are analyzed. Other traditional alternative methods such as impedance-based methods, voltage-based approaches, and differential relays used instead of traditional overcurrent protective relays. In [12], no non-traditional approaches have been investigated. Conventional protection techniques for the distribution system and the consequences of using these new techniques when DGs installed into the system in [13]. In addition, a discussion is given about the protection coordination schemes for the distribution system with and without the exception of DERs provided by [14]. However, it discussed radial distribution grid protection plans by only using artificial intelligence methods without providing any details on how new protection characteristic construction works.

It is noteworthy to state that the aforementioned investigations resulted in dependable protection strategies that may effectively address the needs of the power system. However, the non-standard characteristics have not been covered specifically. These non-standard characteristics and their requirements discussed in detail in [15]. The authors in [15] identify and analyzes the potential advantages and disadvantages of non-standard characteristics, but without covering the problems of AC and DC microgrid protection. A comprehensive review addressing this gap is discussed in [16], providing a comparison of various protection approaches, including the updating and modification of traditional protection strategies, the introduction of new ones, and the use of fault current limiters and adaptive relays. From a different perspective, another review focuses on the challenges in AC/DC microgrid protection [17]. Both reviews conclude that there are still numerous areas where the development of a reliable, safe, and sensitive protection system must be a priority in the future. Another study by [18] provided a detailed over-view of current challenges in the protection of AC microgrids and a detailed overview of different modern protection strategies to address these challenges. Additionally, it covered the benefits and methods for automatic correction of automatic transfer groups to protection settings in adaptive protection schemes, as well as efficient planned and unplanned microgrid transitions between grid-connected and island mode. The structure of a microgrid, the basic conditions for protecting a microgrid and the challenges of different types of microgrid protection discussed in [19]. It critically analyzed various solutions in order to explore various protection issues. Therefore, the authors in [20] reviewed the different protection methods for AC microgrids in the literature. The authors in [20] focused on analyzing the recent state-of-the-art protection strategies including the application of artificial intelligence. Table 1 gives a brief about all the review studies associated with the protection of microgrids in the last decade. As mentioned above and shown in Table 1 of the available literature, several studies

TABLE 1 Summary of previous review studies related to microgrid protection.

Ref.	Year	Highlights
[11]	2014	Methods for addressing challenges in MG coordination strategies.
[21]	2015	The fault characteristics of both AC and DC distribution systems have been examined at in the review study
[13]	2016	According to the study, conventional protection systems are vulnerable to DG connection while providing different features instead of the standard ones.
[22]	2016	In this work, solutions to the protection issue in a microgrid that have been suggested in various studies are analyzed.
[23]	2016	This study examines the proposed protection challenges, such as auto-reclosure and coordination of protection equipment, associated to significant penetrations of embedded generation in distribution networks.
[14]	2017	The study addressed protection concerns that arise when DG units are added to the system and looked at protection strategies for radial distribution networks and sub-transmission systems. .
[24]	2017	this research examines Basics of MG protection and the effects of DG installation
[25]	2017	This review has carefully examined fault protection remedies, especially for non-ground low voltage AC MG.
[26]	2017	This review is exhausting especially for AC MGs that weren't grounded, the fault protection strategies were carefully investigated.
[27]	2017	This document examines most of the precautions that have been used or suggested to reduce the effect of DG on DNs.
[28]	2017	This article provides a thorough analysis of protection strategies for renewable integrated power networks, covering distribution, transmission, and microgrid systems.
[20]	2017	This study provides an overview of the protection devices and approaches available for AC and DC subgrades.
[29]	2018	This study reviews various strategies for DG protection systems that have been developed in the literature critically and makes a case for a paradigm shift towards voltage-based protection, which could result in the decoupling of protection design from inverter design and control since effective protection might not need a fault current contribution.
[15]	2018	The objective of this paper is to provide a thorough analysis of the techniques that can be used to protect hybrid AC/DC microgrids.
[30]	2018	The paper offers a critical analysis of the issue at hand and a solution that depends on system reconfigurations.
[31]	2018	The present research focuses on non-standard characteristics (N-SCs) that were used in studies on protection coordination.
[32]	2019	The goal of this research is to present a thorough analysis of the protection issues facing AC and DC microgrids, in addition to feasible remedies. A brief discussion of potential microgrid protection patterns is also provided.
[17]	2020	This paper covers a thorough evaluation of many studies in the field of AC/DC microgrid protection.
[33]	2020	This study has investigated potential issues that could arise when DG units are integrated into distribution networks and has critically examined researches efforts carried out to address these issues.
[18]	2021	This paper discusses some real-world experiences in employing various techniques to address issues in microgrid protection system design, engineering, and implementation. It is based on the authors' particular engineering, design, and field experience.
[34]	2021	The purpose of this review paper is to conduct a comparative analysis of various protection techniques implemented to mitigate the impact of integrated resources in DN.
[35]	2021	The purpose of this review is to present an analytical assessment of the most advanced protection techniques for dealing with problems associated with microgrid protection
[36]	2021	The optimal coordination of OCR relays in the power systems with deployed DGs is addressed in this review article, which provides a thorough summary of several recent research advancements.
[19]	2022	For several microgrid topologies with diverse operating requirements, this study gives an in-depth review, comparative analysis, and discussion of protection strategies and the difficulties in implementing them.
[37]	2022	This study provides an extensive summary of the applications of several optimization algorithms. The review focuses at the advantages and disadvantages of the methods employed to resolve DOCR coordination issues.
[38]	2023	This study examines how standards, guidelines, and other basic needs are evolving to and operating microgrids.
[39]	2023	The primary goal is to critically evaluate various AC microgrid protection approaches that have been suggested in the literature, with an emphasis on recent protection strategies that use innovative intelligent approaches.
[40]	2023	This study covers earlier research on prospective AC-MG protection solutions in order to completely evaluate potential network protection issues.
[41]	2023	The penetration of AC microgrid into the distribution network is examined in this article's in-depth analysis of protective systems. This analysis makes our understanding of what happens between microgrids and the distribution network's protection systems and how they might even improve them.

have been critically reviewed to address protection coordination issues arising from microgrid operation. However, none of these studies have taken into consideration the voltage–current–time inverse-based protection coordination of AC microgrids specifically.

1.3 | Contributions and organization of the paper

The level of growth and interest in the issue of coordination protection in AC microgrids, as indicated by the aforementioned research, may be readily apparent. These studies have focused only one part of the suggested current solutions without addressing the voltage–current–time characteristics as a non-standard solution. The discussion, review, and analysis of the voltage–current–time characteristics are within the scope of this study. In particular, the contribution of this study can be highlighted as follows:

- Providing a detailed overview of recent research which focused on the potential advanced and non-standard overcurrent relays (OCRs) schemes, along with the evolution of protection coordination based on voltage–current–time inverse principles.
- The study identifies areas within the technical literature where gaps exist and points toward future directions for research for voltage–current–time characteristics as a non-standard solution.
- It compiles fundamental attributes that define effective features, serving as a valuable reference for researchers engaged in the domain of AC microgrid protection.

The review paper is formed as follows: Sections 2 presents the concept of the microgrid with outlines the essential knowledge of traditional protective relay philosophy and its impact on the modern power system. Section 3 illustrates the formulation of IEC standard and the coordination problems. Section 4, summarizes, discusses and analyzes the voltage–current-based characteristics as optimization protection methods. Section 5 presents a realistic example of voltage–current–time inverse approach and future trend. Finally, this work is summed up in the conclusion in Section 6.

2 | MICROGRID SYSTEM: POWER PROTECTION CONCEPT

Microgrids (MGs) are described as self-sufficient small-sized networks that include DERs and ESSs (energy storage systems) that operate some local loads, as shown in Figure 1. Technical and financial assessments showed that MGs can operate in grid tied or Island mode and the rapid-switching isolator at the point of common coupling (PCC) can control them [42, 43]. Generally, to sustain the main grid, and keep it healthy, stable, and unaffected by any outages, the grid-connected mode is the appropriate mode for the grid. However, in the case of the power remote places and military installations, the islanded mode is deferentially the one options for automatically switching on when the main is interrupted [44, 45]. According to the electrical power source, MGs are generally classified as AC, DC, or hybrid. Any type of electrical generator or consumer can be directly connected to the main bus using AC-MG. In contrast, DC/AC converters require a connection to DC installations. Quite the contrary, DC-MGs were developed in response to the growing trends towards DC-RE, high-voltage DC techniques, rechargeable devices (such as electrical cars), and so on. The hybrid network combines separated components of AC-MG and DC-MG, the flexibility of future installations will increase by using power electronics and many conversion procedures (AC/DC and DC/AC) will be limited, capital costs will be reduced, and overall, of the efficiency will increase [46, 47].

2.1 | The weaknesses of conventional protective relays in AC-MGs

The concept of MGs has posed a variety of issues and restrictions with conventional protection devices due to its decentralized nature, encouraging the creation of novel techniques to avoid internal faults and separate them when the main utility is interrupted to protect MGs [48, 49]. The majority of these issues are listed in Figure 2.

2.1.1 | Short-circuit capacity

The operating mode and DGs technologies, especially synchronous or inverter-based generators, both have an impact on the short circuit current level in MGs [50]. When faults occur, synchronous generators can generate between five and ten times of the rated current, as shown in Figure 3, however, just less than 2 times of the rated current can be provided by the converter-based resources [51, 52]. The fault level is significantly influenced by the way that MGs are configured, a great fault current occurring with the grid-connected mode that is caused by the involvement of both the main grid and DGs. However, when the island mode is presented, a reduced contribution current is excited, especially when the inverted -based DERs predominate [44] wide fluctuations in short-circuit current levels make it difficult to configure protection relays for both operating modes. These have the potential to substantially decrease the performance of protection relays [12, 47].

2.1.2 | Protection blindness

Overcurrent relays, directional relays, and reclosers are examples of current-based relays whose pickup values are frequently set to be lower than the minimal fault current at the distant ending for protective areas and higher than the rating current at the location of the relay [53]. Due to the DGs such as distributed renewable energy sources (DER's) contribution to the fault current at the downstream relay location, the utility

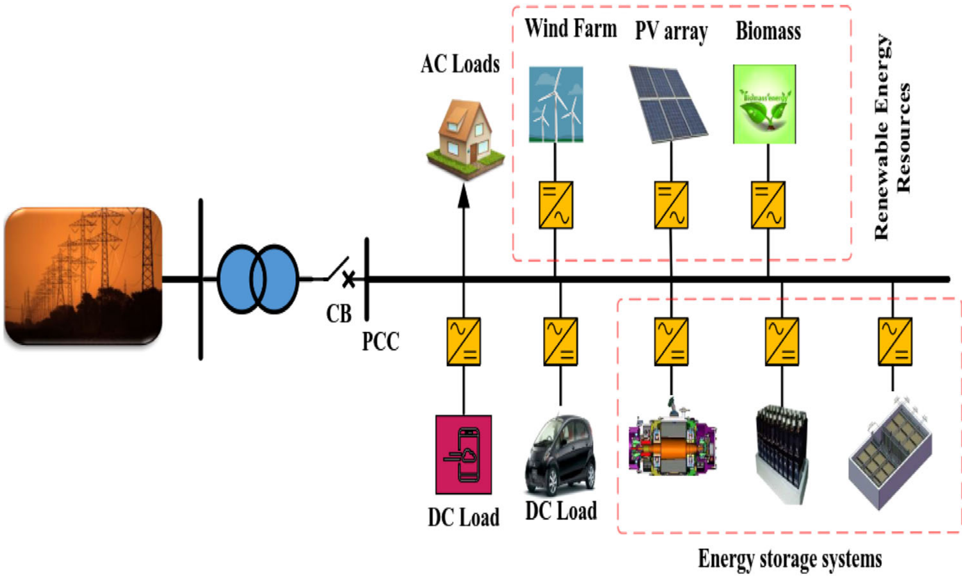

FIGURE 1 A typical AC-microgrid topology.

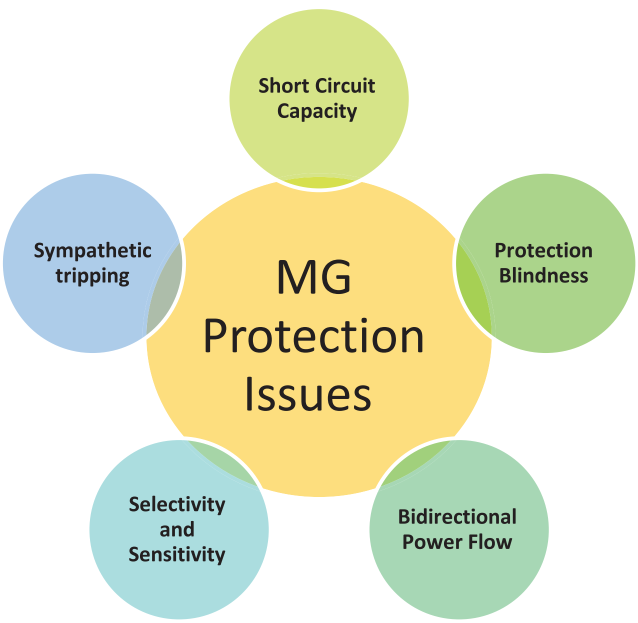

FIGURE 2 MG protection issues.

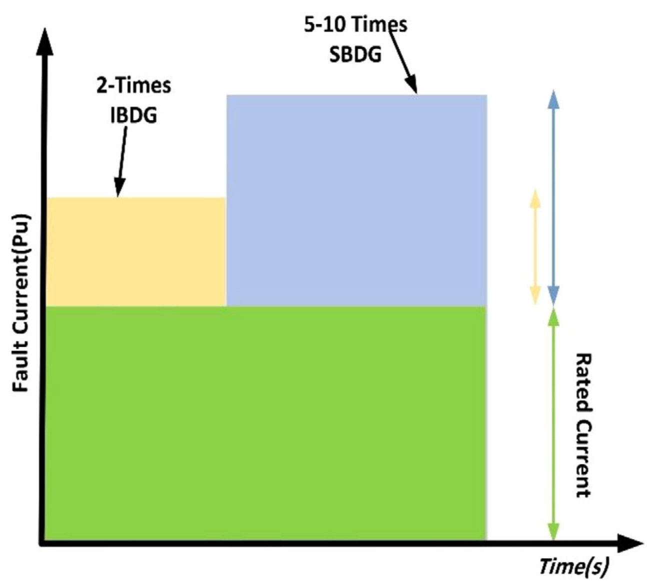

FIGURE 3 Fault current contribution due to different types of DG.

contribution is severely impacted and reduced up to the point where the fault current drops below its pickup values, making it impossible to detect the fault current and making it impossible for the relay to clear the fault area. Figure 4 illustrates this occurrence, where Figure 4(a) explains an illustrative model, and Figure 4(b) depicts Thevenin's equivalent at the fault location. Based on Thevenin principles, this is used to calculate how much the upstream relay (R_A) measured due to the grid (I_{Grid}) and Thevenin's voltage (V_{th}) after determining Thevenin's impedance (Z_{th}) at the fault location as cleared in Equation (1). In Figure 4, the bus impedances Z_{MG}, Z_{AB}, Z_{DER}, and Z_{BF} are shown and defined. The total fault current (I_f) is then obtained as in Equation (2). Following that, the grid contribution of the grid is established using the current-divider criteria as in Equation (3).

$$Z_{th} = \frac{(Z_{MG} + Z_{AB})(Z_{DER})}{Z_{MG} + Z_{AB} + Z_{DER}} + Z_{BF} \quad (1)$$

$$I_f = \frac{V_{th}}{\sqrt{3}\, Z_{th}} \quad (2)$$

$$I_{Grid} = \frac{(Z_{DER})}{Z_{MG} + Z_{AB} + Z_{DER}} + I_f \quad (3)$$

where V_{th} is represented by Thevenin voltage, Z_{MG} and Z_{DER} stand for the main network's and the DER. According to

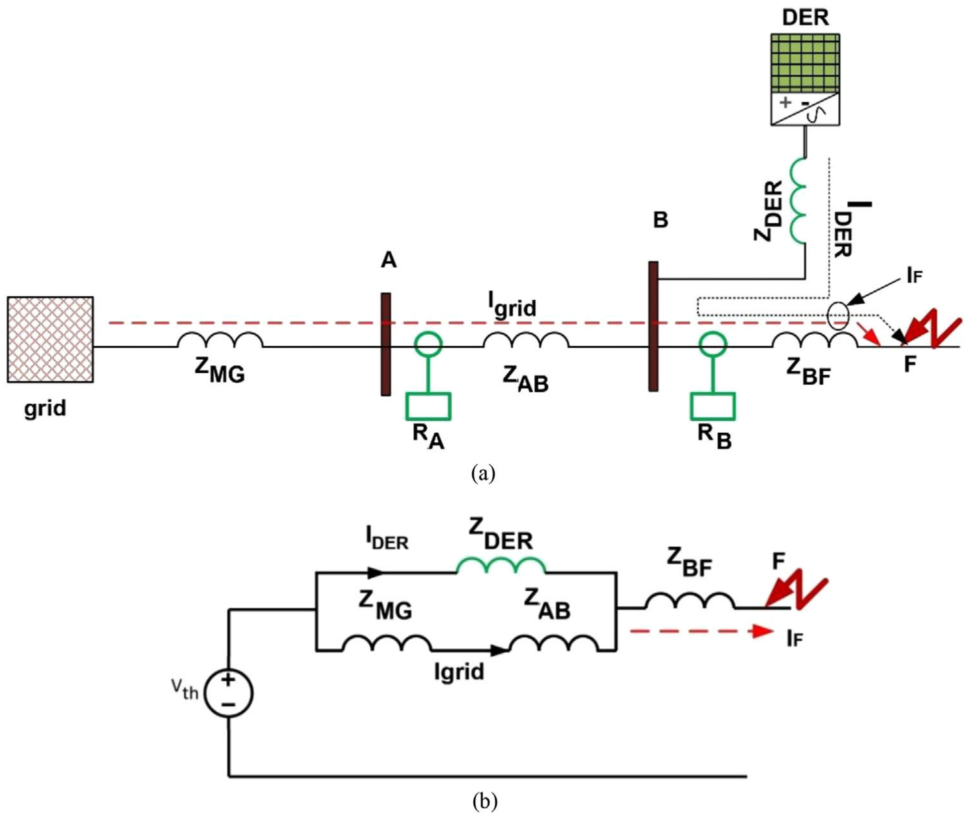

FIGURE 4 Blinding phenomenon. (a) Location of fault related to blinding issue. (b) The location of fault by using Thevenin's equivalent.

Equation (3), the size, location, and fault distance of the DER unit significantly affect the level of the current of the grid contribution that flows via the upstream relay RA. Due to the DER source's limited contribution, the upstream fault current is decreased to lower values [53, 54].

2.1.3 | Bidirectional power flow

Electrical power flows from the source towards the consumption terminals in radial power systems. While MGs can add two-way current flow in power circuits after faults, dynamic changes brought on by local imbalances in generation and consumption, scheduled power exchanges with the main grid, this affects the voltage profile, current levels, and flow direction. Reverse power flow in MGs generally puts more voltage stress on system components and seriously threatens the coordination and performance of conventional protective relays. This needs to be considered when developing the protective relays [55].

2.1.4 | Sympathetic tripping

False or sympathetic tripping typically occurs when a relay serves for a fault beyond its allowed zone after being triggered by a significant current value, which is against the reliability of the relay. This is typically occurring when a DER is connected at one feeder and fault event occurs at the adjacent feeder which connected to same substation, as a result of DER connection the healthy feeder will trip in a false manner due to their contributions to a fault current. The relay R2, R1, and main grid relay R_{MG} as illustrated in Figure 5, is expected to respond promptly to the fault (F). However, due to the greater DER contribution during this fault, R1 could respond faster than R2 and falsely interrupt feeders 1 [56–58].

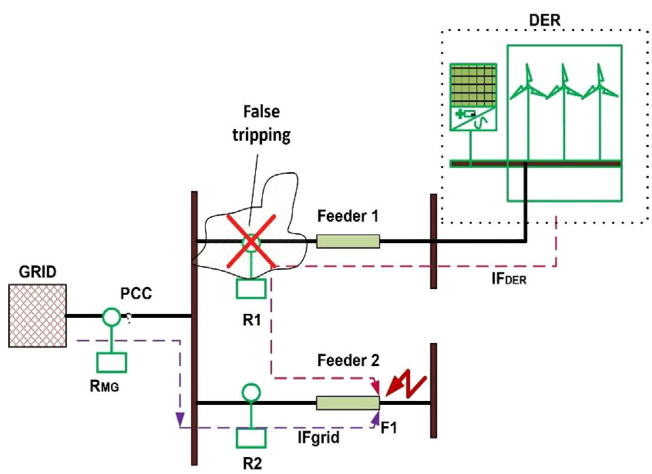

FIGURE 5 False/sympathetic tripping.

2.1.5 | Selectivity and Sensitivity

Selectivity and sensitivity are essential components of any protective devices. Selectivity describes the relay's ability to precisely identify and isolate the faulty area, on other hand sensitivity describes the relay's ability to recognize even the tiniest flaw and continue to function as designed without changing its selectivity features [59]. However, the nominal current and minimum fault current in MGs, as well as the size, location, and type of DERs (synchronous-based or inverter-based), all have a significant impact on the pickup values of conventional overcurrent relays in particular [60]

2.2 | The uncertainties and contingencies in MGs

MGs are decentralized power network systems that have the capability to function autonomously or in parallel with the primary or traditional electrical grid. MGs have been designed to offer a dependable and sustainable power supply, especially during periods of power grid failures and increase the integration of renewable energy sources in the grid. However, MGs including complicated energy system, which subject to uncertainties and different operation scenarios.

In addition to the uncertainties in network topology, the MG protection processes might be further complicated by the presence of unexpected variables of complex generation and net load profile nature. This introduces additional challenges to the effective implementation of power protection models. Operational uncertainties arise during the functioning of protection systems in the presence of faults, leading to potential outages and a decrease in network dependability. In contrast, online protection solutions that depend on communication connections necessitate resilience, near-constant accessibility, and limitations on delay. Furthermore, in the event of faults, online protection systems that depend on communication links must exhibit resilience, consistent availability, and tightly controlled potential. The failure to achieve these standards might cause a risk to the dependable operation of the protective system [45, 46].

In term of the MG topologies and contingencies, the configuration of MGs can also be influenced by any number of unanticipated events or circumstances. The N−1 contingency concept, as defined in the standards set out by the North American electric reliability corporation (NERC), applies to the occurrence of an outage in either a generator or a transmission line, with the exception of other branches [46]. The various operating modes, such as grid-connected or islanding, have the potential to induce modifications in microgrid topologies. The literature has presented efforts at developing protective coordination solutions for transmission and sub-transmission systems, with consideration given to line outages and eventualities. A number of studies have examined the effects of DGs on the coordination of relay protection in microgrids. Saleh et al. [47] presented a technique for enhancing the efficiency of protection coordination inside MGs. Their approach especially focused on handling N−1 contingencies, which potential disruptions such as DG failures.

Different methodologies, including k-means clustering and adaptive protection strategies, have been suggested for coordinating OCRs with potential network topologies. Moreover, there have been recent introductions of online adaptive protection methods that are designed to accommodate a wide range of operating situations in power distribution networks. Various optimization strategies, such as particle swarm optimization and genetic algorithm optimization, have been utilized to tackle the issue of protection coordination. These techniques consider different network topologies that arise from contingencies such as line, substation, and distributed generation outages [49, 58]. However, it is important to mention that the existing research have mostly concentrated on synchronous-based distributed generators (SBDGs) and have not thoroughly examined Inverter-interfaced distributed generators (IIDGs).

3 | IEC STANDARD AND PROTECTION COORDINATION PROBLEM FORMULATION

3.1 | OCRs characteristics curves

The standard relay characteristics (relay characteristic curve) are considered as the basis of adjusting the time OCR functions. There are two main standards namely the International Electrotechnical Commission (IEC) and Institute of Electrical and Electronics Engineers (IEEE) standards, which are inverse time characteristics. These IEC and IEEE standards are categorized into three types of curves, namely Normal Inverse (NI), Very Inverse (VI), Extremely Inverse (EI) and (A, B, C) time curve characteristic constants. IEC NI A = 0.14, IEC VI A = 13.5, IEC EI A = 80, IEC NI B = 0.02, IEC VI B = 2, IEC EI B = 2, IEC NI C = 0, IEC VI C = 0, and IEC EI C = 0. While IEEE NI A = 0.0515, IEEE VI A = 19.61, IEEE EI A = 28.2, IEEENI B = 0.02, IEEE VI B = 2, IEEE EI B = 2, IEEE NI C = 0.114, IEEE VI C = 0.491, IEEE EI C = 0. 1218. Equations (4) and (5) from the IEC and IEEE standards, respectively, are used to determine the OCR tripping time (t) for a specific short-circuit current (I_{sc}) and pickup current (I_p) [31]. The IEC standard characteristics for various fault current magnitudes are shown graphically in Figure 6(a), whereas the IEEE standard characteristics provide a visual representation of the responses in Figure 6(b):

$$t = \left[\frac{A}{\left(\frac{I_{sc}}{I_p}\right)^B - 1}\right] \mathrm{TMS} \tag{4}$$

$$t = \left[\frac{A}{\left(\frac{I_{sc}}{I_p}\right)^B - 1} + \mathrm{C}\right] \mathrm{TMS} \tag{5}$$

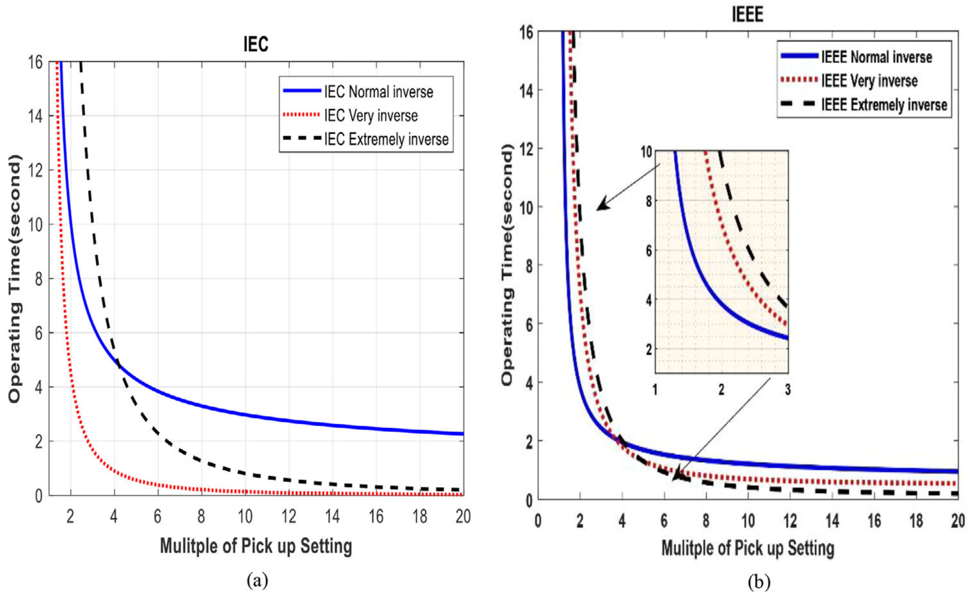

FIGURE 6 IEC and IEEE standardized curves. (a) The IEC 60255-3 standard curves (b) the IEEE C37.112-1996 standard curves.

3.2 | Coordination problem formulation

The OCRs a coordination issue in interconnected power systems is often described as constraints in optimization problems, in which objective functions (OFs) are used to reduce the entire operational time of primary and backup relays, as described by Equation (6).

$$\mathrm{OF} = \sum_{i=1}^{m} t_{i,j} \tag{6}$$

where m is the primary relays' numbers and $t_{ij}$is the primary relay's operation time for a near end fault. The following constraints have made this goal achievable, which is illustrated by Equations (7) to (9).

3.2.1 | Coordination criteria

The criteria time inverse (CTI) represents the selectivity constrains of the OCRs coordination.

$$t_{\mathrm{b}} - t_{\mathrm{p}} \geq \mathrm{CTI} \tag{7}$$

where the primary relay operating time for near end fault is presented by t_{p}, while the backup relay operating time is presented by t_{b}. CTI is usually chosen between 0.2 and 0.5 s.

3.2.2 | Bounds of operating time, relay setting

In order to maintain operational time constraints, the operating time constraints of the minimum and maximum OCR need to be presented. However, the protection relay must operate quickly and take the minimum time, and if OCR operations take longer, the equipment and unstable power systems are damaged. Equation (8) shows the minimum and maximum time multiplier setting (TMS). Equation (9) illustrates the minimum and maximum operating times.

$$\mathrm{TMS}_{\min} \leq \mathrm{TMS}_i \leq \mathrm{TMS}_{\max} \tag{8}$$

$$t_{\min} \leq t_i \leq t_{\max} \tag{9}$$

where the minimum and maximum TMS value are represented by $\mathrm{TMS}_{\min}$ and $\mathrm{TMS}_{\max}$, whereas the minimum and maximum tripping time for OCR, t, value of relay are represented by $t_{\min}$ and $t_{\max}$.

3.2.3 | Bunds of plug setting, relay setting

The plug setting (PS) bounds expression is formulated mathematically in Equation (10), where the minimum and maximum PS are represented by $\mathrm{PS}_{\min}$ and $\mathrm{PS}_{\max}$.

$$\mathrm{PS}_{\min} \leq \mathrm{PS}_i \leq \mathrm{PS}_{\max} \tag{10}$$

4 | VOLTAGE–CURRENT–TIME INVERSE BASED PROTECTION COORDINATION

In traditional OCR, the relay basically analyze the current behaviour by comparing the current value with the pickup current. In case of the measured current are more than the pick value and the ratio of $M_{\mathrm{I}} = \frac{I_{\mathrm{f}}}{I_{\mathrm{s}}}$ the ratio of fault and pickup currents more than 1, the OCR will send a trip signal to circuit breaker, as shown in Figure 7. As previously discussed in

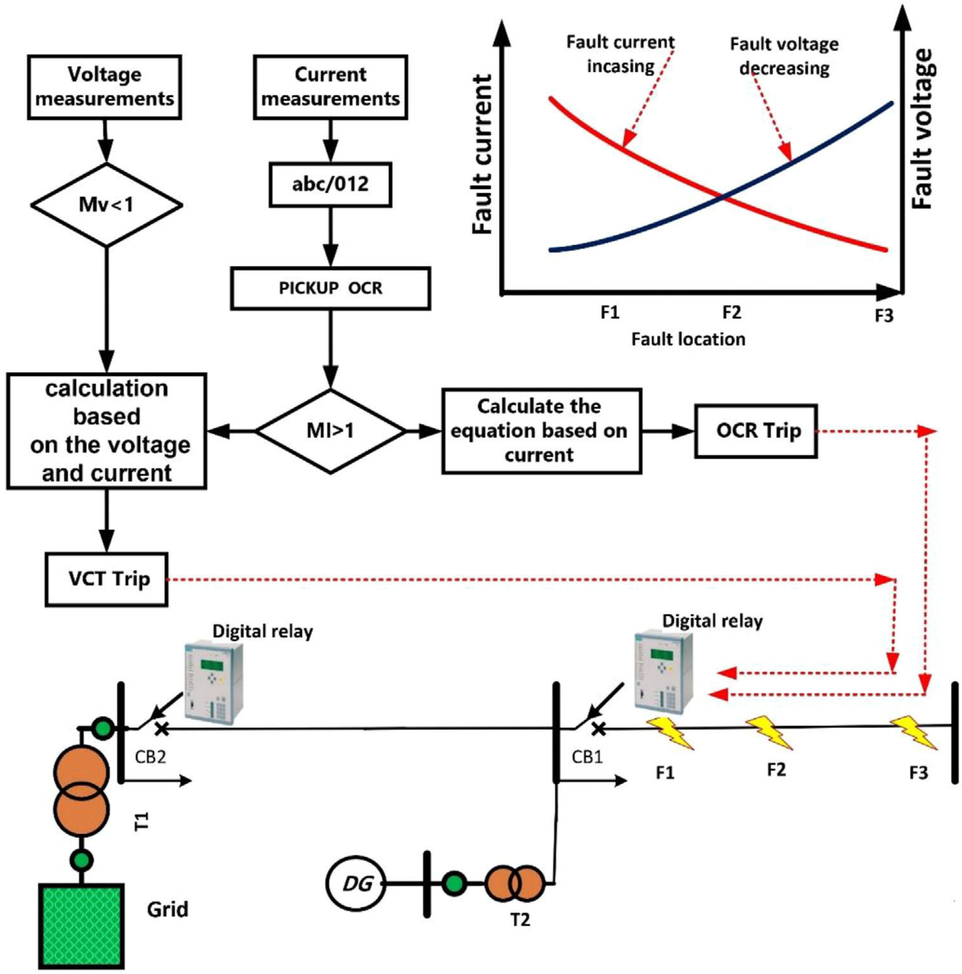

FIGURE 7 Voltage–current protection scheme.

Sections 2 and 3, the traditional OCR faced many protection performance challenges and miss-coordination events due to the high DG penetration. Therefore, the main goal of using the voltage value that the relay discovers is to offer reliable relay coordination under high DG penetration. As the DG contributes to the fault current, the varying fault current indirectly impacts the system bus voltages. The voltage behaviour during fault occurrences is shown in Figure 7, where the voltage of fault decreased for location fault near the relay location (F1). To trigger the relay, a threshold voltage level is defined beyond the nominal voltage range and $M_I > 1$. However, if, during a fault, the voltage dip remains within the nominal range, a current starter is employed to activate the relay, provided that the current exceeds the pickup current level.

The study [61] was one of the first to employ the observed voltage value, as shown in Equation (11). Furthermore, when the recorded voltage value is zero, the relay operating time (t) takes a minimal value, indicating an issue at the relay contact point. It should be noted that a new constant k is used in this equation to alter the contribution of the voltage, although the per-unit value of the measured voltage (V_f) is still utilized. It is also important to note that [61] did not give any novel methods to calculate the constant parameter (k), therefore this issue still requires additional investigation. Furthermore, the voltage effect on the protection scheme as proposed in [61, 62] is depicted in Figure 8.

$$t = \left[\frac{A}{(M_I)^B - 1}\right] \left(\frac{1}{e^{1-V_f}}\right)^k \text{TMS} \tag{11}$$

Where $M_I = \frac{I_f}{I_s}$ the ratio of fault and pickup currents, A and B are a decision variable for the log curve. The non-standard curve (N-SC) suggested in [61] was also used for a transmission system with wind power plants (WPP) in [63]. The goal of the study was to properly operate the WPP by setting the relays according to the relationship between the voltage at the point of common coupling and the behaviour of wind turbines during fault-ride through. In the event of any fault, the grid codes' critical voltage and duration of the detected voltage are typically utilized to determine the state of the WPP connection. Consequently, in [63] the backup relays utilized in Equations (12) and (13) were therefore considered to have an upper limit of this maximum allowed duration. By turning on the feeder protection relays before the wind turbine generator's low voltage protection tripped, the likelihood of keeping the generators connected

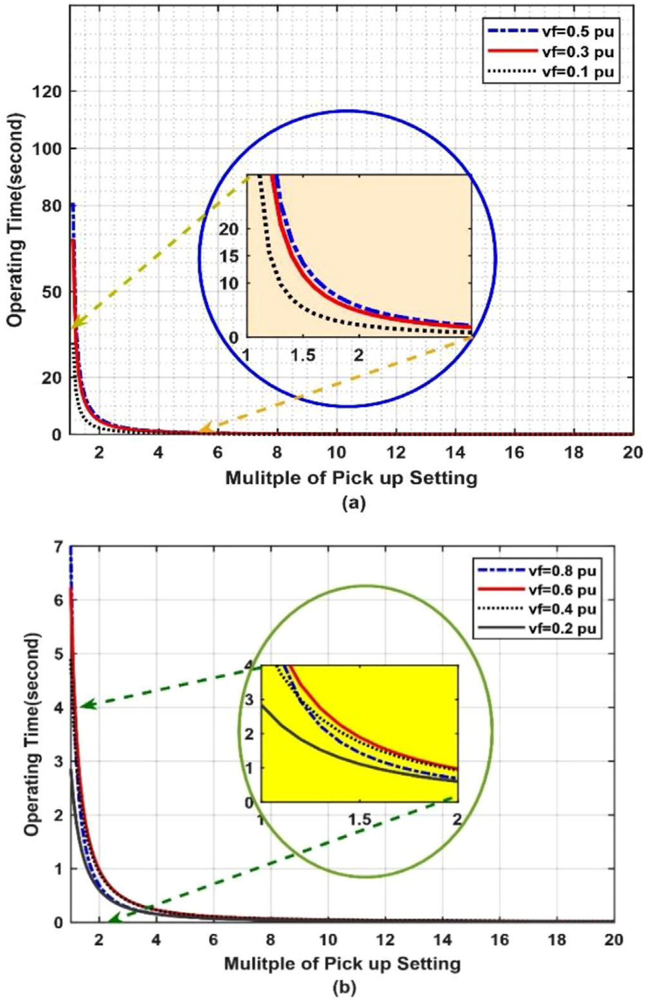

FIGURE 8 (a) Impact of voltage change on the non-standard characteristics made by Equation (14), (b) Impact of on the N-SC made by Equations (16) and (17).

was increased. Another noteworthy aspect of this study was that it served as an illustration of the use of innovative the N-SC for satisfying protection needs at the transmission system level, in contrast to the majority of studies which have only concentrated on distribution systems. Furthermore, Equation (14) was evaluated in the wake of power system failures in various network topologies [64].

$$t = \left(\frac{1}{e^{(1-V_f)}}\right)^k \left[\frac{\mathrm{A}}{\left(\frac{I_{sc}}{I_p}\right)^{\mathrm{B}} - 1}\right]\mathrm{TMS} \tag{12}$$

$$t = \left(\frac{V_f}{e^{k-V_f}}\right) \left[\frac{A}{\left(\frac{I_{sc}}{I_p}\right)^{B} - 1}\right]\mathrm{TMS} \tag{13}$$

$$t = \frac{A}{(M_I)^B - 1}\left(\frac{V_f}{e^{k \cdot V_f}}\right)\mathrm{TMS} \tag{14}$$

The strategy used in [65] was utilizing standard characteristics (SCs) advantages while developing a new characteristic, whereby the voltage parameter was utilized to enhance fuse-relay coordination when DG was present. Equation (12) provides the characteristic equation developed in [65]. Similarly, to Equation (14) the proposed characteristic equation included a constant k and the per-unit voltage value (V_f). Figure 7(a) shows how voltage change and the proposed N-SC characteristic relate to each other. Furthermore, the constant K's value was provided in [65], since it was mentioned that values of k less than 2 are the only ones that result in a monotonically reducing characteristic.

It is important to note that the process is developed without taking DG insertion into account and that the k values for single phase to ground faults or three phase faults and two phase-to-ground faults are calculated using two different equations. The solution suggested in [65] has the advantage of being able to guarantee protection coordination without any communication approaches. Similar methods for using voltage magnitudes were published in [66], which provided an innovative perspective by using a logarithmic function as the denominator. Given that it contains both an "unconventional" mathematical expression and electrical magnitudes, as shown in Equation (15), the characteristic described in [66] can be considered as a combined approach. As can be seen from Equation (15), the relay's OT depends only on the constant D when the voltage observed by the relay is zero. Additionally, the natural logarithm was utilized to limit the large changes in voltage and current. Finally, although the suggested equation was created for communication-free protection schemes, users may find it difficult to understand due to the complex structure of the characteristic equation [31].

$$t = \mathrm{TMS} \times \frac{(V_f)^k}{e^{V_f}}\left[\frac{A}{\left(I_n\left(V_n\frac{I_{sc}}{V_f}\right)\right)^B - \left(I_n\left(V_n\frac{I_{set}}{V_{set}}\right)\right)^B} + C\right] + D \tag{15}$$

$$A = V_f \times (1 - V_f) \tag{16}$$

$$t = A \times \left[\frac{1}{1 - (\log V_f)^C} + 0.121\right]\mathrm{TMS} \tag{17}$$

where V_{set} and I_{set} are the voltage and current of relay settings, I_n is natural logarithm of the nominal phase voltage V_n and fault current and voltage ratio. Another form of voltage-based characteristic presented in [67] is given by Equations (16) and (17). The N-SC was developed to enhance the coordination between reclosers and fuses in a distribution system that includes DG units. The advantages and disadvantages of the proposed strategy are similar to those of [66]. Therefore, it should be noticed that when the voltage is zero, the tripping signal is generated at $t = 0$ instead of waiting for the subtransient fault current to decrease in order to protect the circuit breaker. In Figure 8, it is shown how changes in the proposed characteristic arise from

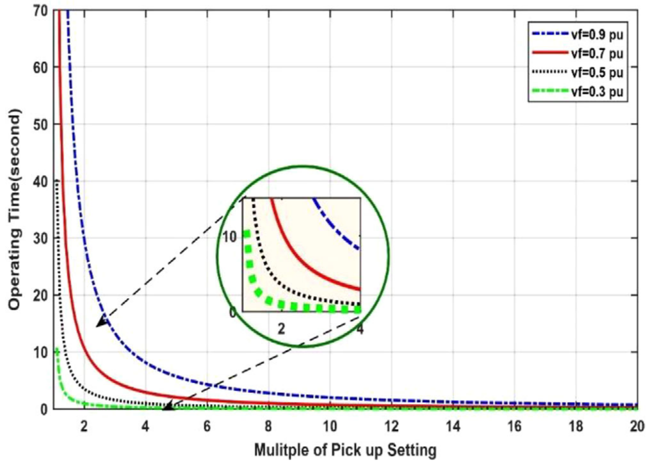

FIGURE 9 Voltage change impact on non-standard characteristics generated by Equation (18).

voltage variation [31].

$$t = \left(\frac{1}{1-\left(\log V_{\mathrm{f}}\right)^{C}}\right)^{k}\left[\frac{A}{\left(M_{\mathrm{I}}\right)^{B}-1}\right] \tag{18}$$

In [68, 69],a new voltage-based N-SC was devised, which is provided in Equation (18) Although the voltage was utilized using a logarithmic function, the characteristic equation was comparable to Equation (11), where V_{f} is the per-unit value of the measured voltage, $M_{\mathrm{I}} = \frac{I_{\mathrm{f}}}{I_{\mathrm{s}}}$ is the ratio of fault and pickup currents, A, B, and C are a decision variable for the log curve, as defined in previous equations. Here, the value of the observed voltage value was used to include it in the characteristic equation, and the k parameter was used to modify the voltage contribution. The response of the N-SC proposed in [70] to voltage variation is depicted in Figure 9 [31].

$$t = \left[\frac{\log V_{\mathrm{f}} + A}{\left(M_{\mathrm{I}}\right)^{B}-1}\right] + C \tag{19}$$

In [71], a novel approach based on voltage measurement and a logarithmic function was introduced to tackle issues related to overcurrent protection. The characteristic equation presented in Equation (19) offers improved coordination, minimizing the effect of DG and providing lower operating times (OTs). This method addresses the concern of increasing the OTs towards the power source. The parameters of the equation, A, B, and C, are adjusted for proper coordination. Despite these advances, the optimization process remains complex, particularly for more extensive power networks, which demands further research. To address prior challenges [70], the authors proposed combining time–overcurrent relay curves with under-voltage protection concepts to maximize their advantages. This strategy led to the development of relay operation curves as outlined by Equation (20) for K and Equation (21). The variables D, V_{f}, A, p, m, and TMS play specific roles in these equations. The proposed scheme aims to enhance coordination and response times by integrating time-overcurrent and under-voltage protection. The amalgamation of these protection strategies seems promising, although practical application in complex scenarios and large networks warrants further investigation.

$$K = \left(\frac{V_{\mathrm{f}}}{2} \times \left(1-\frac{V_{\mathrm{f}}}{2}\right)\right)^{m} \tag{20}$$

$$t = \mathrm{TMS} \times \left[\frac{A}{\left(\frac{1}{K}\right)^{p}-1}\right] \times \log_{2}\left(\frac{1}{K}\right)\left(\frac{1}{K}\right) + D \tag{21}$$

It can be obvious that external and internal faults can be distinguished clearly by applying the proposed method. Yet, due to the loop collection circuit between the two generators is too short, the voltage drop between the two relay points is small and the relay coordinate is difficult to handle using the proposed algorithm. In this incident, the time–current curve slope must be as sharp as possible.

$$t = \left[\frac{A}{\left(M_{\mathrm{I}}\right)^{B}-1} + C\left(1+M_{\mathrm{V}}\right)\right] \mathrm{TMS} \tag{22}$$

$$M_{\mathrm{V}} = \frac{\Delta V}{V_{\mathrm{rated}}} \tag{23}$$

The authors of [66] have presented a self-tuning relay strategy of recloser function for fuse saving when the DG units preserve the coordination between the fuse and recloser with the DG units. Reclosers use just local voltage and current magnitude measurements and are configured with novel, non-standard characteristics; the issues of integrated DGs in the DN cannot be solved by the standard fuse-saving method. Equation (21) depicts the standard characteristics, whereas Equation (22) shows the ability of the proposed N-SCs to overcome these issues without establishing relay miscoordination.

$$t = A \times \left[\frac{28.2}{\left(M_{\mathrm{I}}\right)^{2} - \left(\frac{1}{e^{(1-V_{\mathrm{f}})}}\right)^{B}} + 0.1217\right] \mathrm{TMS} \tag{24}$$

$$t = A \times \left[\frac{28.2}{\left(M_{\mathrm{I}}\right)^{2} - \left(\frac{1}{e^{(1-V_{\mathrm{f}})}}\right)^{B}} + 0.1217\right] \mathrm{TMS}\left(V_{\mathrm{f}}\left(1-V_{\mathrm{f}}\right)\right) \tag{25}$$

The proposed scheme aims to enhance coordination in high DGs penetration scenarios through a straightforward and cost-effective scheme, overcoming limitations of conventional approaches and modern N-SCs. The importance of protective equipment installation to safeguard power systems against fault scenarios is emphasized, with a focus on OCRs as a primary protection measure. The emergence of superconducting fault current limiters (SFCLs) in response to growing fault currents is explored, highlighting their potential to reduce voltage sag and fault current. However, it should be noted that the installation of SFCLs can affect other protective devices such as relays and reclosers. To mitigate this, the integration of a voltage component in OCRs has been suggested to counteract the influence of SFCLs on trip operations. The proposed OCR improvement is investigated using the PSCAD/EMTDC simulation tool [72].

$$t = \frac{A}{\left(\left(\frac{1-V_f}{1-V_s}\right)^D (M_I)^B\right) - 1} \text{TMS} \tag{26}$$

The proposed scheme in [73] involves the use of relays that act as agents with advanced capabilities such as data acquisition, self-testing, multifunctioning, data communication, and numeric calculations. These relays gather measurements of multiple electrical parameters, including phase current, phase voltage, negative sequence current, and zero sequence current, before and during fault conditions. They keep track of the prefault values of these parameters in their memory and modify them into reference values by multiplying them with the appropriate reference multipliers when a fault occurs. The relays then calculate the ratios using Equation (27) and compare the measured fault values with their associated reference values. They create bits using Equation (28) that correspond to the electrical parameters based on the associated Q values. The relays' PS is then calculated by adding all of the ai bits, as illustrated in Equation (29). Overall, this proposed scheme allows efficient and accurate fault detection and management, ensuring the safety and reliability of electrical systems.

$$Q_1 = \left[\frac{I}{I_{ref}}\right]\%,\ Q_2 = \left[\frac{\%V_{ref}-V}{\%V_{ref}}\right]\%,\ Q_3 = \left[\frac{I_{neg}-I_{ref}^{neg}}{I_{ref}}\right]\%,\ Q_4 = \left[\frac{I^{z}-I_{ref}^{z}}{I_{ref}}\right] \tag{27}$$

$$t = \left(\frac{A}{(\text{HPMS})^P - 1}\right) \text{TMS} \tag{28}$$

$$\text{HPMS} = x_1 Q_1 + x_2 Q_2 + x_3 Q_3 + x_4 Q_4 \tag{29}$$

A protection scheme that combines DOCRs and VROCRs is proposed for networks connected to SPVGs. The DOCRs detect high fault current on the grid side and VROCRs detect low fault current from the SPVGs. Coordination between the relays is a challenge, but a hybrid (HSA-BB) approach is proposed to solve this problem [74].

$$t = \left[\frac{A}{\left(\frac{V_S}{V_f}\frac{I_f}{I_s}\right)^B - 1}\right] \text{TMS} \tag{30}$$

Other work presented in [75] offers an enhanced Inverse-time over-current (I-ITOC) protection approach that overcomes the shortcomings of the standard over-current protection methods stated above. To increase the relay's speed, a mixture of fault acceleration factors based on low voltage and observed impedance was created based on Equation (31). Then, the beetle antenna search (BAS) optimization technique is used to optimize the coordination of the protection relay. The proposed approach significantly speeds up operation compared to the traditional over-current method. Additionally, because the proposed approach doesn't require additional instruments, it may be more cost-effective and simpler to apply in practice.

$$t = \frac{A}{(M_I)^B - 1} \text{TMS} \left(\frac{V}{Z}\right) \tag{31}$$

This study's contribution introduces an innovative protection method for microgrids. This method effectively combines multiple strategies and leverages tripping characteristics, providing fixed grading for relays without relying on communication systems. The use of voltage measurements to differentiate between fault scenarios enhances relay performance, particularly in scenarios with low-fault-current conditions. The proposed method's viability is substantiated through a combination of simulation and hardware experiments, underlining its practical application potential for enhancing microgrid protection and stability. This method I-ITOC presents an innovative approach by integrating various strategies and relying on tripping characteristics. Notably, this scheme offers fixed grading for relays, independent of the operation mode, and eliminates the need for communication infrastructure, as evidenced by the formulation in Equation (32). The method exploits voltage measurements to distinguish between overloading and low-fault-current situations, leading to a substantial reduction in the operating time of the relay, particularly during low-fault-current scenarios when the system is in island mode. The assessment of the proposed protection method's efficacy involved the utilization of PSCAD simulations and hardware experiments. Furthermore, the functionality of this approach was implemented on a digital signal processor (DSP) board for practical validation [76].

$$t = \frac{A}{(M_I)^B - 1} + C\left(\frac{A}{1-(M_V)^B} + D\right) \text{TMS} \tag{32}$$

In order to address the operation and protection of solar PV plants within grid requirements, the approach of utilizing local positive sequence voltage and current measurements is utilized to detect faults in PV-integrated distribution systems. The proposed technique offers a comprehensive framework involving current–voltage characteristics for fault detection and determination of trip times. By incorporating both voltage and current parameters, the method aims to provide effective fault detection during fault ride-through conditions, ensuring the protection and reliability of distribution systems with integrated PV plants. During fault ride-through events while remaining connected to the grid, a PV plant operates in various modes [77]. Regarding ensuring the distribution system's protection when integrated with PV plants, the author of [78] proposed a technique. This approach involves the utilization of local positive sequence voltage and current measurements, where a positive sequence current–voltage curve is employed to detect potential faults. If the positive sequence fault current surpasses the pickup current threshold, a fault is identified, and the trip time is

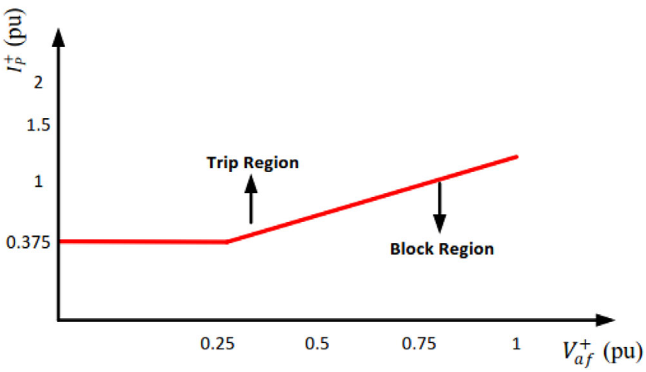

FIGURE 10 Pickup setting based on the proposed current–voltage curve.

determined through a three-dimensional time positive sequence current–voltage characteristic. The utilization of both voltage and current measurements is emphasized due to the potential occurrence of voltage drops as a result of power system short circuits. According to the method's proposed current–voltage curve, the pickup current (I_{p}^{+}) is a function of the positive sequence voltage (V_{af}^{+}) [79]. The function can be defined mathematically as in Equation (33).

$$I_{\mathrm{p}}^{+} = 0.375\,\mathrm{u}\,(V_{\mathrm{af}}^{+} + 1.5\left(V_{\mathrm{af}}^{+} - 0.25\right)\mathrm{u}\left(V_{\mathrm{af}}^{+} - 0.25\right) \quad (33)$$

where $u\,(V_{\mathrm{af}}^{+})$ and $u\,(V_{\mathrm{af}}^{+} - 0.25)$ are unit step functions at 0 and 0.25 pu voltages, respectively. Figure 10 shows the detailed proposed pickup current–voltage curve for fault detection. The relay is required to be activated with a current equal to 100% of the maximum pickup current at the rated voltage. The pickup current decreases with the input voltage, and at 0 input voltage, the relay must be operated with 25% of its maximum pickup current. Typically, the distribution system's maximum pickup current is calculated as 150% of the rated load current. Therefore, 0.375 and 1.5 pu at 0 and 1 pu voltages, respectively, are chosen as the pickup current values. A fault is demonstrated when the positive sequence current is greater than the pickup current determined for the positive sequence voltage from the curve.

$$t = \frac{A}{\left(I_{\mathrm{f}}/0.375\,u\,(V_{\mathrm{af}}^{+} + 1.5\left(V_{\mathrm{af}}^{+} - 0.25\right)u\left(V_{\mathrm{af}}^{+} - 0.25\right)\right)^{B} - 1}\ \mathrm{TMS} \quad (34)$$

In islanded microgrids, low fundamental current contributions from IIDGs can pose significant protection challenges. Overcurrent relays cannot differentiate between nominal and fault currents, which can result in unnecessary tripping. To tackle this issue, a harmonic-based overcurrent protection strategy has been developed. During faults, IIDGs generate decoupled harmonic voltages that produce a separate harmonic current flow from the fundamental currents [18]. This enables the creation of distinct harmonic and fundamental layers of current flow, ultimately enhancing reliability without necessitating communication. The short-circuit current of the harmonic layer is calculated using the modified nodal method (MNM) and verified using PSCAD/EMTDC. Finally, an optimal protection coordination (OPC) program is created, utilizing a novel time–current–voltage (TCV) characteristic and harmonic directional element. This program provides affordable and reliable protection for microgrids [35].

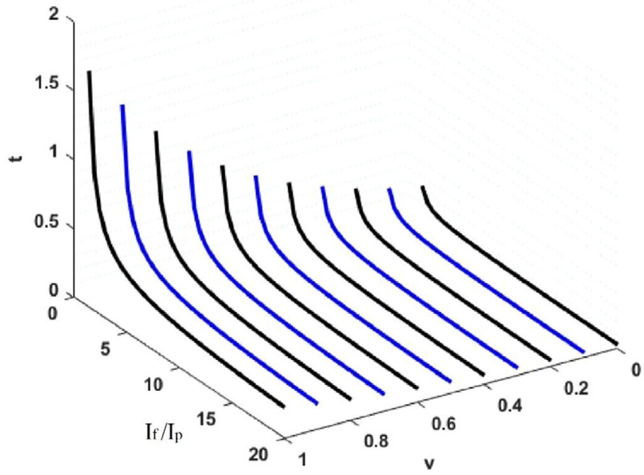

FIGURE 11 Proposed time–current–voltage curve.

$$t = \frac{A}{(M_{\mathrm{H}})^{B} - 1}\ \mathrm{TMS} \quad (35)$$

where vs stands for the harmonic relay voltage measured by relay r. K is a constant parameter that is allowed to take values between 0 and 2.5. The characteristics given by Equation (4) represent the extended version of the TCV characteristics, i.e. the harmonic-based-time–current–voltage (HTCV) characteristics. Figure 11 displays the HTCV characteristics for $K = 1.8$, $M_{\mathrm{s}} = 0.1$, $A = 0.14$, and $B = 0.02$.

A new protective method has been developed via Equation (35) and time–current–voltage curve for meshed distribution systems. This method does not require a communication system and can safeguard the IEEE 14-bus system, regardless of fault type, location, or resistance. It also improves system stability and isolates the faulted portion [66].

$$t = \mathrm{TMS}\,\frac{A}{(M_{\mathrm{I}})^{B} - 1}\log\left(9V_{\mathrm{f}} + 1\right) \quad (36)$$

The standard and time–current characteristics rely on the impact of fault current values, with a focus on their impact on tripping times. It is highlighted that these characteristics tend to reduce tripping times as the fault location approaches the source. However, it's mentioned that these standard curves, despite their effectiveness, pose limitations that lead to slow tripping in systems equipped with distributed generators (DGs)[80–82]. This is attributed to the inability of fixed standard and non-standard characteristic curves to effectively handle the significant penetration of DGs and their varying

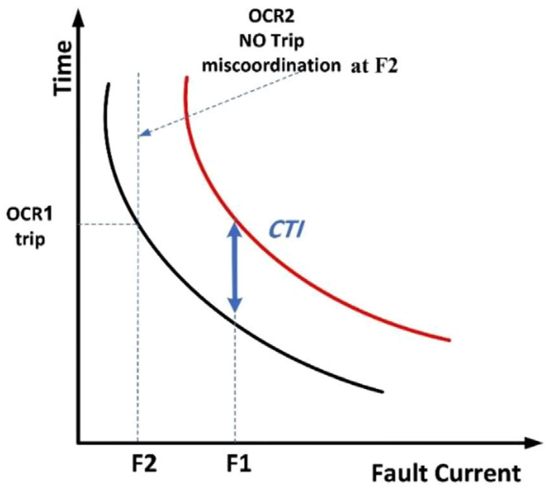

FIGURE 12 Standard time–current characteristic curve.

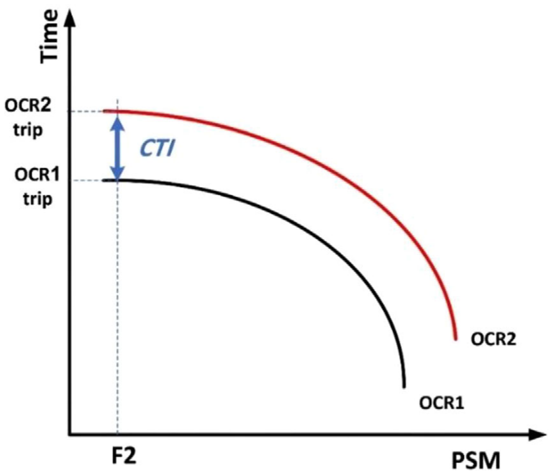

FIGURE 13 Non-standard characteristic curve.

operation modes as illustrated in Figures 12 and 13. To address this issue, the study introduces a proposed non-standard current–voltage curve, aiming to create an adaptive characteristic that can adjust to different fault locations and types [81]. The objective is to achieve the shortest possible tripping time for OCRs while avoiding miscoordination problems. This new approach is described mathematically by equations (Equations (37) and (38)), effectively adapting the current–voltage characteristic to accommodate DG integration in the system [83].

$$t = \left(5.8 - 1.35\, M_{\mathrm{v}} \log_{\mathrm{e}}(M_{\mathrm{I}})\right) \mathrm{TMS}\; M_{\mathrm{v}} > 1 \tag{37}$$

$$\mathrm{t} = \left(5.8 - 1.35 \log_{\mathrm{e}}(M_{\mathrm{I}})\right) M_{\mathrm{v}} \mathrm{TMS}\; M_{\mathrm{v}} < 1 \tag{38}$$

A novel approach to designing the non-standard current–voltage characteristic for OCRs. This approach utilizes voltage terms, constant grading times, and non-standard terms to create an adaptive and effective characteristic that enhances selectivity and coordination among OCRs in power systems, even in scenarios involving minimum fault levels and islanding operation mode. As illustrated in Figure 14, the development of a proposed non-standard current–voltage characteristic for OCRs in power systems is a complex task. This characteristic is defined using equations (Equations (39) and (40)), incorporating logarithmic, bus voltage, and constant coefficients. Two critical aspects of relay protection strategies are to be considered in protecting the Microgrid. The adaptive characteristic using voltage term employs the bus voltage and logarithmic function to create an adaptive relay characteristic, improving selectivity without compromising fault current or location considerations. It is important to maintain a constant grading time for selectivity, emphasizing its role in coordinating overcurrent relays effectively within the protection system.

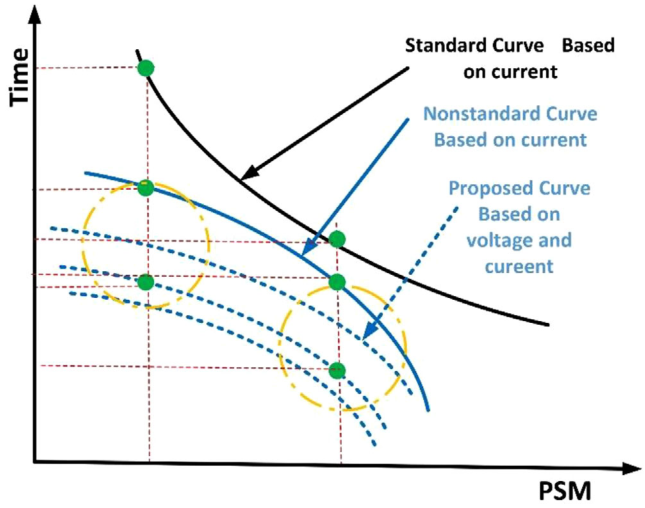

FIGURE 14 Proposed characteristics against standard and non-standard characteristics.

The adaptive characteristic using voltage term introduces the utilization of the bus voltage per unit and the logarithmic function as determinants of the operational tripping time (t) for the relay. The main idea is to create an adaptive relay characteristic that can dynamically adjust based on the real-time voltage and the current operational mode. This adaptability is aimed at enhancing the selectivity of the protection system without interfering with fault currents or fault locations. On the other hand, those approaches focus on the significance of constant grading time for selectivity in the coordination of OCRs. It underlines that to ensure proper coordination between OCRs and enhance the system's selectivity, the grading time should remain consistent and independent of variations in fault current levels or the fault's location within the network. This consistent grading time contributes to effective coordination among the OCRs. Moreover, for addressing minimum fault level and islanding mode, the non-standard term ($\log_e$) is incorporated to address the challenges of detecting minimum fault levels and islanding operation mode. Normal inverse curves were often insufficient in locating minimum faults. As illustrated in Figure 13, the proposed non-standard current–voltage tripping characteristic is designed to provide a sufficient region for detecting and coordinating the OCRs during minimum fault scenarios. This design aims to ensure selectivity while avoiding miscoordination issues [83].

$$t = \left(5.8 - 1.35\log_e(M_I)\right)\log_e(9M_v + 1)\,\text{TMS} \tag{39}$$

$$t = \left(\frac{1}{e^{1-V_f}}\right)^k \frac{A}{(M_H)^B - 1}\text{TMS} \tag{40}$$

A new approach for developing time–current curve (TCC) in loop power systems, was presented by the authors [84]. The authors propose a dynamic active time–current curve (ATCC) strategy based on these observed characteristics. This approach involves calculating a shorter opening operation delay time in response to lower fault voltage and higher fault current detected by the protection device. As a result, the protection device closest to the fault source triggers a quicker opening operation. This proposed approach eliminates the need for assigning different TCCs to each protection device. Equations (41) and (42) are used to express this flexible ATCC strategy. The new strategy aims to enhance fault detection and response in loop systems by considering fault location, fault current, and impedance characteristics, thus improving the overall effectiveness of protection devices in loop power systems. The authors emphasize that as a fault location is approached, the fault voltage tends to drop. Consequently, the lowest voltages can be measured at the circuit breakers (CBs) nearest to the fault point, especially if the line's length is significant. Moreover, the author mentioned that a protection device connected to a faulty line detects a fault current larger than that of a non-faulty line due to the higher fault current in the faulty line compared to intact lines. The upstream fault impedance is usually lower than the opposing impedance unless the fault is close to the terminal connection point. This leads to the upstream protection device detecting a greater fault current than the downstream devices.

$$\text{ATCC} = \text{TCC} \times X_{TD} + X_{TA} \tag{41}$$

$$t = \frac{A}{(M_I)^B - 1}\,C\left(\frac{V_{ams}}{V_{ref}}\right)^2 + D\left(\frac{V_{ams}}{V_{ref}}\right) \tag{42}$$

ATCC and its parameters focus on achieving effective coordination of protective devices in fault situations. The author emphasizes ATCC parameters' significance in effectively coordinating protective devices in fault scenarios. By optimizing coefficients based on fault characteristics and conducting simulations, a well-coordinated protection system can be established with prompt response times, ensuring the reliability and efficiency of power system protection. The constants A and B are selected based on the overcurrent relay (OCR) type, while V_{ams} represents the actual measured voltage after fault current pickup. V_{ref} stands for reference voltage, representing the phase voltage of the system. Constants X_{TD} and X_{TA}, related to time delay and extra time, are influenced by the measured voltage's distance to the fault factor, reflecting the specific location of the protective device in a fault scenario. TCCs are adjusted with varying X_{TA} and X_{TD} values for each protective device, leading to minimized device coordination time. This approach proves efficient in handling fault resistances, except for high-resistance ground faults. The coefficient C is calculated using the maximum short-circuit current, pickup current, distance between circuit CBs, and line impedance. The coefficient D incorporates mechanical and environmental blocking durations and is also calculated to ensure minimum cooperation time intervals. Simulations are conducted to determine optimal coefficients C and D values based on fault locations, types, and resistance, ensuring successful protective coordination with swift response times. It's noted that a lower C value leads to faster protective device response, but a deficient C can lead to coordination failure. The primary objective is to ensure that only the CB connected to the fault location opens during a malfunction, and this response time should be faster than the substation's response time under similar fault conditions.

4.1 | Comparison and discussion

The adoption of microgrids is increasing due to their environmental, economic, and technical benefits for various voltage distribution networks. However, it highlights significant challenges, especially regarding ensuring network stability and an effective protection system. While surge protection devices offer a cost-effective and feasible solution for distribution networks, the complexity arises from the diverse types of distributed generation sources, variations in fault current contributions, fault current directions, control methods, and the impact of inverters on fault detection. A notable evolution in protection strategies has occurred in response to these challenges from 2014 to the present by using voltage–current–time inverse protection schemes. This involves incorporating voltage considerations into fault detection equations alongside current-related factors and has led to the development of protection systems that combine current increase and voltage decrease characteristics, enhancing the accuracy of fault detection and ensuring prompt isolation. Table 2 provides a brief overview of the advantages and limitations of the main two microgrid protection approaches: standard overcurrent schemes and the voltage–current–time inverse approach. Standard overcurrent schemes, a well-established and widely-used method, offer the advantage of the utilization of existing protection infrastructure. However, with increasing the DG at DN and microgrid systems, the standard overcurrent schemes faced difficulties when dealing with forward and reverse faults, limiting their effectiveness in dynamic microgrid environments. On the other hand, the voltage–current–time inverse approach proves beneficial for islanded microgrids and detecting low fault currents commonly faced at DN with DGs. However, it requires a more complex coordination process and may be facing miss-coordination events with high impedance faults.

Since 2014, the voltage–current–time inverse protection approach has received significant attention as an attractive solution to the complex challenge of microgrid protection. This methodology has been discussed over 28 research articles in total with collectively over 734 citations, as illustrated in Table 2 and Figure 15. Table 3 illustrates the progress of employing

TABLE 2 Summary of the advantages and limitations of standard overcurrent schemes and voltage–current–time inverse approach.

Protection approach	Advantages	Limitation
Standard overcurrent schemes	• Well-known.	• Coordination did not cover forward and reverse faults • The need for communication link • Fixed settings are not suitable for a dynamic network.
Voltage–current–time Inverse	• Suitable for islanded mode • Efficient in the detection of low fault currents.	• Complex coordinate process. • Failure to operate for high-impedance faults

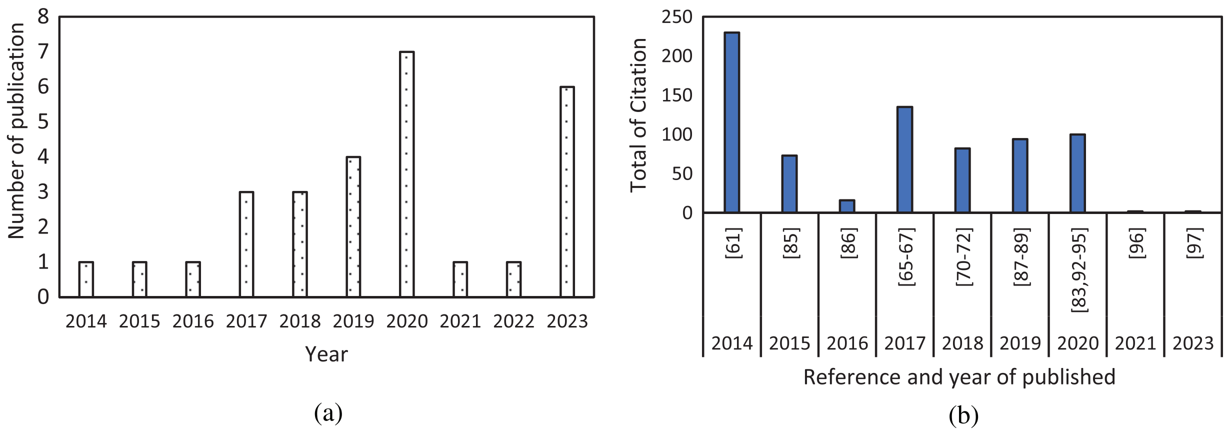

FIGURE 15 Then number of publications and citations in the area of voltage–current–time inverse protection schemes since 2014. (a) Number of publications. (b) Total number of citations.

voltage–current–time schemes in protection power grids over the last decade. It encompasses characteristics curves, variable quantities, operational states (isolated or connected), types of distributed generation, network topology (radial or looped), and failure types. Various optimization techniques have been employed to derive these variables, applied to IEEE networks, as shown in Table 3. The abbreviations in Table 3 are illustrated as follows: standard inverse (SI), non-standard (NS), time multiplier setting (TMS), *K* and *B* constant parameters, pickup current (IP), inverter-based distributed generations (IBDGs), synchronous-based distributed generations SBDGs, and induction generator-based distributed generation (IGBDG), grid connected (GC), islanding (IS).

A comparison for the performance of the main non-standard characteristics, as discussed in Section 4, is presented in Table 4. These non-standard characteristics tested using three different size of power networks 8, 9, and 30 IEEE bus networks [89]. Equation (11) recorded the lower simulation times at the 8 IEEE bus network, making it suitable for scenarios where computational speed is essential. However, for larger power networks (9 and 30 bus networks) Equation (30) was more efficient in term of computational cost. In term of tripping time, Equation (14) recorded the minimum tripping time at 30 bus networks, while the Equations (18) and (19) recorded minimum tripping for 9 bus and 8 bus IEEE network, respectively. In general, these non-standard characteristics offer many advantages in term of adaptability and cost-effectiveness. Furthermore, varying the parameters of non-standard characteristics can enhance the selectivity and sensitivity of these relays. Consequently, they emerge as a promising option for coordinating power systems in microgrids. However, it is important to identify that each non-standard characteristics is specifically designed to address particular issues, and no single non-standard characteristics can effectively resolve all protection challenges. Additionally, the mathematical expressions of non-standard characteristics tend to be more complex due to the incorporation of additional control parameters and the use of logarithmic and exponential functions. These complexities result in increased computational demands when determining relay coordination, necessitating the implementation of efficient optimization algorithms.

5 | REALISTIC OF VOLTAGE–CURRENT–TIME INVERSE APPROACH AND FUTURE TREND

5.1 | Borrego springs microgrid

The Borrego Springs Microgrid, developed by the San Diego Gas and Electric Company, stands out as one of the primary real-world microgrid systems employing a voltage–current–time-inverse approach. This approach offers a practical and realistic solution for enhancing overcurrent protection sensitivity challenging in the microgrid's islanded mode. This microgrid feeds 615 customers and supports a peak load of 4.6 MW through a 69/12 kV substation connected to the utility grid, dual diesel generators (2 × 1.8 MW), a

TABLE 3 Summary of protection schemes over different power networks.

Ref.	Year	Curve used	Number of variables	Modes of the operation	DNs types	DGs types	Fault types	Optimization algorithm	Test network	System level
[61]	2014	SI	TMS,K	GC, IS	meshed	SBDGsIGBDGs	ALL	SQP	IEEE 14 IEEE 30	HV
[85]	2015	SI	TMS	GC	Radial	IGBDGs	3 phase	–	–	MV
[86]	2016	NS	TMS,K,A	GC	Meshed	SBDGsIGBDGs	3 phase	DEA	IEEE 8-bus	HV
[66]	2017	NS	TMS,K	GC, IS	Meshed	SBDGs	ALL	NLP	IEEE 30-bus	MV
[67]	2017	SI	TMS	GC	Radial	SBDGs	ALL	–	Iranian DN	MV
[65]	2017	NS	TMS,K	GC	Radial	SBDGs	ALL	–	Iranian	MV
[71]	2018	NS	TMS,IP,A,B,C	GC	Meshed	SBDGs	ALL	GA	IEEE 14	MV,HV
[72]	2018	SI	TMS	–	Radial	–		–	KEPCO DN	MV
[70]	2018	NS	TMS,K	GC, IS	Radial	SBDGsIGBDGs	ALL	–	IEEE33-bus	MV,LV
[87]	2019	NS	TMS,K,A	GC	Meshed	IGBDGs	3 phase	–	IEEE 8-bus IEEE 30-bus	HV
[88]	2019	SI	TMS	GC	Radial	IBDGs	ALL	–	IEEE 13	MV
[89]	2019	SI	TMS, K	GC	Radial	IGBDGs	3 phase	–	Isfahan DN	MV
[90]	2019	SI	TMS	GC,IS	Meshed	SBDGsIGBDGs	ALL	–	IEEE 37-bus	MV
[91]	2020	SI	TMS,IP	GC,IS	RadialMeshed	IGBDGs	3 phase	HAS-BB	IEEE 8-bus IEEE 9-bus IEEE 33-bus	MV,HV
[92]	2020	NS	TMS	GC,IS	Radial	IGBDGsBESS	1 & 3phase	–	IEEE33-bus	MV
[83]	2020	SI	TMS,IP,B	GC,IS	Radial	IGBDGs	3 phase	BAS	–	MV
[93]	2020	SI	TMS,K	GC	Meshed	SBDGs	3 phase	GA, PSO	IEEE33-bus IEEE 8-bus	MV
[94]	2020	SI	TMS	GC,IS	Radial	SBDGsIGBDGs	ALL	–	18-bus	MV
[95]	2020	SI	TMS	GC	Radial	IGBDGs	ALL	–	14-bus CIGRE	MV
[78]	2020	SI	TMS,K	IS	Radial	IGBDGs	ALL	GAMS	IEEE33-bus IEEE 9-bus	MV
[76]	2021	SI	TMS	GC	Meshed	IGBDGs	3 phase	αHHO	IEEE8-bus	HV
[96]	2022	SI	TMS	GC	Meshed	–	ALL	–	IEEE14-bus	MV
[75]	2023	SI	TMS	GC,IS	Radial	IGBDGs	ALL	GA	IEEE 33-bus IEEE 9-bus	MV
[97]	2023	SI	TMS	GC	Radial	IGBDGs	3 phase	VPS	14-bus CIGRE	MV
[74]	2023	SI	TMS,K	IS	Radial	IGBDGs	ALL	GA	IEEE 9-bus	MV
[73]	2023	SI	TMS	GC,IS	Radial	SBDGsIGBDGsBESS	ALL	–	14-bus CIGRE	MV
[84]	2023	SI	TMS	GC	RadialMeshed	–	3 phase	–	IEEE14-bus	MV
[98]	2023	SI	TMS	GC	Radial	SBDGs	3 phase	GA	IEEE 33-bus	MV

photovoltaic (PV) system (0.7 MW), and a substation battery system, BESS, (500 kW/1500 kWh) with three feeders, as shown in Figure 16. However, due to the microgrid's specific characteristics, conventional overcurrent relays are insufficient to trip during fault conditions with low fault current magnitudes. Therefore, the introduction of a voltage-restrained overcurrent protection system was essential based on the voltage–current–time-inverse approach. While this approach greatly enhances sensitivity for small fault currents, it's crucial to acknowledge that the microgrid's unique conditions continue to impact the selectivity of the protection system along its infrastructure [99].

TABLE 4 Summary of protection schemes over different power networks.

Ref.	Year	Equation of the voltage current curve	Equation number	Comparison
[61]	2015	$t = \left[\frac{A}{(M_{\mathrm{I}})^{B}-1}\right]\left(\frac{1}{e^{1-V_{\mathrm{f}}}}\right)^{k}\mathrm{TMS}$	(11)	• Lower simulation time at 8 IEEE bus network
[65]	2017	$t = \frac{A}{(\mathrm{M_I})^{B}-1}\left(\frac{V_{\mathrm{f}}}{\mathrm{e}^{k\cdot V_{\mathrm{f}}}}\right)\mathrm{TMS}$	(14)	• Best mean of total tripping time at 8 IEEE bus network • Best tripping and mean tripping time at 30 IEEE bus network
[69]	2017	$t = \left(\frac{1}{1-(\log V_{\mathrm{f}})^{C}}\right)^{k}\left[\frac{A}{(\mathrm{M_I})^{B}-1}\right]\mathrm{TMS}$	(18)	• Best tripping time and mean tripping time at 9 IEEE bus network
[71]	2018	$t = \left[\frac{\log V_{\mathrm{f}}+A}{(\mathrm{M_I})^{B}-1}\right]+C$	(19)	• Best tripping time at 8 IEEE bus network
[72]	2019	$t = \frac{A}{\left(\left(\frac{1-V_{\mathrm{f}}}{1-V_{\mathrm{s}}}\right)^{D}(\mathrm{M_I})^{B}\right)-1}\ \mathrm{TMS}$	(26)	• ————
[74]	2020	$t = \left[\frac{A}{\left(\frac{V_{\mathrm{S}}}{V_{\mathrm{f}}}\frac{I_{\mathrm{f}}}{I_{\mathrm{S}}}\right)^{B}-1}\right]\mathrm{TMS}$	(30)	• Lower simulation time at 9 and 30 IEEE bus networks

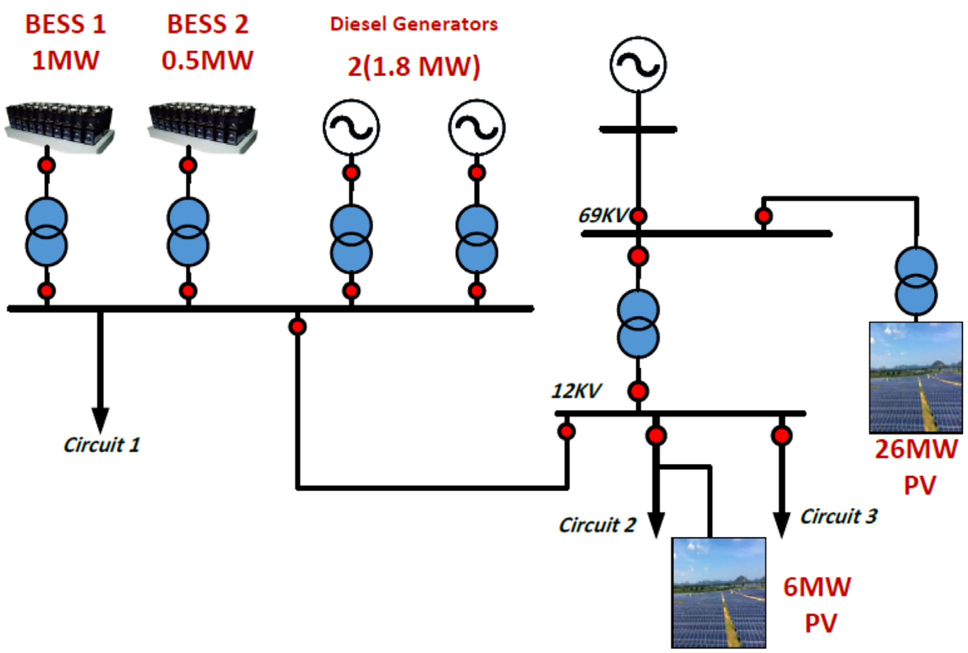

FIGURE 16 Borrego springs microgrid.

5.2 | Challenges and future trends

Focusing on integrating voltage–current–time characteristics and their benefits could offer a promising solution for microgrid protection challenges. The advancement of communication technologies, autonomous systems like multiple agents, and intelligent technologies such as inverters and grids are crucial for enhancing microgrid security. The voltage–current–time inverse protection coordination concept will improve fault detection sensitivity and coordination reliability. The following ideas for future research in microgrid protection emerge:

- Investigating protection strategies for microgrids dominated by inverter-interfaced distributed generators (IIDGs), considering their non-linear behaviour, impedance characteristics, and fault ride-through transients during faults.
- Exploring DG sizing and allocation methodologies while accounting for the fault ride-through behaviour of various DG types and their influence on overall grid performance.
- Developing intricate simulation models for meshed microgrids, encompassing diverse DG sources and types, catering to different load scenarios and fault conditions.
- Recognizing the growing reliance on communication networks for advanced protection methods and studying the impact of network latencies and noise on protection systems.
- Addressing potential cybersecurity threats in future microgrids that heavily depend on communication and IoT devices,

ensuring resilient protection schemes against potential cyber-attacks.

- Designing decentralized backup protection mechanisms capable of detecting faults in both operational modes of microgrids, even in communication or primary protection failures.
- Emphasizing the need for real-time experimental investigations to validate the feasibility and effectiveness of proposed protection techniques.

6 | CONCLUSIONS

The integration of distributed generation systems and the evolving operational dynamics of microgrids have reshaped the power system landscape, showing new challenges that conventional overcurrent protective schemes struggle to address. As a response, non-standard protection approaches have gained significant attention recently. Engineers and operators have proposed diverse non-standard methodologies to enhance power system reliability and ensure the selectivity of protective relays in contemporary protection systems. While the principles and requisites of non-standard characteristics have been broadly delineated in existing literature, hybrid-based characteristics, and various non-standard optimization techniques, have yet to be explored. This paper has provided a comprehensive overview of recent research and advancements in hybrid-based characteristics to fill this gap. It systematically evaluates pertinent studies' potential advantages and drawbacks, presenting a meticulous classification and analysis of these approaches.

The paper emphasizes amalgamating voltage–current–time characteristics and their benefits as a promising direction to overcome microgrid protection challenges. The progression of communication technologies, the emergence of autonomous systems such as multiple agents, and the integration of intelligent components like inverters and grids are pivotal to fortifying microgrid security. The concept of voltage–current–time inverse-based protection coordination holds the potential to heighten fault detection sensitivity and bolster coordination reliability. Finally, the reviewed literature highlights the imperative of adapting protection strategies to the evolving power system field, particularly in microgrids. The insights presented provide a basis for improving protective measures and guiding toward more secure, reliable, and responsive energy systems.

NOMENCLATURE

AC	Alternative current
BESS	Battery energy storage system
CB	Circuit breaker
CTI	Coordination time interval
DC	Direct current
DER	Distributed energy resources
DG	Distributed generation
DN	Distribution network
DOCR	Directional over current relay
EI	Extremely inverse
ER-WCA	Evaporation rate water cycle algorithm
ESS	Energy storage systems
FDMT	Fuzzy decision-making
GA	Genetic algorithm
GC	Grid-connected
GR	Ground relay
HOT	Hybrid optimization technique
HV	High voltage
HVDC	High voltage direct current
IF	Fault current
IGBDGs	Induction generator-based distributed generation
I-ITOC	Improved inverse time over current
IP	Pickup current
IPM	Interior point method
IS	Islanding
ISC	Short circuit current
ITT	Inverse time harmonic
LP	Linear Programming
MGM	Microgrid
MO	Metaheuristic optimization
MOHO	MO-hybrid optimization
MOPSO	Multi-objective particle swarm optimization
MRFO	Manta ray foraging optimization algorithm
NI	Normal inverse
NLP	Non-linear programming
NS	Non-standard characteristics
OA	Optimization algorithm
OCR	Over current relay
OPC	Optimal protection coordination
PCC	Point of common coupling
PR	Phase relay
PS	Plug setting
RA	Upstream relay
RCS	Relay characteristic selection
RMS	Root mean square
SBDGs	Synchronous-based distributed generations
SC	Standard characteristics
SFCL	Super condition fault current limiter
SI	Standard inverse
SPVG	Solar photophilic generator
SQP	Sequential quadratic programming
TCC	Time current curve
TCV	Time current voltage
TD	Time delay
TDGC	Transformer DG connection
TODG	Type of DGs
TOF	Type of faults
VF	Voltage fault
VI	Very inverse
VROCR	Voltage restrained over current relay
WPP	Wind power plants
XTA	Time adder
αHHO	Alpha Harris Hawks optimization

AUTHOR CONTRIBUTIONS

Feras Alasali: Conceptualization; formal analysis; investigation; methodology; project administration; software; validation; writing—original draft. **Naser El-Naily**: Conceptualization; data curation; investigation; methodology; resources; software; writing—original draft. **Abdelaziz Salah Saidi**: Methodology; project administration; software; supervision; validation; funding acquisition; writing—review and editing. **Haytham Mustafa**: Formal analysis; investigation; methodology; supervision; validation; writing—review and editing. **William Holderbaum**: Formal analysis; methodology; project administration; software; supervision; validation; visualization; writing—review and editing. **Emad Omran**: Conceptualization; data curation; investigation; project administration; software; validation; writing—review and editing. **Salima Abeid**: Methodology; project administration; software; supervision; validation; writing—review and editing. **Saad M. Saad**: Formal analysis; investigation; methodology; supervision; validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Not applicable

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