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REVIEW

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Comparative framework for AC-microgrid protection schemes: challenges, solutions, real applications, and future trends

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Abstract

With the rapid development of electrical power systems in recent years, microgrids (MGs) have become increasingly prevalent. MGs improve network efficiency and reduce operating costs and emissions because of the integration of distributed renewable energy sources (RESs), energy storage, and source-load management systems. Despite these advances, the decentralized architecture of MGs impacts the functioning patterns of the entire system, including control strategy, energy management philosophy, and protection scheme. In this context, developing a convenient protection strategy for MGs is challenging because of various obstacles, such as the significant variance in short-circuit values under different operating modes, two-way power flow, asynchronous reclosing, protection blinding, sympathetic tripping, and loss of coordination. In light of these challenges, this paper reviews prior research on proposed protection schemes for AC-MGs to thoroughly evaluate network protection's potential issues. The paper also provides a comprehensive overview of the MG structure and the associated protection challenges, solutions, real applications, and future trends.

Keywords Microgrid, Active distribution network, Microgrid protection, Renewable energy sources, Smart grids, Distributed energy resources, Energy storage

1 Introduction

Renewable energy sources are becoming the primary providers of power in electricity grids. This is because of the negative environmental impact of fossil fuels, the depletion of fossil fuel resources, power quality issues, the deterioration of traditional power networks, and the increasing demand for energy [1]. Consequently, microgrids (MGs) have evolved to handle the widespread use of renewable energy sources (RESs). MGs are regarded as independent networks comprised of distributed energy resources (DERs) and intelligent loads that can function in either a standalone or grid-connected mode driven by economic and technical constraints [2]. In this context, MGs have allowed different resources such as solar photovoltaic, wind turbines, geothermal, biomass, wave energy, and energy storage systems (ESSs) like batteries or fuel cells to be engaged in the generation process to lessen the reliance on traditional sources, reduce hazardous emissions and pollution, and secure a sustainable and reliable source of energy [3–5].

The growing adoption of renewable energy sources, as well as innovations in semiconductor switches, have pushed the concept of MGs or decentralized grids as a way to address the challenges posed by traditional power networks. MGs can also contribute to smart grid features such as DERs, digital and pilot communications, self-observation and restoration, and distant and adaptable inspection, etc. [6, 7].

Despite the significant contribution of MGs, their configurations have posed significant challenges in

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terms of operating philosophy in grid-connected and islanded modes, load balancing, stability, power quality, power flow, voltage profile, frequency regulation, and energy management, protection, etc. [8, 9]. MG protection is considered crucial in establishing a reliable power network, and demands adequate configuration of protective relays to handle electrical faults promptly in both operating modes. However, it is challenging in decentralized networks because of fault level discrepancies, power flow inconsistencies, islanding incidents, and relay reach settings, etc. [10–12]. Thereby, studying the functioning of MGs under normal and abnormal conditions serves as the basis for developing effective protection schemes. This work delves deeply into the pertinent challenges and investigates remedial procedures.

Table 1 outlines the main limitations of conventional protection schemes in AC-MGs and prospective remedies as discussed in previous publications, reflecting the leading contributions of this work. As seen, this work investigates a wider range of protection concerns in AC-MGs, with more issues such as autorecloser deficiency, asynchronous reclosing, loss of coordination, and transformer winding connections being taken into account. This study also examines further protection schemes such as wavelet transform, traveling waves, S-transform, Hilbert–Huang, decision tree, and support vector machine-based methods. Additionally, it considers the impact of using external-helping devices such as fault current limiters, energy storage units, and intelligent electronic devices to aid conventional protective relays. This study offers various real MGs and accompanying protection systems as practical applications, demonstrating the most frequently used protection schemes. Based on the preceding, it provides a thorough survey of the most reported protection frameworks to assist electrical engineers in recognizing impending concerns and developing adequate solutions to enhance system quality. It also addresses gaps in the literature by including the majority of research related to AC-MG protection. Generally, the principal contributions of this paper can be outlined as follows:

- Examines a wide variety of difficulties posed by DER penetration and the resulting impact on conventional protection schemes.
- Investigates various protection strategies for MGs, demonstrating the primary operating principles besides the merits and demerits of each methodology in comparative tables.
- Highlights some real-world MGs alongside the ratings of RESs and implemented protection schemes.
- Reveals further concerns, tendencies, and trends for future development and innovation in this research area.

The rest of the paper is structured as follows. Section 2 outlines the review methodology; Section 3 gives an overview of the structure, different types, and modes of operation of MGs. Section 4 then examines the main limitations to implementing the traditional relay concepts, while Section 5 outlines the suggested methods for protecting AC-MGs. Section 6 presents practical examples of MGs and their protection strategies. In Section 7, some challenges that need to be considered for future research are identified, and finally, the conclusion of the work is presented in Section 8.

2 Review methodology

The review methodology of this paper involves a comprehensive examination of the relevant literature and research studies of AC-MGs. The first stage of this research is to collect previous publications that are clearly relevant to MG protection by using databases and search engines such as IEEE explorer, Egyptian Knowledge Bank, ResearchGate, Google Scholar, Springer, Scopus, Web of Science, IET Inspec, Wiley, and MDPI. Then, irrelevant documents to MGs protection are removed to allow a thorough and robust review. The remaining papers are then grouped into categories such as reviews, journal and conference papers, book chapters, online articles, and scientific theses. The study delves into examining the major limitations of traditional protection schemes and offers detailed insights into the proposed solutions. The study also takes into account practical applications by discussing various real MGs, highlighting the implemented protection schemes in the real projects. Subsequently, the paper identifies some notable challenges and emerging trends that could be a focus of future research. Figure 1a and b outline different statistics about the investigated research papers in this work in terms of year of publication and the type of these publications, respectively.

3 Background

MGs are defined as independent small-scale networks that comprise DERs and ESSs to supply some local loads. They are interfaced directly or through the use of power electronic converters, such as AC/DC and DC/AC converters as shown in Fig. 2. According to technical and economic evaluations, MGs operate in either

Table 1 Principal features of this study against other review works

Reference	Year	Examined Protection challenges											Examined Protection schemes																		Real applications in actual MGs
		SCC	Imp. RR	Pr. Bl	Bi. PF	Sy. Tr	Sel. and Sen	LOM	AR. Def	Asy. Rec	LOC	Int. Tx	Ad. Pr	Diff. Pr	Dis. Pr	OC. Pr	V. Pr	WT-Pr	TW. Pr	ST. Pr	HH. Pr	HrC. Pr	ANN. Pr	FL-Pr	DT. Pr	SVM. Pr	MA. Pr	FCL	ESSs	IEDs	
[2]	2020	✓		✓		✓				✓			✓										✓	✓			✓		✓		
[3]	2014	✓									✓		✓	✓	✓		✓														
[6]	2021	✓	✓		✓	✓	✓	✓					✓	✓	✓	✓	✓														
[7]	2014	✓			✓								✓	✓	✓	✓	✓											✓	✓		
[10]	2020	✓	✓	✓	✓	✓			✓	✓			✓		✓			✓	✓			✓	✓				✓				
[14]	2021	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓			✓	✓			✓	✓				✓	✓			
[18]	2019	✓												✓	✓	✓	✓	✓				✓			✓			✓	✓		
[28]	2015	✓				✓		✓			✓		✓											✓			✓	✓			
[35]	2017	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓		✓						✓	✓				✓	✓	✓	
[36]	2015	✓	✓		✓	✓	✓	✓						✓		✓															
[46]	2021	✓	✓	✓	✓	✓			✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	
[58]	2014	✓			✓			✓					✓	✓	✓	✓	✓											✓	✓		
[72]	2020	✓		✓		✓	✓	✓			✓		✓	✓	✓	✓	✓					✓	✓	✓				✓			
[73]	2022	✓		✓		✓		✓	✓	✓			✓	✓	✓	✓	✓	✓	✓		✓		✓				✓	✓			
[86]	2021	✓	✓	✓	✓	✓					✓		✓	✓	✓	✓	✓		✓			✓					✓	✓	✓		
[94]	2016	✓		✓		✓			✓	✓			✓	✓	✓	✓	✓	✓		✓											
[107]	2017	✓			✓	✓		✓	✓		✓		✓	✓	✓	✓	✓										✓				
This paper		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

In Table 1, SCC: Short circuit capacity, Imp.RR: Impedance relay reach, Pr.Bl: Protection blindness, Bi.PF: Bidirectional power flow, Sy.Tr: Sympathetic tripping, Sel. and Sen.: Selectivity and sensitivity, LOM: Loss of main (Islanding), AR. Def.: Deficiency of autoreclosers, Asy. Rec.: Asynchronous reclosing, LOC: Loss of coordination, Int. Tx.: Interface transformers, Ad.Pr.: Adaptive protection, Diff. Pr.: Differential protection, Dis. Pr.: Distance protection, OC.Pr.: Overcurrent-based protection, V.Pr.: Voltage-based protection, WT-Pr.: Wavelet-based schemes, TW.Pr.: Travelling wave-based schemes, ST.Pr.: S-transform-based schemes, HH.Pr.: Hilbert–Huang-based schemes, HrC.Pr.: Harmonic content-based schemes, ANN.Pr.: Artificial Neural Network-based schemes, FL-Pr.: Fuzzy logic-based schemes, DT.Pr.: Decision trees-based schemes, SVM.Pr.: Support vector machine-based schemes, MA.Pr.: Multiagent-based schemes, FCL: Fault current limiters, ESSs: Energy storage systems, and IEDs: Intelligent electronic devices

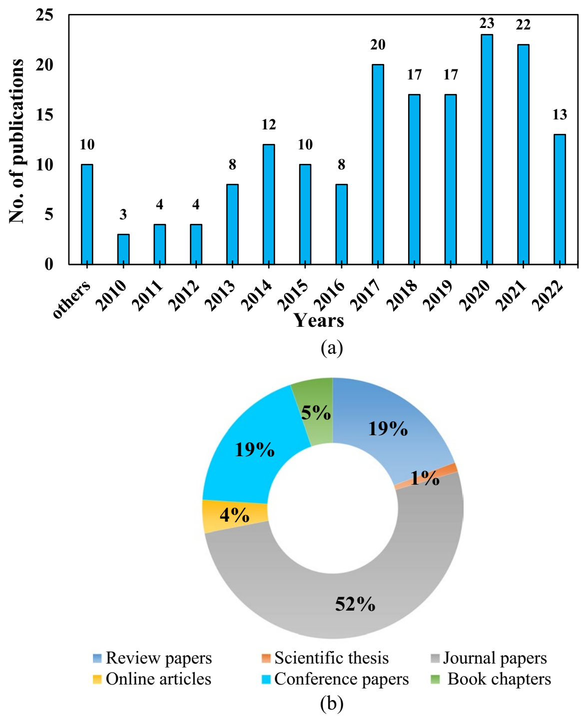

Fig. 1 Classification of surveyed-publications in this paper **a** by year, **b** by type

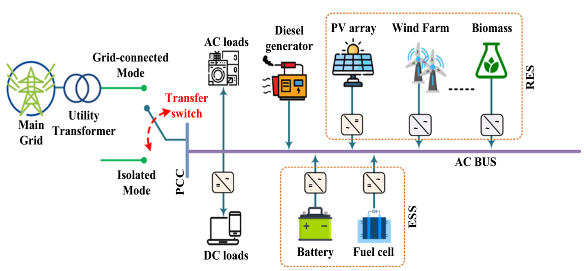

Fig. 2 A typical AC-MG arrangement

grid-connected or autonomous mode, controlled by a fast-switching isolator located at the point of common coupling (PCC) [2, 13]. Generally, the grid-connected mode is a typical arrangement when the main grid is healthy and stable without any disturbances. On the other hand, the autonomous / islanding mode can be deliberately activated to power rural areas and military zones [1] or be automatically triggered as a response to perturbations in the main grid [14, 15].

MGs can be mainly classified as AC, DC, or hybrid, based on the electrical power type. AC-MGs allow for the direct connection of any facilities that generate or consume AC power to the main bus. Conversely, DC/AC converters are necessary to interface with DC installations. This is in stark contrast to DC-MGs, which emerged as a response to increased tendencies toward DC-renewables, HVDC systems, rechargeable appliances (i.e., electric vehicles), etc. Hybrid grids, on the other hand, combine the individual structures of both AC- and DC-MGs, providing increased flexibility for new installations through the use of power electronics and limiting multiple conversion processes (i.e., AC/DC and DC/AC) to reduce capital expenses and improve overall efficiency [16–21].

4 Limitations of traditional protective relays in AC-MGs

The decentralized framework of MGs has imposed various challenges and limitations on conventional protection strategies, prompting the need for innovative methods to protect MGs from internal faults and isolate them during disruptions from the main grid [22, 23]. Figure 3 depicts most of such obstacles, which will be discussed in more detail.

4.1 Short circuit capacity

In MGs, the short-circuit current level is influenced by both the operating mode and the distributed energy resources (DERs) technology, such as synchronous or inverter-based generators [24]. Regarding the technology used by DERs, synchronous generators can produce around 5–10 times the rated current during a fault. In contrast, converter-based resources typically produce less than twice the rated current, as illustrated in Fig. 4. Additionally, Fig. 4 illustrates the behavior of three different DERs during a fault. The first source is a synchronous

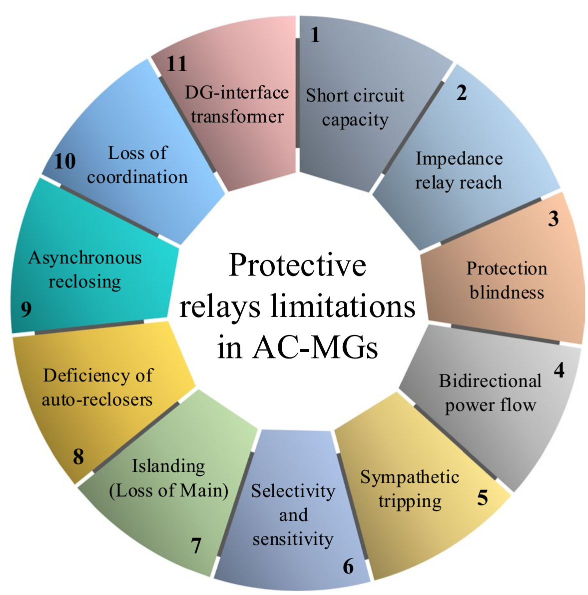

Fig. 3 Problems encountered by conventional protective relays in AC-MGs

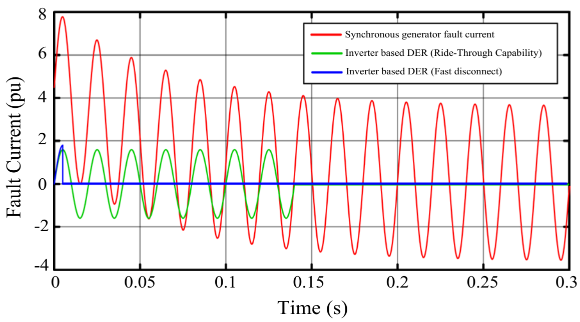

Fig. 4 Fault current characteristics with generation technology

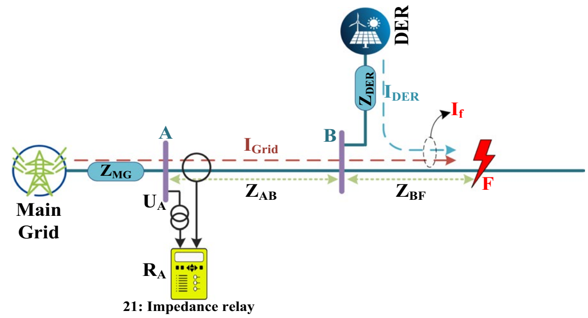

Fig. 5 DER-infeed current effect

generator, the second is an inverter-based DER that takes 7 cycles to disconnect because of its ride-through capability, and the third disconnects immediately [25–27]. The operating mode of MGs has a significant effect on the fault level, with higher fault current when in grid-connected mode due to the participation of the main grid in addition to the DERs. This is reduced when the grid is disconnected during islanding mode, particularly if inverter-based DERs predominate [14]. Consequently, configuring protective relays for both operating modes is challenging because of the significant variations in short-circuit current levels. These can severely compromise the performance of existing relays [21, 28].

4.2 Impedance relay reach

Impedance or distance relays are widely employed to protect transmission networks and have recently been recommended to protect MGs, as they can detect and respond to both forward and backward faults. However, these relays face various challenges that can hinder their reliability, including issues with fault resistance, compensation factors during ground faults, and the effects of infeed currents [29, 30]. In this context, DER infeed may obstruct the decision of impedance relays in MGs, as it causes the perceived impedance at the relay to be higher/lower than the actual impedance between the relay and the fault point, resulting in the relay either under- or over-reaching. Thereby, the relay trip signal may be completely blocked or delayed, impacting the coordination of other relays [31, 32]. In MGs, the most common problem with impedance relays is under-reaching, compared to over-reaching, which requires larger settings to address the infeed consequences as a possible solution. However, this adjustment may cause the relays to malfunction during disturbances, heavy loads (line loadability), system swings, etc. [29, 33]. For illustration, Fig. 5 clarifies the impact of the DER infeed on the upstream relay ($\mathrm{R_A}$) during a solid fault at (F). During the fault, the voltage ($\mathrm{U_A}$) at the relay position can be computed as outlined in (1), and then the impedance to the fault location as observed from R_A can be determined as in (2) or (3).

$$\mathrm{U_A} = \mathrm{Z_{AB}I_{Grid}} + \mathrm{Z_{BF}(I_{Grid} + I_{DER})} \tag{1}$$

$$\mathrm{Z_R} = \frac{\mathrm{U_A}}{\mathrm{I_{Grid}}} = \underbrace{\mathrm{Z_{AB} + Z_{BF}}}_{\substack{\text{True impedance}\\ \text{to fault point}}} + \underbrace{\frac{\mathrm{I_{DER}}}{\mathrm{I_{Grid}}}\mathrm{Z_{BF}}}_{\substack{\text{error due to}\\ \text{infeed current}}} \tag{2}$$

$$\mathrm{Z_R} = \mathrm{Z_{AF}} + \mathrm{K_i\,Z_{BF}} \tag{3}$$

where $\mathrm{U_A}$ and $\mathrm{I_{Grid}}$ are the measured voltage and current at the relay primary side during a fault (F), respectively. $\mathrm{Z_{AB}}$ is the impedance of line AB, $\mathrm{Z_{BF}}$ is the impedance between bus B and fault point F, Z_R is the relay apparent impedance during the fault, and $\mathrm{Z_{AF}}$ is the actual fault impedance, which equals ($\mathrm{Z_{AB} + Z_{BF}}$). K_i represents infeed constant ($\mathrm{I_{DER}/I_{Grid}}$).

The relation in (3) can be written in the polar form as:

$$\mathrm{Z_R} = \mathrm{Z_{AF}} + |\mathrm{K_i}|\angle\vartheta_i| * \mathrm{Z_{BF}}|\angle \emptyset_{\mathrm{BF}} \tag{4}$$

$$\mathrm{Z_R} = \mathrm{Z_{AF}} + |\mathrm{K_i} * \mathrm{Z_{BF}}|\angle(\vartheta_i + \emptyset_{\mathrm{BF}}) \tag{5}$$

According to (5), the influence of the infeed current on impedance calculations is highly dependent on the previously determined angles ϑ_i and $\emptyset_{\mathrm{BF}}$, leading to three different outcomes, which are illustrated in Table 2 and summarized in Fig. 6 [34].

4.3 Protection blindness

In general, the pickup value for current-based relays, such as overcurrent relays, directional relays, and reclosers, is set to be greater than the rated current at the relay location and less than the minimum fault current at the remote end of the protected zone [35]. Normally, the

Table 2 Infeed current impact on impedance value for impedance relay

Case	ϑ_i	$Ø^*_{BF}$	$\vartheta_i + Ø_{BF}$		Impedance relay condition	
1	+	+	+	−	**Under reach**	**increased fault distance**
2	-	+	+	if $\lvert Ø_{BF}\rvert > \lvert\vartheta_i\rvert$	Under reach	increased fault distance
3	-	+	-	if $\lvert Ø_{BF}\rvert < \lvert\vartheta_i\rvert$	Over reach	reduced fault distance

* $Ø_{BF}$ has always a positive value assuming that $Z_{BF} = R_{BF} + jX_{BF}$

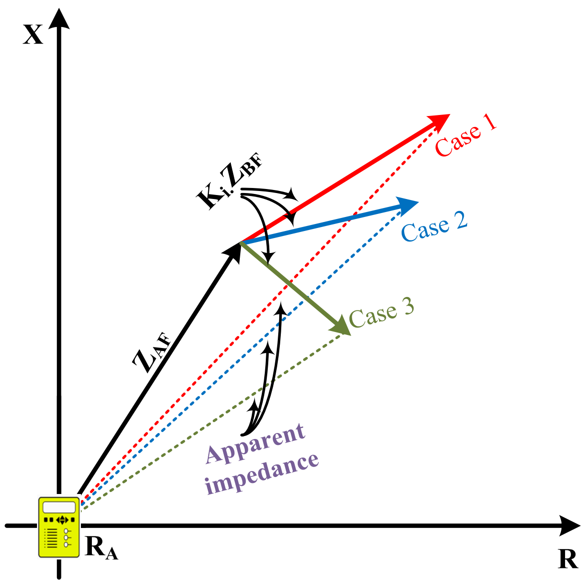

Fig. 6 Infeed current impact on apparent impedance to the relay R_A

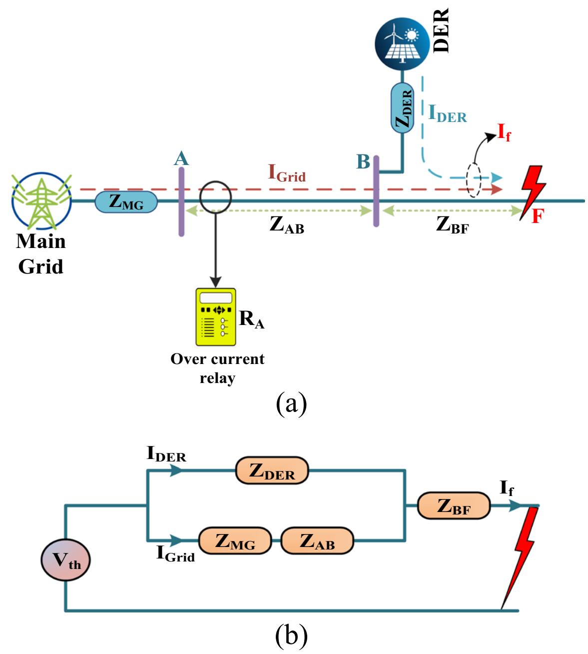

Fig. 7 Overcurrent relay blindness: **a** illustrating network, **b** Thevenin's equivalent

simultaneous feeding of a downstream fault from the DER and the main grid causes the actuating current of the upstream relay to drop below its pickup value, resulting in the relay failing to detect the fault [35, 36]. This phenomenon is demonstrated in Fig. 7, where Fig. 7a clarifies an illustrating network, while Fig. 7b represents the Thevenin's equivalent at the fault location. This is used to determine the extent of the grid contribution (I_{Grid}) through the upstream relay (R_A) based on Thevenin principles. Thevenin's impedance (Z_{th}) at the fault point is first determined as in (6), and then the total fault current (I_f) is calculated as in (7). The grid contribution is then defined using current-divider rules, as in (8).

$$Z_{th} = \frac{(Z_{MG} + Z_{AB})(Z_{DER})}{Z_{MG} + Z_{AB} + Z_{DER}} + Z_{BF} \tag{6}$$

$$I_f = \frac{V_{th}}{\sqrt{3}Z_{th}} \tag{7}$$

$$I_{Grid} = \frac{Z_{DER}}{Z_{MG} + Z_{AB} + Z_{DER}} I_f \tag{8}$$

where V_{th} represents the Thevenin voltage while Z_{MG} and Z_{DER} denote the equivalent impedances of the main network and DER, respectively. Based on (8), the grid contribution current through the upstream relay R_A is significantly dependent on the size and location of the DER unit and fault distance. This reduces the upstream fault current to lower levels because of the partial participation from the DER source. This participation impacts the relay functionality [35, 36].

4.4 Bidirectional power flow

In radial-configured power systems, electrical power flows in one direction, from the source toward consumption points. In contrast, MGs can introduce two-way current flow in power circuits after faults, dynamic changes due to local generation/consumption imbalances,

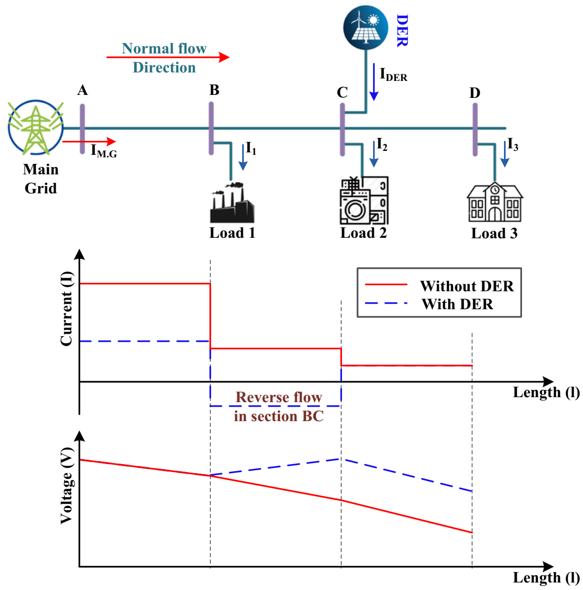

Fig. 8 Current and voltage profile along a distribution feeder with/without a DER source considering that $I_{DER} > I_2 + I_3$, considering that Loads are concentrated not distributed ones

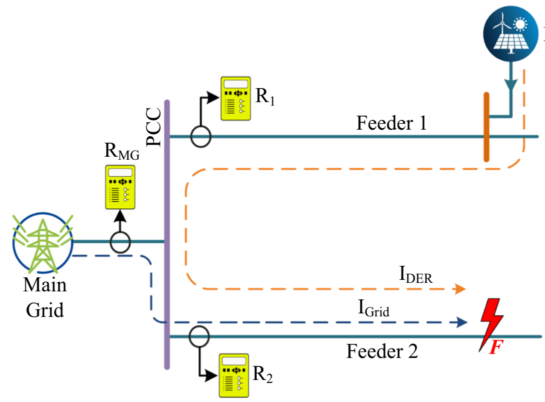

Fig. 9 False tripping (sympathetic tripping) concept

scheduled power exchange with the main grid, etc. This impacts the flow direction, current levels, and voltage profile, as shown in Fig. 8, which illustrates the RMS steady-state current amplitude and flow direction, as well as the voltage profile along different sections, with and without considering the effects of DER integration [6, 36]. In Fig. 8, the DER unit contributes to the generation-deficient area at the bus (B), creating a reverse stream of system current in section BC. Generally, the occurrence of reverse power flow in MGs can severely compromise the performance and coordination of conventional protective relays and increase voltage stress on system components, This must be considered when designing the protective relays [37].

4.5 Sympathetic tripping

False/sympathetic tripping generally occurs when a relay serves for a fault beyond its permitted zone after being triggered by a substantial current value, which violates the relay's reliability. This usually happens when a DER at a certain feeder contributes to a fault in another feeder where both feeders are attached to the same substation. As shown in Fig. 9, the relay R_2 is supposed to respond promptly to the fault (F). However, the increased contribution of the DER during this fault may substantially exceed the pickup value of R_1, causing R_1 to respond faster than R_2, resulting in inaccurate interruption of feeder 1 [38–40].

4.6 Selectivity and sensitivity

Selectivity and sensitivity are critical features of all protective devices. Selectivity refers to the ability of the relay to accurately detect and isolate the faulty object, while sensitivity refers to the ability of the relay to detect even the smallest fault and operate correctly without altering its selectivity properties [41]. However, in MGs, conventional overcurrent relays, in particular, have their pickup values determined by the nominal current and minimum fault current, both of which are greatly influenced by the operating mode of the MGs, as well as the size, location, and type of DERs (i.e. inverter-based or synchronous-based) [6, 41].

4.7 Islanding (loss of main)

Islanding or loss of main (LOM), occurs when the MG is detached from the main grid but still feeding its local needs via the connected DERs. Basically, LOM can occur intentionally or unintentionally, with deliberate islanding resulting from load shedding or maintenance activities, while accidental islanding is caused by faults in the main grid or the coupling breaker at the PCC, as shown in Fig. 2. Accordingly, significant deviations in system parameters such as voltage, frequency, and current level, among others, occur, affecting the protective relays and posing a risk to personnel and equipment [42, 43]. Thus the prompt detection of islanding events is crucial, typically within 2 s [6].

4.8 Deficiency of automatic reclosers

Auto reclosers (ARs) are commonly used in radial systems to clear temporary faults by disconnecting the downstream side of the AR due to the absence of back-feed, as shown in Fig. 10a, as opposed to transmission networks, which require the simultaneous seclusion of both ends of the faulted line to clear the fault [44]. MGs, in turn, operate similarly to transmission networks in

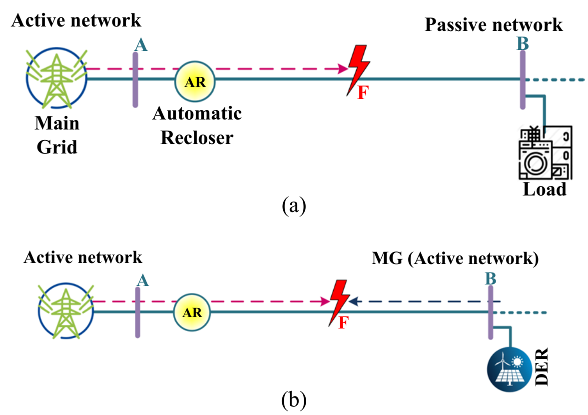

Fig. 10 AR basic operation **a** in radial networks, **b** in MG

that the fault is fed from both sides, namely the main utility and the DER, as shown in Fig. 10b, making the single-side interruption through the AR ineffective [14, 45]. Consequently, the prompt disconnection of the DER is crucial to revert to the radial configuration; otherwise, the temporary fault will be replaced by a permanent one, which reduces the AR functionality. The early disconnection of DER in the dead-time of AR as depicted in Fig. 11 is needed for proper operation [44].

In Fig. 11, the waveforms depict the operation of AR in Fig. 10b during the fault (F), where Fig. 11a represents the response of AR during the fault, while Fig. 11b, c reflect the circuit current and connectivity status of both the grid and DER, respectively. Figure 11 clarifies that the fault is initiated at (t_f) and it takes until (t_r) for the AR to detach the utility side, to consider the breaker separation time and arc extinguishing, at which point the recloser begins its dead time ($t_{R\text{-dead}}$). However, the fault is still back-fed from the DER, which is disconnected at (t_{disc}) to completely clear the fault for a period ($t_{interruption}$). After that, the AR only reconnects the utility side to start the reclaim time at (t_{con}) to see whether the temporary fault is cleared or still powered by the main grid, while the DER remains isolated until the system is completely healed.

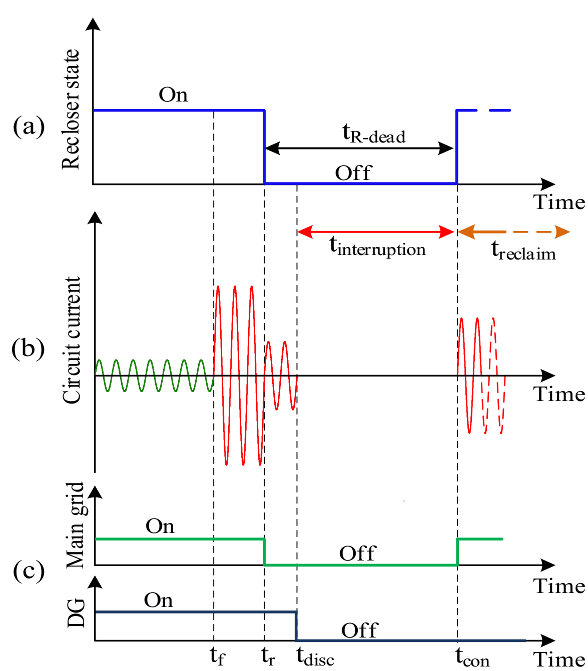

Fig. 11 AR response to the fault (F) in Fig. 10b

4.9 Asynchronous reclosing

Asynchronous reclosing is a normally expected activity when linking two active regions, as depicted in Fig. 10b, typically following fault events or MG islanding. Consequently, synchronization checking is indispensable when attaching active areas, to avoid harming the DERs and connected devices. It does this by preventing the parallel operation of multiple sources before synchronization [45, 46]. In most cases, after islanding, the detached region may witness frequency variation due to the mismatch of active power (i.e. $\sum \text{generation}, P_{DER} < \sum \text{load}, P_{load}$), causing it to run asynchronously with the utility grid. Figure 12 demonstrates a MG that initially operates in grid-connected mode at frequency f_s, before being entirely separated at (t_{island}), and then the islanded area frequency falls by Δf, forcing it to operate asynchronously at frequency f_i. Thereby, synchronization factors must be confirmed preceding the reconnection with the main grid, to avert multi-phase faults and deleterious consequences on facilities of both sides, notably rotating machinery, etc. [44].

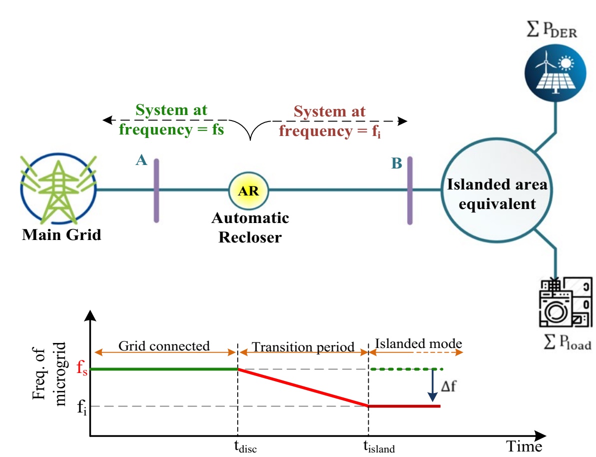

Fig. 12 Asynchronous reclosing of main grid and MG

4.9.1 Loss of coordination

Generally, relays are properly coordinated so the primary relay operates faster than the backup relay for a specific fault in order to maintain system reliability. Consequently, the operating time of the backup relay for the same fault must exceed that of the primary relay by a time slot known as "coordinating time interval (CTI) as in (9)," which varies from 0.2 to 0.5 s [47–49]:

$$t_{\text{backup}} - t_{\text{primary}} \geq \text{CTI} \tag{9}$$

where t_{backup} and t_{primary} are the backup and primary relay operating times, respectively.

As aforementioned, the participation of DERs in the system, particularly those that are synchronous-based, boosts the fault current magnitude and may also change its direction. This impedes the coordination protocol among overcurrent relays (OCRs). Accordingly, the operating time of inverse-characteristics-featured OCRs declines as the fault current increases. Thus, the minimum CTI margin cannot be fulfilled, compromising coordination between primary and backup relays. Figure 13 [47, 48] depicts the effect of increased fault current due to DER integration on both the operating and coordination timings. As observed, as the fault current increases, the primary relay may be unable to coordinate with the backup relays because of the reduction of the coordinating time (below the marginal CTI). Furthermore, if this current goes beyond the primary relay rating, it will malfunction and may even be damaged [47].

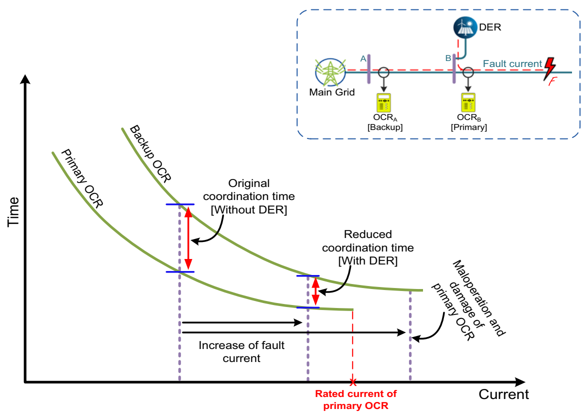

Fig. 13 Coordination relationship between relays

4.9.2 DER-interface transformer

Besides the challenges discussed in the preceding paragraphs, there are others already noted from traditional power systems, such as those caused by winding connections of transformers (Y_G, Y, and Δ) [32]. Although direct integration of DERs into power systems is attainable, they are commonly interfaced via power transformers to guarantee insulation coordination and the security of the associated facilities [50]. Consequently, this requires a precise selection of winding arrangements to limit their impact on the fault current path during ground faults, insulation coordination, triple-harmonics circulation, resonance events (i.e.,

Table 3 Winding configurations of interface transformers and associated protection challenges

Configuration		Advantages	Disadvantages
HV (utility-side)	LV (DER-side)		
Y_G	Y_G	Low ferroresonance sensibility in cable-fed applications System voltages in HV and LV sides are in-phase Mitigates TOV after ground faults on both sides	Permits circulation of triplen-harmonics (zero-sequence) on both sides Has an effect on relay coordination Permits the DER to feed ground faults in the utility zone and vice versa, which increases damage
Δ	Y_G	Prevents the DER to feed ground faults in the utility zone and vice versa. Blocks triplen-harmonics at DER side to flow in utility	Ungrounded side expose utility to TOV during ground faults Permits circulation of triplen-harmonics (zero-sequence) at DER side Highly sensitive to ferroresonance in cable-fed applications
Y_G	Δ	Blocks triplen-harmonics at DER side to flow in utility Prevents the utility to feed ground faults in the DER zone No TOV at utility side due to ground faults	Permits circulation of triplen-harmonics from utility which heating-up the transformer Participates in utility ground faults increasing the damage level Increases possibility of sympathetic tripping towards adjacent ground faults due to the transformer contribution Ground-relays settings are dependent on the existence of the transformer in service to keep proper coordination and sensitivity of relays

ferroresonance), overvoltage incidents (i.e., temporary overvoltages (TOV)), etc. Table 3 highlights the upsides and downsides of three typical winding connections from the protection standpoint [51–55].

5 Proposed techniques for protecting Ac-MGs

As previously stated, traditional protection schemes are inadequate for effectively protecting AC-MGs becaiuse of the significant variations in short circuit levels depending on the operating mode, DER type, etc. As a result, various strategies have been proposed in the literature to address these limitations. This section will review the advantages and disadvantages of some proposed approaches for protecting AC-MGs in a comparative framework. A schematic categorization of some strategies is provided in Fig. 14 to help in the readability and comprehension of this manuscript.

5.1 Traditional approaches

Traditional protection schemes have been successfully used in conventional power grids, but the integration of DERs has presented new challenges that can affect the reliability and functionality of these approaches. As a result, various strategies have been proposed in the literature to improve the philosophy and technology of traditional relays. This section briefly overviews some of these methods and summarizes their features in Table 4.

5.1.1 Adaptive protection

Adaptive protection refers to the capability of protective relays to adapt automatically to any changes in power systems by updating their settings via external signals, as depicted in Fig. 15 [56, 57].

In general, digital relays of different setting groups are more suited to this form of protection, together with intelligent controllers and efficient communication routes for sharing regulating signals in centralized or decentralized frameworks [58–60]. Reference [61] proposes a hybrid (centralized/decentralized) scheme using IEC 61,850-based smart electronic devices to reduce the computational burden and capabilities of controllers, whereas [62] employs a wide-area wireless network based on WiMAX concepts to alleviate data transfer uncertainties. In [63], a technique that relies on periodically gathered information, such as MG probable configurations, the status of circuit breakers, simulated abnormalities, etc., is used to build a database of novel settings and commands. The work in [64] suggests a strategy for optimizing the setting groups to determine the optimal pickup value and time-dial setting (TDS) of adaptive overcurrent relays using non-linear programming, while [65] employs linear programming for radial/meshed systems. The dual simplex approach is used in [66] to optimize both the TDS and operating time of relays by building a look-up table (LUT) that records network currents and relays parameters, which are all updated through a central protection system (CPS) to meet all probable setups and events. Reference [67] uses directional overcurrent relays with single and dual settings that are optimized using the interior point approach to accomplish effective relay coordination in networked MGs. In contrast, reference [68] employs ant colony optimization to optimize the operating time of primary and backup relays while keeping their selectivity. The study in [69] outlines an adaptive overcurrent scheme for ungrounded distribution systems based on local measures and real-time estimation of Thevenin's system parameters. It precisely calculates fault currents to re-configure the overcurrent relays according to the existing topology. An adaptive strategy based on two directional elements, i.e., overcurrent and undervoltage, is reported in [70]. This approach applies an online robust optimization strategy to tackle

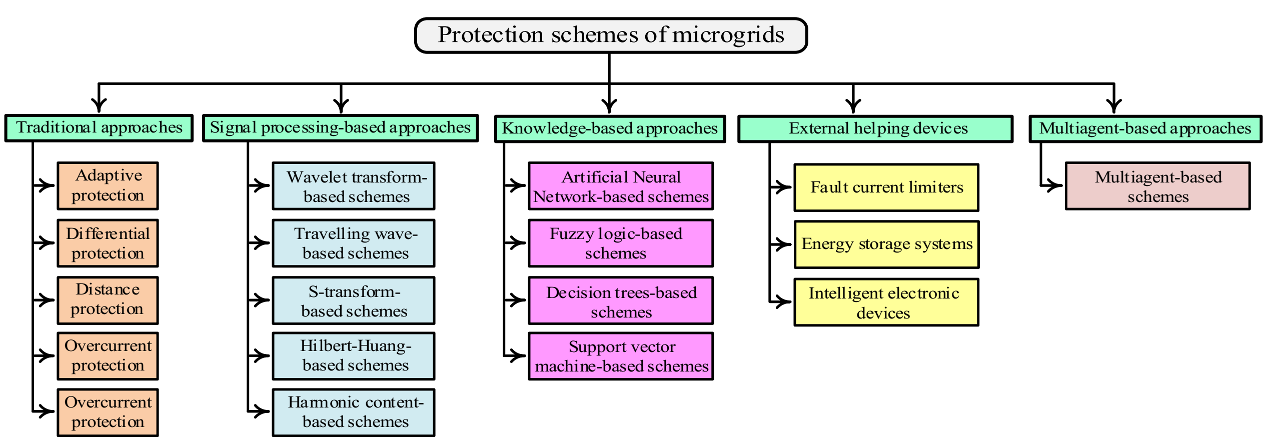

Fig. 14 Classification of AC-MG protection techniques

Table 4 Distinctive features of investigated traditional-based protection schemes

References	year	Citation	DER technology	Relay type/Required measures	Protection scheme	Features
[61]	2016	22	Synchronous and inverter based	Not reported	Adaptive	Simple Lessens computational burden of intelligent controllers
[62]	2013	48	Synchronous and inverter based	Not reported	Adaptive	Depends on wireless communication to transfer data
[63]	2018	4	Synchronous and inverter based	Overcurrent	Adaptive	Prepares new settings offline Mitigate communication challenges Specifies a reference to which all changes are attributed to identify new patterns
[64]	2015	144	Not reported	Directional overcurrent	Adaptive	Employs optimization techniques to optimize setting groups Setting groups can be calculated online or offline
[65]	2017	52	Synchronous based	Overcurrent	Adaptive	Independent TDS settings for MG operation mode Based on constraints reduction that makes it fast and simple
[66]	2015	8	Not reported	Overcurrent	Adaptive	Simple but need a huge database of simulated topologies Optimize operating times of relays using dual simplex algorithm
[67]	2020	21	Inverter based	Directional overcurrent	Adaptive	Directional overcurrent relays with single and dual settings are used. The interior point approach is used to adjust relay settings in order to achieve optimal coordination
[68]	2015	118	Synchronous and inverter based	Directional overcurrent	Adaptive	Ant colony optimization is employed to solve the non-linearity of directional overcurrent relays coordination Comparisons with Genetic algorithms are established The optimization phase is preceded by a sensitivity analysis to guarantee proper coordination, which significantly reduces the computational burden when discarding insensitive relay pairs
[69]	2015	102	Inverter based	Overcurrent	Adaptive	Relays settings are based on Thevenin's equivalent parameters Employs local data instead of communicated or GPS based one
[70]	2018	23	Inverter based	Overcurrent and undervoltage	Adaptive	Adopts a technique for defining primary/backup pairs to ensure appropriate coordination. Robust Optimization Strategy is applied to overcome variables uncertainty
[71]	2015	27	Synchronous and inverter based	Distance	Adaptive	Employs synchrophasors from PMUs Adopts Mho characteristics-based distance relay of 3 zones

Table 4 (continued)

References	year	Citation	DER technology	Relay type/Required measures	Protection scheme	Features
[74]	2013	41	Synchronous and inverter based	Current	Differential	Current differential based protection Optimizes relays locations and numbers The optimization issue takes into account the expenses of the protection scheme as well as customer interruptions; for both overhead lines and underground cables
[75]	2014	187	Inverter based	Current sequence components	Differential	High selectivity and sensitivity Uses symmetrical components of current Detects high impedance faults Suitable for islanded MGs with inverter-based DERs
[76]	2016	92	Inverter based	Positive sequence current	Differential	Suitable for islanded MGs Applicable for high impedance faults
[77]	2020	9	Inverter based	Negative-sequence impedance angle	Differential	Detects low/high impedance faults Based on difference of impedance angle (phase comparison) Discriminates fault and switching transient events Independent of DER type and fault impedance Applicable for asymmetrical faults only
[78]	2021	1	Inverter based	Positive-sequence impedance angle	Differential	Detects low/high impedance faults Based positive sequence phase comparison Employs DFT to estimate impedance angle Independent of DER type, fault impedance, and fault type
[79]	2018	3	Inverter based	Voltage angle	Differential	Based positive voltage angle comparison Optimal placed PMUs are used to estimate voltages angles
[80]	2016	13	Inverter based	Instantaneous power	Differential	Applies Fuzzy with Hilbert space logics Operates after fault inception by less than two cycles Handles CTs saturation and data mismatch Based on active/reactive power differences to detect faults Simple and high computational efficiency
[81]	2017	198	Synchronous and inverter based	Current and voltage measurements	Differential	Differential features are estimated using DFT are employed Showed high dependability, security, accuracy for radial/mesh and connected/isolated topologies. Response time is close to 0.5–1 cycle

Table 4 (continued)

References	year	Citation	DER technology	Relay type/Required measures	Protection scheme	Features
[82]	2018	144	Synchronous and inverter based	Current measurements	Differential	Differential features are estimated using HHT are employed Three distinctive differential features are used: phase current energy, standard deviation of phase current, and zero-sequence current energy Three distinct machine learning models are evaluated. Showed high dependability, security, accuracy for radial/mesh and connected/isolated topologies
[83]	2013	190	Inverter based	Fault current energy	Differential	Based on time–frequency transform (S-transform) Adaptive thresholds are required to handle MG layouts and fault conditions, etc. Slow response time of 4 cycles High computational burden
[84]	2016	132	Inverter based	Fault current energy	Differential	Based on time–frequency transform (HHT-transform) Adaptive thresholds are required Threshold setting is easier than S-transform, in which the differential energy is not steep
[87]	2020	1	Synchronous and inverter based	Harmonic voltage and current signals	Distance	Implements high-frequency voltage and current to estimate apparent impedance to fault Considers fault resistance and infeed effects
[89]	2018	5	Not reported	Voltage and current at one end	Distance	Employs a directional feature to handle false tripping The trip area is adjusted to solve blinding events Does not consider relays coordination nor reach
[90]	2015	41	Synchronous and inverter based	Voltage and current at one end	Distance	Zone settings are DERs-infeed dependent Coordination among different relays is adopted Reflects high selectivity and sensitivity
[91]	2018	56	Inverter based	Voltage and current at beginnings of all feeders	Distance	Uses π-line model parameters Each line is studied separately Iterative, resulting in a long computing time
[92]	2019	17	Synchronous and inverter based	Voltage and current phasors at main buses	Distance	High impedance faults are undetectable Based on local measurements Low computational burden since the feeder is only investigated if admittance phase and/or amplitude are changed Recommended only for small MGs
[96]	2020	9	Not reported	Voltage and current data at relays	Overcurrent	Simple Improves relay speed and coordination System configuration is reflected through a compound factor in the operating time of the relay Handles fault types and different operating modes effectively

Table 4 (continued)

References	year	Citation	DER technology	Relay type/Required measures	Protection scheme	Features
[97]	2012	131	Inverter based	Current measures at DERs	Overcurrent and overload	Exploits voltage controller response after faults to decide fault conditions Signals noise sensitivity High computational time *Overcurrent protection objectives:* Fault current limitation Controller restoration following fault clearing *Overload objectives:* Regulating the output power of the DER
[100]	2016	58	Synchronous based	Voltage and current data	Directional overcurrent	Reduced operating time owing to the relay dual-setting Uses system currents as the operational amount, while the fault transient energy sign acts as the directional element Addresses DER plug-and-play and high impedance problems
[101]	2018	57	Not reported	Voltage and current data	Directional overcurrent	Single/dual setting DORs share the protection Coordination problem is optimized which ensures a better and accurate operation of relays Operating time of relays is improved
[102]	2019	43	Synchronous and inverter based	Voltage and current data	Directional overcurrent	Two separate coordinating parameters are provided according to the mode of operation Genetic algorithms provide better performance than particle swarm
[103]	2021	12	Inverter based	Actual system current with injected harmonic current	Directional overcurrent	Employs two different operating quantities for DORs: actual and harmonic currents Applicable for islanded/grid-connected modes Simple coordination process Relays coordination is based on the variance of operating quantity of DORs
[104]	2006	207	Inverter based	Voltage data	Voltage relay	Relies on abc/dq transformation Relay sensitivity depends on the threshold value High impedance faults are ignored
[105]	2020	18	Synchronous and inverter based	Voltage data	Voltage relay	Only one cycle of disturbed voltage waveform is processed Low computational time (typically 2 cycles) High impedance fault is a limitation High immunity against noise
[106]	2020	24	Synchronous and inverter based	Voltage phasors	Voltage relay	High computational burden Relay sensitivity depends on the threshold value False action due to high impedance faults High selectivity

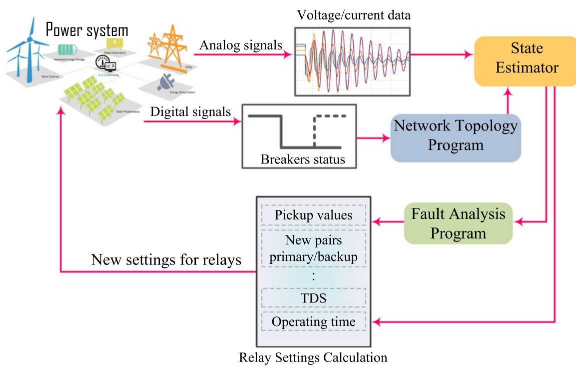

Fig. 15 Adaptive protection philosophy

parameter uncertainties when tuning relays for varied operating circumstances. The scheme is mainly based on two essential modules, those of monitoring and protection adjustment, where the former assesses the operational state of all power sources to recognize normal/abnormal occurrences and then communicates to the second module to determine the right relay settings. Reference [71] suggests an adaptive distance scheme of Mho characteristics, outperforming adaptive overcurrent and differential strategies in terms of sensitivity and selectivity when using real-time data from phasor measurement units (PMUs).

5.1.2 Differential protection

Differential protection is a unit/pilot scheme that works whenever the difference between two or more comparable electrical values surpasses a certain threshold. Figure 16 depicts a current-differential protection scheme in which system currents at both ends of the protected line are measured and then compared through the differential relay to investigate abnormalities within the protected area [72, 73]. Generally, differential protection schemes provide a better degree of selectivity and sensitivity, while their reliance on data communication between the ends of the protected equipment supports them in protecting the MGs. In [74], a genetic algorithm is implemented to optimize the number of relays and their zones to identify MG faults, using current differential protection. Reference [75] recommends a differential scheme based on sequence components (positive, negative, and zero) and data mining concepts to adjust relay settings to handle low fault currents caused by high impedance faults and/or inverter-based DERs, while the study in [76] employs only positive-sequence current as a differential feature.

Reference [77] suggests a fault detection scheme based on the differential negative-sequence impedance angle between both ends of the protected line for identifying low and high impedance asymmetric faults as shown in Fig. 17. In contrast, reference [78] employs the positive-sequence impedance angle to detect all fault types, symmetric and asymmetric, while [79] uses positive-sequence voltage angles at protected line terminals. The work in [80] proposes a differential scheme based on instantaneous power differences between protected line terminals using a fuzzy algorithm with Hilbert space theory to recognize fault occurrences.

A data-mining-based differential methodology for MGs is given in [81]. It uses a discrete Fourier transform (DFT) to extract some distinctive differential features (e.g., rate of change of frequency, voltage, active power, reactive power, power angle difference, negative sequence voltage, and negative sequence current) for data-mining models that decide fault events. Similarly, the study in [82] uses the Hilbert–Huang transform (HHT) and machine learning algorithms, where the HHT is used instead of the DFT to compute the differential features from current measures to be fed into machine learning algorithms to define the fault instances. Reference [83] presents a differential energy-based protection approach that uses a time–frequency transform (S-transform) to estimate the spectral energy contents of fault currents at both ends of the protected line, whereas [84] uses then HHT instead of the S-transform. Both [83] and [84] employ differential energy to identify fault events and the predefined

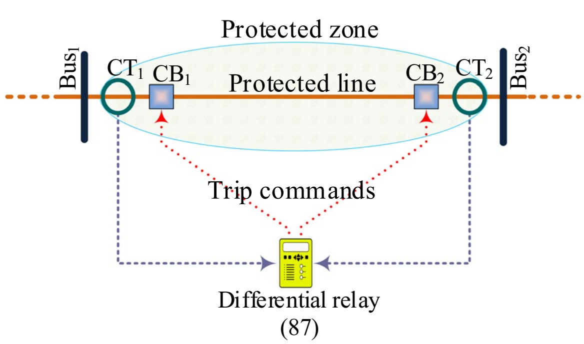

Fig. 16 Current differential protection scheme

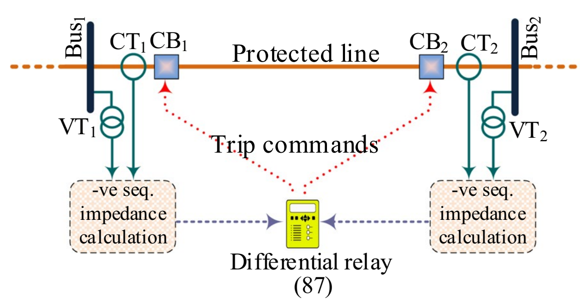

Fig. 17 Negative-sequence impedance angle differential protection

threshold value is adapted to match all probable modes of MGs and fault scenarios [83, 84].

5.1.3 Distance protection

Distance protection is a highly selective scheme for power systems. one that detects fault incidences based on the measured impedance at the relay point [85, 86]. In such approaches, the currents and voltages of the protected line at one or both ends are recorded to compute the apparent impedance to the relay, as described in (2). This is then compared to the preset settings to detect the fault [10, 30]. Distance relays have diverse characteristics and different patterns on the R/X diagram, such as impedance, resistance, mho, reactance, quadrilateral, and blinders. For time-settings, each distance relay typically covers six/seven zones, including one instantaneous zone and up to five/six time-delayed zones [18, 86]. Figure 18 shows the time settings for different distance relays in the depicted system, with R_{12} as an example having three settings: an instantaneous setting (zone$1_{(R12)}$), and two time-delayed settings with different time delays and reaches (zone$2_{(\mathrm{R12})}$ and zone$3_{(R12)}$). R_{32} is shown with three time-setting zones: instantaneous and two time-delayed ones, while R_{23} is depicted with only an instantaneous and a time-delayed zone. It is worth mentioning that the number of actual zones and associated time delays are defined according to design and technical requirements.

The study in [87] proposes a distance-based protection technique for inverter-based MGs using high-frequency current/voltage signals. This method employs the ability of controllers of inverter-based DERs to generate harmonic currents of different orders (*h*). Accordingly, fundamental and superimposed harmonic currents stream together in the circuit once a fault is initiated. Given that only the inverter-based DER can supply harmonic current, the remaining system components are modeled as passive elements in the h-harmonic domain, mimicking a conventional system. This eliminates the effect of the infeed current of multiple sources in addition to fault resistance when compared to system reactance that is magnified by the harmonic order (*h*) [88]. Another scheme in [89] addresses sympathetic tripping and blindness concerns, where a distance-based protection strategy characterized by two features is suggested: directionality and adaptability of the trip area. However, it neglects the coordination philosophy and the impact of high impedance faults and DER infeed percentage on the relay reaches. Reference [90] develops a mho-characteristic distance relay in which the time-distance settings are upgraded to be reliant on the infeed percentage of DERs (adaptive logic) rather than their absolute values by considering a counterbalancing factor for DER infeed. In [91], an impedance-based technique based on the π-line model is proposed to derive a quadratic equation as a function of fault distance. Once a fault has occurred, all lines are eligible for fault location, and thus an iterative procedure is used to examine all lines to track the fault based on the estimated distance. This provides a valid location if it is not greater than the length of the investigated line; otherwise, another section is then evaluated. Reference [92] develops a fault detection technique for MGs based on monitoring the changes in magnitude and phase difference of bus admittances to consider the protection of bus loads, not only interconnecting lines [92, 93].

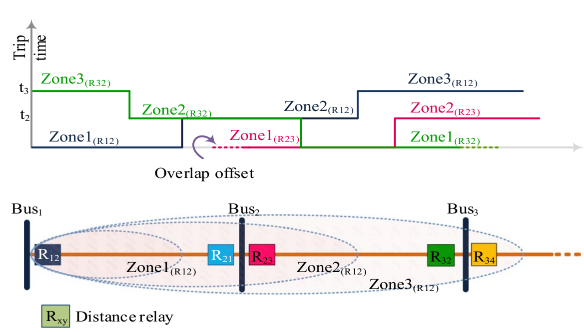

Fig. 18 Zone settings of distance relay

5.1.4 Overcurrent-based protection

Overcurrent relays are among the most effective devices in conventional networks. They are, however, prone to various challenges in MGs depending on the operating modes of the MGs, DERs technologies, etc., all of which affect the amount and/or direction of short circuit current, and may mislead overcurrent relays with conventional settings [94, 95]. Accordingly, the concepts of adaptive relaying, in which relay parameters are upgraded dynamically based on network conditions and fault current level, are employed in MGs. In [96], another philosophy is discussed based on a composite acceleration coefficient and a beetle antennae search optimization approach. The suggested scheme not only improves the protection coordination but also significantly boosts the operating speed of the relay. In this scheme, a distinct factor (K_{vi}) depending on system voltage and measured impedance during fault is embedded into the operating time formula of an inverse-time over current relay (ITOCR), to accelerate its response, as described in (10). Then, the beetle antennae search algorithm is employed to enhance the coordination framework and further parameters i.e., pickup settings, TDS, and shape coefficients of relay curves.

$$t_{op} = \underbrace{\left(\frac{A}{\left(\frac{I_f}{I_p}\right)^{\alpha} - 1} * TDS\right)}_{\text{Standard operating time of ITOCR}} * \underbrace{K_{vi}}_{\text{Voltage - impedance composite acceleration coeff.}} \tag{10}$$

where t_{op} is the relay operating time, A represents a constant coefficient, TDS reflects the time dial setting, α is the ITOCR curve shape coefficient, while I_f and I_p indicate fault and pickup currents, respectively.

Reference [97] adopts overcurrent and overload protection schemes for islanded MGs that depend on voltage-controlled DERs. Since the DER terminal voltage drops once the fault occurs, the voltage controller raises this voltage value to a specific amount, causing the current to reach a higher level that activates the overcurrent relay, whereas overload protection restricts the DER output to a safe limit when a larger demand is desired.

In the context of the aforementioned overcurrent-based protection methods, reverse power flow in MGs owing to fault events remains problematic. A directional overcurrent relay (DOR) offers a robust option for such issues by upgrading the tripping philosophy of typical overcurrent relays to consider both the magnitude and direction of the fault current before releasing any trip commands [98, 99]. In [100] a dual-setting directional overcurrent relay-based intelligent protection scheme is described for islanded MGs. This technique uses voltage and current measurements to compute the transient energy caused by the fault event, and its sign is used as a directional indicator, ensuring a precise direction independent of network topology. The consequences of DER plug-and-play, high-impedance faults, and insufficient power production due to DER shutdowns are then evaluated. In [101], a combination of single-and dual-setting DORs is used to protect the mesh-configured MGs, where a particle swarm algorithm is employed to define the optimal number of dual-setting DORs and their settings to reduce the operating time of all relays. In contrast, reference [102] only employs single-setting (traditional) DOR to protect islanded and grid-connected MGs. To address the non-linearity of the protection coordination problem, a genetic algorithm is used to determine relay parameters such as the time multiplier, plug-setting multiplier, and relay curve coefficients. A novel directional overcurrent approach based on the harmonic current injection ability of converter-based DERs is suggested in [103]. The operational signal in this scheme uses the system actual current for grid-connected mode or with synchronous-based DERs, whereas the harmonic current is employed for islanded mode with inverter-based DERs. This current decoupling makes coordination among primary and backup relays easier for both modes of operation. The directional element, in turn, is based on a normalized harmonic current factor instead of current/voltage phase angles.

5.1.5 Voltage-based protection

Voltage dip is typically induced by faults, overloading, or large motor startup, whereas overvoltage events are caused by lightning, capacitor energization, large-loads switching off, ferroresonance, insulation failures, etc. The integration of DERs impacts the voltage level because of reversal power flow, generation-load imbalance, etc. Accordingly, overvoltage and undervoltage relays are implemented in MGs [18]. In [104], a robust technique is developed for detecting internal and external failures based on transforming the DER terminal voltage using the *dq* reference frame into DC values. Consequently, fault occurrences may be identified smoothly when the terminal *dq* voltages are compared to predefined reference values, as illustrated in Fig. 19.

The study in [105] uses a short-time Fourier Transform to assess voltage depression events by extracting some distinguishing features, typically nine for symmetrical faults and another six for asymmetrical faults. All features are then used as input variables to a decision tree algorithm to distinguish real faults from other normal conditions such as overloading, capacitor switching, etc. An improved scheme based on voltage synchrophasors from PMUs is discussed in [106], in which two fault detection indices are estimated from voltage phasors at each busbar. One index is based on differential active and reactive power (ΔP and ΔQ), voltage magnitude, and phase changes (ΔV and Δδ), while the other relies on different sensitivity coefficients (ΔP/ΔV), (ΔP/Δδ), (ΔQ/ΔV), and (ΔQ/Δδ), and then both coefficients are compared with the threshold values for detecting a disturbance. However, most voltage-based protection schemes are only applicable for particular topologies of MGs because of their limitations with high impedance faults, distinguishing momentary from permanent voltage depression events, as well as complicated data processing in large grids, e.g., Park transformation,

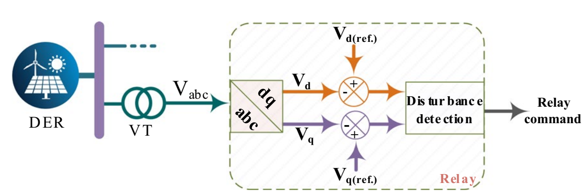

Fig. 19 Voltage disturbance detection based on abc-dq (Park's) transformation

etc. Therefore, MGs commonly implement voltage-based relays as backup protection devices [72, 86, and 107]. Table 4 presents the previously examined works in a comparative context, indicating the publication year and the number of citations per document. It also refers to the generation technique of DERs. These can be synchronous or inverter-based. In addition, the relay type and essential data for executing the proposed protection methods are recorded, as well as the major aspects of each technique.

5.2 Signal processing-based approaches

As a result of the significant changes in system parameters due to fault incidents, system output signal patterns are correlated to such failures and their features. Thus, signal-processing-based fault detection algorithms can be adopted for both traditional and MG systems. In such strategies, some distinguishing characteristics are extracted from system signals to be processed using various signal-processing schemes, such as Wavelet transform (WT), traveling waves (TWs), Stockwell transform (ST), etc., to define the fault situations [98]. This section briefly discusses some of these techniques, with features summarized in Table 5

5.2.1 Wavelet transform-based schemes

Unlike the Fourier transform or short-time Fourier transform, WT is a signal processing tool that analyses non-stationary signals into the time–frequency domain using an adjustable data window for better resolution. Wavelets have been employed in various fields, such as data compression, transient analysis, image processing, time–frequency spectrum estimation, etc. [98, 108]. In power engineering, WT has been used to identify fault events by capturing the transient components holding fault data from the system disturbance signals. Consequently, the extracted transients are then broken into a sequence of wavelets, each of which refers to a time-domain signal covering a particular frequency band with certain information [109].

Reference [110] employs discrete WT and decision trees to detect high-impedance faults in MGs. In this strategy, fault currents are pre-processed using discrete WT to reveal some discriminating time–frequency information, which is then used to train the decision tree to identify high-impedance faults from normal conditions. Another scheme suggested in [111] uses an integration of both WT and data mining (decision tree) to detect and classify the faults. Fault current signals at relay locations are decomposed using WT to derive basic features such as mean, standard deviation, entropy, change in energy, etc., to train the decision tree to detect all possible failures. The fault current sequence components are also analyzed using the WT to extract different properties to train the decision tree to classify the fault type. In [112], voltage and current total harmonic distortion indices are extracted using WT to train a random forest (RF) classifier, a data mining method, and reactive and active power negative-sequence components to identify and categorize fault occurrences. In this scheme, the RF classifier is subjected to a diversified input dataset for efficient training by varying fault type, location, resistance, inception timings, as well as capacitor switching and load fluctuation events. The work in [113] combines Park's transformation and WT to detect faults in MGs. This method converts system voltages or currents to the *dq0* reference frame before being processed using WT to extract the required parameters for fault detection.

5.2.2 Travelling wave-based schemes

After a fault occurrence in power lines, electromagnetic waves are produced at the defect point, propagating in both directions at nearly the speed of light, providing high-speed communication of fault data at line end/ends for later analysis. In general, TWs-based detection schemes can either use the naturally generated signals at the fault location or those externally injected after fault inception to recognize fault events. Figure 20 demonstrates the traveling waves with different timings of reflection and refraction on the lattice diagram [30, 114].

The study in [115] employs TWs to detect single line-to-ground (SLG) faults in MGs based on the polarities of initially recorded current and voltage waves at line terminals. Forward-oriented relays are then operated with a specific coordinating time dependent on their position to isolate the fault, similar to directional overcurrent protection. Reference [116], in turn, proposes a high-speed fault detection approach for inverter-based MGs using current TWs following fault incidence. The approach considers wave magnitude and timing and polarity data to eliminate magnitude inaccuracies induced by fault location, type, resistance, and initiation time. In [117], a TW-based scheme is suggested for detecting faults in MGs using local measurements and some exchanged data with adjacent protection devices. This scheme detects internal faults based on the extracted data from fault current traveling waves using WT.

5.2.3 S-transform based schemes

S-transform is a time–frequency representation of non-stationary signals that combines the positives of short-time Fourier transform and WT for a satisfactory time–frequency distribution. The S-transform can be

Table 5 Distinctive features of investigated signal processing-based protection schemes

References	Year	Citation	DER	Required measures	Method	Features
[110]	2016	20	Synchronous and inverter based	Fault current	WT and decision tree	Twelve statistical features such as: mean, standard deviation, energy, entropy, etc., are extracted from fault current decomposition to train the decision tree High impedance faults are detectable Requires offline training, and high computational burden
[111]	2016	260	Inverter based	Actual and sequence components of fault current	WT and decision tree	Nine features are used for fault detection, while fifteen for fault classification 70% of input data are used for training, remaining 30% for testing High computational burden due to required trainings Low-impedance faults are only used for training
[112]	2021	10	Synchronous and inverter based	Voltage and current data	WT and random forest	Random forest is used as a data mining tool to accurately process a large input database, unlike the decision tree. 75% of input data are used for training, the remaining for testing Considers DERs outages and fault initiation periods Robust against measurement noise Requires high capability software for training
[113]	2017	35	Synchronous and inverter based	Voltage or current data	WT and park's transformation	The d-q voltages/currents feed wavelet model Not preferable for high-impedance faults High sampling frequency, and low accuracy Large time response for data processing Detection signal is delayed to distinguish false faults
[115]	2019	19	Not reported	Voltage and current waves	TWs	Fault is detected based on traveling waves polarities Considers zero-sequence voltage to avoid false detection Considers fault inception time, type, and resistance Applicable for SLG faults in non-effectively grounded systems
[116]	2014	123	Inverter based	Fault current wave	TWs	Low-bandwidth communication is employed for high-speed operation Stable during normal transients i.e. motor starting Considers traveling wave amplitude, timing, and polarity for accurate detection

Table 5 (continued)

References	Year	Citation	DER	Required measures	Method	Features
[117]	2017	5	Synchronous and inverter based	Local currents and fault current wave	TWs	Detect fault based on WT of the traveling wave, while zone classification relies on wave signs Applicable for close-in faults Stable during switching transients and external abnormalities
[121]	2022	2	Synchronous and inverter based	Currents at both ends of line	S-transform-based differential current	Varied threshold value with the operating mode and fault impedance, i.e. high impedance fault. High impedance faults are detectable Robust against measurement noise
[122]	2021	10	Inverter based	Current and voltage data	S-transform-based distance relay	Fault energy is used as a fault indicator, while distance relay defines trip timings. Low computational burden High impedance faults are addressed
[123]	2014	15	Synchronous and inverter based	Currents at both ends of line	S-transform and decision tree	Low computational burden Fast response (1–1.5) cycle Requires offline training
[126]	2021	8	Synchronous and inverter based	Currents at both ends of line	Hilbert–Huang transform	Low required time for fault detection and classification processes Limited to fault impedance larger than 1000 Ω Self-adaptive threshold: large in normal conditions and decreases with faults
[82]	2018	144	Synchronous and inverter based	Current measurements	Hilbert–Huang transform	Three distinctive differential features are used: phase current energy, standard deviation of phase current, and zero-sequence current energy Applicable for high-impedance faults Machine learning model uses 70% of input data for training, remaining 30% for testing Offline training is needed
[127]	2008	120	Inverter based	Voltage data	Harmonic content-based	THD value is dependent on network configuration Individual values of THD are used to classify fault type Applicable only for identical DERs High impedance faults are not investigated
[128]	2016	13	Inverter based	Harmonic current (5th harmonic)	Harmonic content-based	Inverter-based DER injects harmonic currents Not applicable for high-impedance faults Inaccurate in a harmonic rich system

Table 5 (continued)

References	Year	Citation	DER	Required measures	Method	Features
[129]	2022	1	Inverter based	Multiple Harmonic components	Harmonic content-based	Multiple harmonics injection ameliorates sensitivity Reliable and low-cost due to communication-free protocol Injected harmonic component has a magnitude of 10% of fault current Each inverter injects a distinct harmonic content Detects high-impedance faults
[130]	2018	4	Inverter based	Voltage and current data Harmonic current	Harmonic content-based	Optimized coordination settings using Particle Swarm Optimization Only low-impedance faults are verified Avoids resonance conditions when selecting the injected harmonic

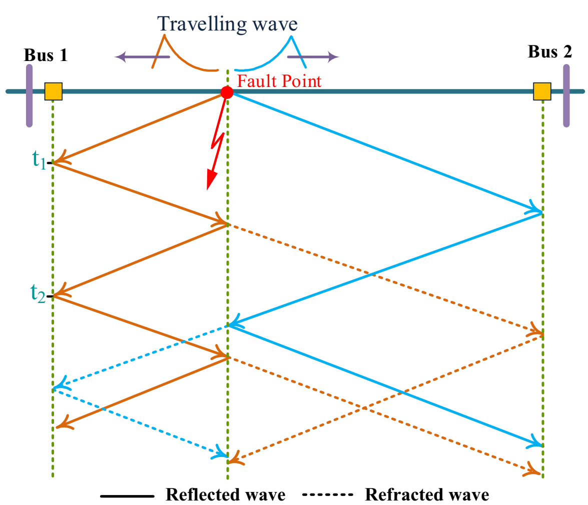

Fig. 20 TW-based protection approaches

considered as a phase-corrected WT, thereby offering more precise data on the local features of a signal in the time–frequency domain [118–120]. In [121], a protection scheme is suggested for radial/meshed MGs using differential protection and S-transform concepts. The differential currents of protected line terminals and differential fault energy (E_{diff}) are calculated as:

$$I_{diff} = I_x - I_y \tag{11}$$

$$E_{diff} = (I_{diff})^2 \tag{12}$$

where I_{diff} is the differential current between line $(x-y)$ terminals, and I_x and I_y are currents at bus (x) and bus (y), respectively. The S-transform is applied to the

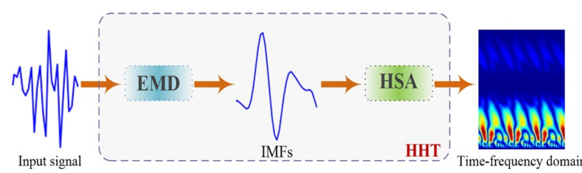

Fig. 21 HHT schematic

differential energy, E_{diff}, to define the peak value of the resultant curve, which is then compared to a specified threshold to identify fault situations. The S-transform is also considered in [122] to enhance the functionality of distance protection-based schemes in MGs. In this incorporated module, fault current energy is estimated using the S-transform to define a fault detection indicator, namely S-energy, which is almost flat under normal conditions but increases during disturbances. Voltage and current samples are then employed to identify fault directionality to trigger the distance relay. This defines the zone settings and related time delays. Work in [123] discusses a hybrid S-transform and data mining-based protection scheme. In this strategy, fault currents at both ends of the protected feeder are processed using the S-transform to reveal some differential features between both terminals, such as median, mean, energy, standard deviation, etc., to train the decision tree model and to detect and classify faults in MGs regardless of their operating mode.

5.2.4 Hilbert–Huang-based schemes

The Hilbert–Huang transform (HHT) is a time–frequency-based approach for processing nonlinear and non-stationary time-series data based on two subsequent algorithms: Empirical mode decomposition (EMD) and Hilbert spectral analysis (HSA), where the first algorithm, EMD, processes the input signal of mixed frequencies to extract a set of finite components, namely intrinsic mode functions (IMFs), which are then used to compute the instantaneous frequency signal through HSA, as illustrated in Fig. 21 [124, 125].

In power systems, voltage and current signals are applied to EMD to retrieve the intrinsic mode functions. HSA then processes the instantaneous magnitude, phase angle, frequency, etc., to determine fault incidents [48]. A self-adaptive scheme for identifying and categorizing faults in MGs is proposed in [126]. HHT decomposes fault currents at protected line terminals to extract the instantaneous differential phase, which is compared to a pre-defined threshold to decide the fault, whereas the zero-sequence component of fault current is employed to categorize the fault type. Another strategy discussed in [82] uses a combination of both HHT and machine learning to detect the faults in MGs. Fault current signals are pre-processed by HHT to capture fault detection features such as standard deviation, change in energy, etc., to feed a support vector machine, a machine learning model, to decide fault conditions.

5.2.5 Harmonic content-based schemes

The integration of inverter-based DERs has raised harmonic levels in MGs. Accordingly, different strategies for protecting MGs based on harmonics analysis have been recently proposed. In [127], the total harmonic distortion (THD) of terminal voltages of inverter-based DERs is used to identify faults when exceeding a predefined threshold value., as THD is almost null ($\text{THD} \approx 0$) under normal conditions and increases under fault situations because of contributions from the fault current. Also, the THD values of each phase, besides their fundamental frequency, are employed to classify fault types. Injected fifth-harmonic current is employed in [128] to define faults in MGs, in which the injected component activates related digital relays to decide the fault event when it surpasses a specified value, overcoming the insensitivity of traditional relays to low fault currents in islanded MGs. In contrast, reference [129] suggests a communication-free protection scheme based on injecting multiple harmonics to recognize faults in grid-connected and islanded modes. Once the fault is detected, all the inverter-based DERs reduce their current contribution and deliberately inject a particular harmonic component to trigger the protective relays. The study in [130] proposes a combined protection scheme based on harmonics injection and machine learning to detect and isolate faults. In this approach, the output signals of DERs, i.e., voltages and currents, are decomposed using a support vector machine (SVM), a machine learning model, to extract some distinct features to decide fault occurrence. From this the DERs with the lowest voltages, closest to the fault, inject high-frequency currents to enable the harmonic-based relays to operate in coordination. As a summary, Table 5 compares the previously analyzed publications in terms of publication year and citations of each work. Also, it refers to the DER types, the main measurements for implementing the offered strategy, besides the distinct objects of each technique.

5.3 Knowledge-based approaches

Artificial intelligence and machine learning-based protection strategies (e.g., artificial neural network (ANN), Fuzzy logic (FL), genetic algorithm (GA), decision tree (DT), support vector machine (SVM), Random forest (RF), Naive Bayes algorithm) have been widely used in protecting MGs to address the challenges of network complexities and data uncertainties. Essentially, these techniques need a wide range of data, such as system measurement (voltage, current, frequency, power, etc.), the status of breakers, protective devices profile, ambient conditions, and so on [35, 46]. Nevertheless, such techniques' performance and processing time should be considered for rapid and reliable fault detection and categorization [98]. Some of these techniques are briefly described below, while Table 6 illustrates the key elements of the methodologies investigated.

5.3.1 Artificial Neural Network-based schemes

Reference [131] uses a combination of discrete WT and deep neural networks to detect and categorize faults in MGs. Initially, system currents are pre-processed using WT to extract some evaluation metrics, which are then employed as inputs to three neural networks to detect, classify and locate the faults. The study in [132] suggests an adaptive protection scheme based on overcurrent and distance relays, with their settings upgraded using a combined ANN and SVM model. Once the fault is detected, system measurements are directly transmitted to the ANN model to validate the fault occurrence, and if confirmed, the SVM model is then applied to pinpoint the fault and update the relay settings. In [133], a protection scheme is proposed for autonomous MGs using ANN and transient monitoring functions (TMFs), where the fault is identified based on TMF values of the current waveform, while ANN is then employed to categorize the fault type.

Table 6 Distinctive features of investigated knowledge-based protection schemes

References	Year	Citation	DER	Required measures	Method	Features
[131]	2017	216	Synchronous and inverter based	Current data	ANN with WT	Robust against measurement noise and uncertainty High computational burden due to training process Accuracy varies with system configuration
[132]	2019	74	Synchronous and inverter based	Voltage and current signals	ANN-SVM-based overcurrent and distance protection	Adaptive. Self-learning, and self-training High computational burden Complex implementation High accuracy
[133]	2019	13	Inverter based	Current data	ANN	Uses TMF to discern temporary/permanent faults. Improves auto-recloser functionality by discriminating permanent/transient failures. Requires less computing time Online training is feasible
[134]	2018	14	Inverter based	Current data	Fuzzy logic	Two Fuzzy logic models for firstly deciding operating mode, and then detecting/classifying internal faults of MG Response time is about 0.25 – 1 cycle Simple and feasible implementation Robust against DERs outages and load variation
[135]	2015	33	Synchronous and inverter based	Current data	Fuzzy logic and decision tree	High computational burden due to decision tree training Large number of extracted features Response time is about 2.25 cycle High impedance faults are detectable
[136]	2018	46	Inverter based	Voltage and current signals	Type-2 Fuzzy logic	Addresses data uncertainties Identifies fault and its direction Low computational burden No need for training
[139]	2018	18	Inverter based	Voltage and current signals	Bagged decision tree	Considers changes in load, generation, and fault resistance Applicable for high impedance faults Robust against data noise Large dataset for tree training High computational burden due to training
[141]	2017	20	Synchronous and inverter based	Voltage and current signals	SVM and WT	Considers changes in fault resistance, location, and initiation timing High computational burden due to training process Applicable for high impedance faults Fault classification accuracy nears 95.5%

5.3.2 Fuzzy logic-based schemes

The study in [134] proposes an intelligent FL-based protection scheme for detecting and classifying faults for MGs. This scheme initially decides the operating mode of the MG through the phase angle of positive-sequence current and FL, thereby confirming the islanding mode for utility faults (external faults) or grid-connected mode for MG internal faults. Subsequently, both the fundamental and zero-sequence currents are provided as inputs to the proposed fuzzy model to identify and classify the fault in the MG. In [135], DTs and FL are integrated to provide a relaying scheme for MGs. One cycle of the fault current, directly after fault inception, is processed using the S-transform to extract some distinct parameters to train the DT, whose outputs are used as inputs to the fuzzy model for the final fault decision (detection and classification). In this scheme, fuzzy rules are employed to relax DTs' crisp (sharp) logic. In [136], a type-2 Fuzzy logic (T2FL) is employed to address the data uncertainties for providing a reliable protection scheme. In this scheme, voltage and current signals are pre-processed to provide required inputs to the T2FL module, which contains two T2FL subsystems, one for detecting/classifying faults and the other for identifying the fault direction concerning the relay.

5.3.3 Decision trees-based schemes

DT is a supervised machine learning algorithm used for the regression and classification of large amounts of data. As seen in Fig. 22, decision trees are hierarchically organized, comprising three types of nodes (a root node, internal nodes, and leaf nodes), that are connected by branches. A decision tree often begins with a basic node (root node), then branches into many outcomes, each of which leads to other nodes (internal nodes), which divide into further alternatives until reaching terminating conditions (leaf nodes). Essentially, the branching process is executed by selecting the attribute that maximizes the information gain factor or lowering the Gini impurity factor, as detailed in [137, 138].

In power systems, voltage and current signals are usually processed using time–frequency signal processing tools to extract associated characteristics to fault occurrences, which are subsequently used for training the DT for fault detection/classification. In [110, 111], WT is integrated with DT to detect/classify faults in MGs, where distinct features, i.e., mean, standard deviation, change in entropy, and change in energy, are used to train the tree, while [123] employs the S-transform for feature extraction. Reference [105], in turn, employs the short-time Fourier transform to capture the distinguishing features related to voltage dip following fault conditions to train the tree. In [139], wavelet and short-time Fourier transforms are combined to extract the features from voltage and current data, thereby training a bagged decision tree that reduces the overfitting and variance of a normal decision tree.

5.3.4 Support vector machine-based schemes

An SVM is a supervised machine learning algorithm that can be applied for classification, pattern recognition, and regression purposes. In an SVM, various features (datasets) are classified and segregated by an iteratively generated hyperplane; to maximize the margin between these classes, as illustrated in Fig. 23 [140]. This philosophy is

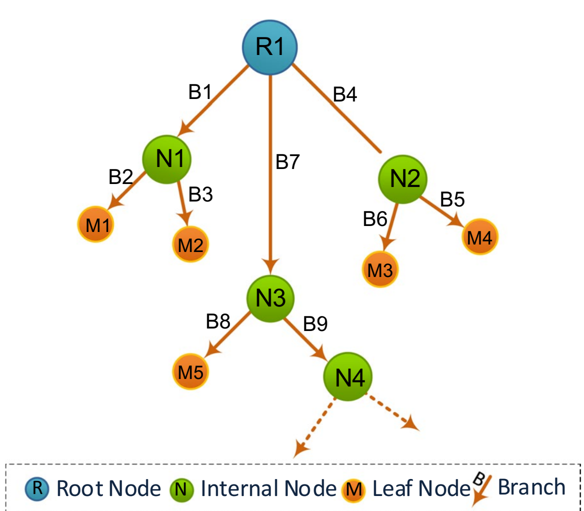

Fig. 22 Decision tree representation

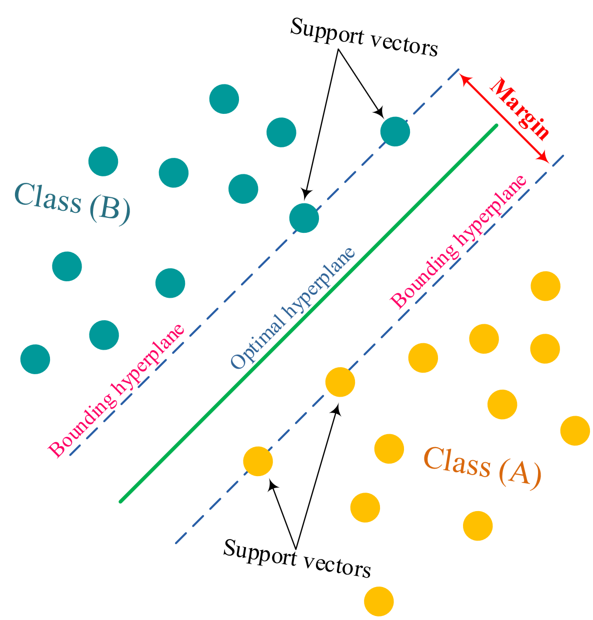

Fig. 23 Support vector machine representation

commonly used in power systems, where fault-related characteristics (classes) are captured when processing voltage and current signals to train the SVM classifier to find abnormalities. In [82], HHT is used to gather fault distinguishing characteristics, such as standard deviation, change in energy, mean, median, etc., in order to train the SVM model to determine fault occurrences, whereas [141] uses WT for features extraction. Voltage and current samples are wavelet-transformed to generate the training data for the SVM-based protection strategy. Table 6 highlights the distinct elements of the discussed studies within the knowledge-based techniques category, presenting the input data for each study and examining DER type in the same manner as in Tables 4 and 5.

5.4 Multiagent-based approaches

A typical multiagent-based protection scheme combines many intelligent agents with linking communication networks, where each agent is supposed to perform a defined task. Smart agents in power systems are required to receive and transmit information/commands in an integrated manner to achieve global goals, i.e., protection of MGs [142]. In this case, the multi-agent protection scheme generally comprises three layers of different responsibilities in a hierarchal configuration, as shown in Fig. 24, namely, the equipment, substation and system layers [107, 143]. In such a configuration, the equipment layer, which is the bottom layer, includes measurement (CT and VT agents), performer (CB agents), and protector agents, etc. Initially, system state variables, i.e., voltage and current signals, are collected through the measurement agents to be analyzed using the protector agents. The protector agents then transfer their analysis and calculations to the management agents in the substation (middle) layer through the regional agent to decide fault existence, type, and location, thereby updating relay settings, and then activating performer agents in the lowest layer to either open or close required CBs. Meanwhile, evaluation agents in the upper layer scrutinize and assess the modifications for further improvements or upgrades [144, 145]. In [146–149], the deployment of multiagent-based protection methods in MGs is examined for fault detection, relay configuration updates, and maintaining adequate coordination, though high impedance faults and communication failures offer significant restrictions in the use of such strategies.

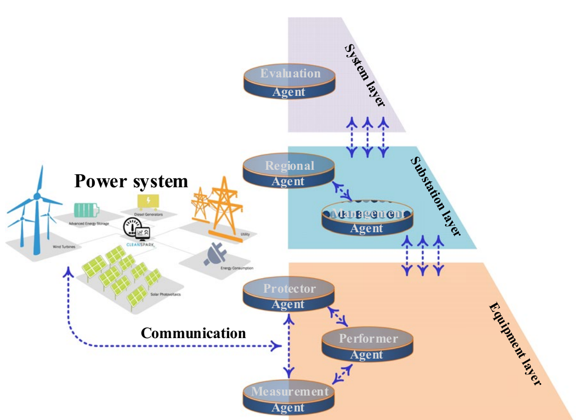

Fig. 24 Multiagent-based protection scheme

5.5 External helping devices

As previously stated, MGs pose significant issues to traditional relaying systems, owing to short circuit capacity variations with operating mode and generating philosophy of DERs, whether synchronous or inverter-based. Therefore, some advocate the use of external devices to ameliorate the problems of effectiveness of conventional relays in MGs. Such devices include fault current limiters, energy storage systems, and intelligent electronic devices. The following section briefly explains the operational philosophies and constraints of their implementation.

5.5.1 Fault current limiters

Fault current limiters (FCLs) are series installed devices to restrict and minimize the fault current contribution from DERs or the main grid to a tolerable level, nearly 3–5 times the rated current [150]. Basically, FCL has a low impedance value under normal conditions that does not affect power flow or quality indices. However, this value drastically increases during faults [151, 152]. FCLs are generally classified into two main types: superconductor and solid state FCLs, which are further subdivided into distinct sub-types as detailed in [58, 153]. According to the literature, FCL installation in MGs has challenging concerns regarding the location, sizing, and tuning of parameters, concerns which necessitate a rigorous study to reveal the optimum solutions, technically and economically [45, 46].

5.5.2 Energy storage systems

As aforementioned, the broad integration of inverter-based DERs has influenced the performance of traditional relays, particularly in islanded operating modes, because of the lowered short circuit levels, which typically are less than double the rated currents. Accordingly, some advocate connecting additional capacity, such as energy storage devices, during fault events in order to support and boost the short circuit level to a sensible and traceable level by traditional relays [35, 98]. Nevertheless, adopting these devices incurs extra expense, besides the

Table 7 Summary of protection schemes for AC-MGs

Protection Scheme	Operation description	Merits	Demerits		
Traditional approaches	Adaptive protection	Predefined group settings are included in digital relays to handle different configurations. Intelligent controllers can be employed in centralized or decentralized frameworks	Adapt automatically to any changes and conditions Relay settings are updated via external signals Setting groups can be calculated online or offline	Requires communication infrastructure Needs a huge database of simulated topologies High implementation costs (digital relays, controllers, and communication links)	
	Differential protection	Compares electrical quantities at input/output terminals of protected facility	High selectivity and sensitivity Detects high impedance faults Simple and high computational efficiency	Requires communication infrastructure Current transformers saturation or mismatch False activation on heavy external faults	
	Distance protection	Apparent impedance to fault point is defined based on voltage/current measurement at relay location This impedance identify fault and its location	Based on local measurement Simple implementation	Errors to fault resistance, lines loadability, and infeed currents Depends on line parameters Time consuming Fundamental components extraction	
	Overcurrent protection	Traditional	Trip decision based on current magnitude comparison with the pickup value	Simple Low cost	Bidirectional flow of fault current Low fault current contribution of inverter-based DERs Influenced by operating mode High impedance faults
		Directional	Trip decision based on current magnitude comparison with the pickup value and fault direction (forward/reverse)	Simple Addresses bidirectional flow of currents	Low fault current contribution of inverter-based DERs Influenced by operating mode High impedance faults
	Voltage protection	Depends on voltage level comparisons to decide faults	Simple Low cost	High impedance faults Influenced by operating mode and system configuration Difficult discrimination of voltage sag in fault and normal events	

Table 7 (continued)

Protection Scheme	Operation description	Merits	Demerits	
Signal processing-based approaches	Wavelet transform	System signals are transformed into time–frequency domain to extract fault related features for further fault identification	Dependable and secure Adjustable data window for signal processing	Needs classification learning models High cost implementation Impacted by signals noise Requires high capability software
	Travelling waves	Based on analysis of induced electromagnetic waves at faults	High accuracy Independent of network data	Un required reflections due to laterals Complex implementation More expensive High sampling rate of fault recorders
	S-transform	System signals are transformed into time–frequency domain to extract fault related features for further fault identification	Dependable and secure Adjustable data window for signal processing	Needs classification learning models High cost implementation Impacted by signals noise Requires high capability software
	Hilbert–Huang	A time–frequency signal processing approach that computes instantaneous frequency signal of input data to be compared with a threshold value	Dependable and secure Adjustable data window for signal processing	Needs classification learning models High cost implementation Impacted by signals noise Requires high capability software
	Harmonic contents	Depends on harmonic content of output currents/voltages due to inverter-based DERs	Simple Mimics traditional networks in the higher-frequency domain	Dependent to network configuration and penetration level of DERs High impedance faults Inaccurate in a harmonic rich system
Knowledge-based approaches	Artificial Neural Network	System signals, relays history, breakers status for offline trainings to define faults	Addresses data uncertainties Simple and feasible implementation	Time consuming during training Requires wide-range of data for training Requires high capability software
	Fuzzy logic	System voltages/currents are processed using fuzzy model to decide faults	Fast and simple Absence of training Addresses data uncertainties	Low accuracy Dependent to network configuration
	Decision trees	Classification and regression model requires data for training to decide abnormalities	Easy to grasp Clear Visualization Handles outliers and missed values	Consumes more memory High computational burden Influenced by noise Overfitting and limited for small database
	Support vector machine	Classification and regression model requires data for training to decide abnormalities	Regularization capabilities, thus no overfitting Stable against data variation	Consumes more memory High computational burden Difficult to understand

Table 7 (continued)

Protection Scheme	Operation description	Merits	Demerits	
Multiagent-based approaches	Comprises three layers of different responsibilities: equipment/substation/system	Layers-based scheme Simple, reliable, and flexible Easy to understand	Requires reliable communications High impedance faults Limited to small-scale systems	
External helping devices	Fault current limiters	Inserts a series impedance to limit fault current	Simple Fast response	High installation and maintenance costs Challenges regarding their size, location, parameters tuning Type selection and associated limitations
	Energy storage systems	Additional storage is provided to support the short circuit capacity to be sensible by relays	Simple Easy implementation	High installation and maintenance costs More suitable for islanded modes with inverter-based DERs Needs islanding detection schemes
	Intelligent electronic devices	Voltage and current data are monitored at different locations to decide faults	Simple implementation	Requires reliable communications Time consuming when combined to learning classifiers High cost Low accuracy and sensitivity

crucial needing for islanding detection technologies [35, 58].

5.5.3 Intelligent electronic devices

Microprocessor and communication technology advances have contributed considerably to real-time measurement using smart equipment, e.g., intelligent electronic devices (IEDs) [154]. In a relaying system, several IEDs are dispersed through the power system to monitor voltage and current data, which subsequently are fed into learning-based algorithms to identify and diagnose fault occurrences [155].

A summary of the examined protection schemes in this work is given in Table 7, highlighting the merits and demerits of each scheme. In traditional approaches, adaptive protection allows automatic adjustment of MG relays using external signals, where several setting groups are created in databases based on MG simulations that take into account all conceivable changes and disruptions. Accordingly, responsible communication channels and controllers are essential for this scheme for safe, fast, and reliable operation. Differential protection, in turn, offers a sensitive and selective solution for protecting MGs, though significant failures beyond the MG boundaries, as well as data discrepancy at protected facility terminals on regular occasions, limit the functionality of this scheme. Furthermore, data transfer between system terminals poses a problem to this method, as delayed or attacked signals will indeed cause associated relays to malfunction. In distance relays, voltage and current data at one or both ends are employed to estimate the system impedance during faults. However, significant constraints restrict the use of these relays in MGs, such as fault resistance and DER infeed currents, which influence the relay selection. Adjustable distance relay settings may be a solution but line loadability in normal instances is a limitation to these adjustments. Traditional overcurrent relays have many limitations in terms of fault current magnitude and direction, limitations which may be addressed by integrating directional features (DOR). Although DOR addresses the issue of bidirectional current flow, the quantity of fault current remains difficult, particularly for islanded MGs. Some proposals use inverters' harmonic current injection capacity as a triggering input instead of the real current, which is only possible with inverter-based DERs. Voltage-based relays also offer simple and low-cost protection for MGs. However, their application is limited because of high impedance faults and difficulties in discriminating between normal and abnormal events that result in system voltage reduction. Accordingly, these relays are commonly used as backup devices for better reliability. In signal processing-based approaches, discriminating properties and statistical metrics of fault events are extracted and processed using appropriate signal processing techniques such as WT, S-transform, and HHT. However, this entails employing data classification models (classifiers) to find defects based on the extracted characteristics, which takes more time and needs high-capability software. Traveling waves are also included in this category, where the investigation of induced/injected electromagnetic waves following faults is employed to determine their occurrences. However, the high implementation costs, high sampling rate of fault recorders, and unwanted reflections limit the use of TWs. This category includes another technique based on correlated harmonics to system voltages and currents. In the higher-frequency domain, this technique mimics conventional networks, but the reliance on system layout and inaccuracies in harmonic-rich systems restrict its widespread adoption. Knowledge and learning-based methods provide safe and dependable frameworks for protecting MGs. In such approaches, system signals, response patterns of relays and breakers, extracted characteristics of fault events via signal processing algorithms, etc., are employed for further training and classification to determine abnormal activity. Most of these approaches, however, are time-consuming, necessitate a large amount of data for training, take more memory, and so necessitate elevated software. In multiagent-based schemes, the main functions of MGs are restructured into several layers with diverse responsibilities, which ease monitoring and protection tasks. Nevertheless, such schemes have only demonstrated their superiority in small-scale MGs, aside from the need for robust communication channels. Finally, several auxiliary devices to conventional relays, such as FCLs, ESSs, and IEDs, are employed for various purposes. However, these devices pose issues in terms of implementation costs, installation location selection, and necessary maintenance.

6 Real applications in MG protection

This section briefly discusses some real MG applications in North America (the USA, Canada, and Mexico), along with the protection systems that were actually implemented, where the available protection scheming data encouraged the investigation of MGs in these countries. However, this work discusses only the implemented schemes since most MGs in North America are relatively new and have not, in reality, been subjected to a large number of fault scenarios. Accordingly, the behavior of the relaying systems under fault conditions is not known for these MGs. In general, most MG projects in Canada and Mexico use hydro and solar DERs, respectively, while the USA employs solar, gas, wind, diesel, and thermal MGs. Accordingly, in the USA and

Mexico, the DERs are a mix of rotating machines-based and inverter-based, in contrast to the Canadian MGs that mainly use rotating machines-DERs [156].

6.1 Electric power board MG, Chattanooga, USA

This MG is a 12.47 kV system with a diesel generator and 4408 solar panels (1.3 MW), which generate backup power for the main operation building and domestic demands, respectively. In this MG, the lateral feeders are protected using fuses of different ratings [156]. Schweitzer Engineering Laboratories (SEL) protective relays (SEL-751) are installed in the main substations to provide multiple protection and fault-locating capabilities, monitoring, control, and communication, all in one package [157]. Furthermore, the 12.47 kV distribution lines are outfitted with multiple IntelliRupters to identify system failures. The IntelliRupter is a directional overcurrent device that uses PulseClosing technology to recognize temporary and permanent faults, lowering potentially destructive stress on system components with each reclosing activity, as opposed to traditional autoreclosers [158].

6.2 Santa Rita Jail MG, Dublin, USA

The Santa Rita Jail MG is equipped with a 1.2 MW PV system, a 1 MW fuel cell, 2×1.2 MW emergency diesel generators, 5×2.3 kW wind turbine generators, and a 2 MW/4 MWh-ESS [159], which provides power to around 4000 inmates [156]. This MG is connected to the main grid through a static switch, which allows for quick isolation of the MG. To identify islanding occurrences, traditional over/under voltage and over/under frequency relays are used while coordinated with MG DERs following an islanding. Furthermore, directional overcurrent relays are installed to detect fault events within the MG (internal faults) [160]. Nonetheless, the protection frame in this MG lacks selective coordination toward islanded MG failures, which means that a defect in the islanded MG trips the whole zone [156, 160].

6.3 Illinois Institute of Technology MG, Chicago, USA

The Illinois Tech MG is a campus MG that is fed through two identical substations, 12.47/4.16 kV, offering additional reliability in case of a feeder loss [156]. This MG, which has a peak capacity of 12 MW, is mainly composed of several DERs: a 300 kW PV system, an 8 MW gas turbine, a 500 kWh ESS, an 8 kW wind turbine, and a 4 MW emergency generation [160]. In terms of the protection strategy, this MG implements a 4-level hierarchical scheme using differential protection. The following points briefly outline the basic function of each level [156, 160].

- *Loads protection level (LPL)*: It mainly comprises directional overcurrent relays to protect against load faults. Over/under voltage and over/under frequency relays are also employed to allow load shedding and other control strategies.
- *Transmission lines (loop) protection level (TLPL)*: Differential protection is employed at this level to identify faults in the MG lines using communication-assisted relays. This level protects the LPL from breaker failure and offers backup protection.
- *Feeders protection level (FPL)*: This upper level employs adaptive overcurrent relays in coordination with LPL and TLPL to handle fault current variations with different modes of the MG. It also offers a backup protection frame for both LPL and TLPL levels.
- *MG protection level (MPL)*: The MPL consists of over/under voltage, over/under frequency, and overcurrent relays, to mainly protect the entire MG against utility failures. In addition, it offers a backup scheme for all the lower levels (LPL, TLPL, and FPL) in the connected mode.

6.4 Borrego Springs MG, California, USA

This MG was constructed primarily to provide energy to around 2800 clients since the community of Borrego Springs was experiencing power outages owing to environmental and technical issues [161]. The MG is fed from the utility through a 69/12 kV substation and comprises 2×1.8 MW diesel generators, a 700 kW PV system, and 500 kW/1500 kWh ESS. Overcurrent relays are mainly employed for protecting the MG. However, the limited fault current during islanded mode has promoted the deployment of voltage-restrained OCRs [156]. This scheme adjusts the OCR settings (pickup value and TDS) dependent on system voltage, enabling the OCR to detect low fault currents. Nevertheless, the coordination with the relays of fixed settings is challenging [162].

6.5 Guásimas del Metate, and Tierra Blanca del Picacho MGs, Mexico

Guásimas del Metate and Tierra Blanca del Picacho are two rural areas in Mexico that have been electrified by two identical MGs, each of which can power around 52 homes. Each MG is driven only by a PV system of 45.9 kW, while both MGs operate only in islanded mode, since the connection to the main grid is neither practical nor economical for such regions [163]. In these MGs, the employment of traditional overcurrent relays is unworkable because of the small fault current of the PV system in the islanded mode. Therefore, the inverter's self-protection is regarded as the primary protection, while undervoltage, voltage balance, and volts-hertz protection are implemented as back-up protections against MG faults and inverter failures [156, 163].

6.6 British Columbia Hydro MG, Canada

This MG is located in Boston Bar, Canada, and comprises two sets of hydropower generators each rated at 2×3.5 MW, which are connected to a 4.16/25 kV bus when synchronized [164]. The MG is connected to the utility via a 25/69 kV substation, and has a peak load of 3 MVA [160]. The MG employs adaptive overcurrent protection to modify the settings according to the operating mode. In addition, a payable telephone line is used for communication purposes within the MG, such as monitoring system breakers and communicating relay settings for adaptive schemes [164].

6.7 British Columbia Institute of Technology MG, Canada

This is a research and educational campus MG located in Burnaby, Canada. It contains 2×5 kW wind turbines, 250 kW steam turbines, 300 kW PV systems, and 550 kW ESS [156]. The MG employs a communication-aided fault diagnosis framework, using differential protection to identify faults and abnormalities within the MG for grid-connected and autonomous modes [160].

To sum up, the pie charts in Fig. 25 show the percentages of protection schemes used in the North America MG projects, where Fig. 25a represents the classical schemes and Fig. 25b represents the other schemes based on [156]. According to Fig. 25a, traditional under-voltage, inverse time overcurrent, and directional overcurrent protection are the dominant schemes in North America, while adaptive protection is the most prevalent nonconventional strategy in these MGs, as shown in Fig. 25b. Table 8 summarizes the main details of the described real MGs in terms of country, voltage level, load rating, mode of operation, types and ratings of DERs, and protection strategy.

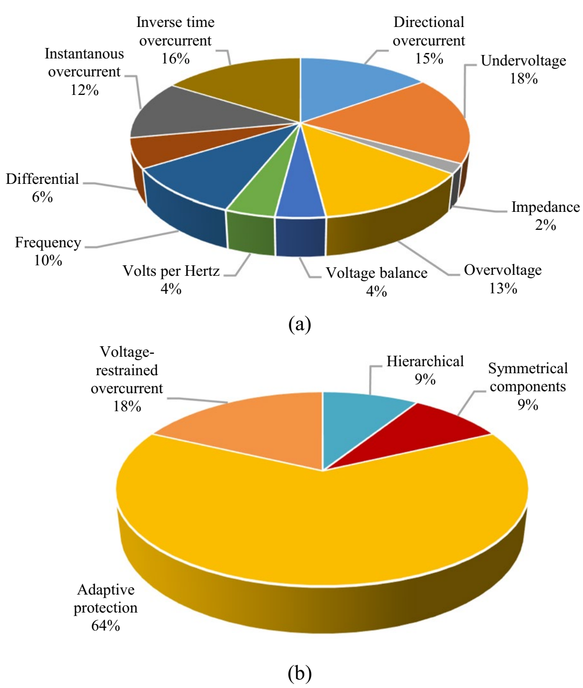

Fig. 25 Protection schemes of MGs in North America **a** classical methods, **b** non-classical methods

7 Challenges and future trends

Based on the evaluation and analysis of the discussed schemes for protecting AC-MGs, these strategies still face considerable challenges influencing their performance, such as data sharing and cyber security. Thereby, the following points may be considered for future research and improvement in this promising area, in order to provide reliable and practical relaying systems.

- Most research on AC-MGs assumes balanced operation, but the increasing use of RESs and single-phase roof-top solar panels have led to an increase in system imbalance. This lead to detrimental impacts such as increased losses, degraded voltage, greater stress on transformers, protection equipment malfunctions, harm to sensitive loads, elevated neutral currents and neutral-ground voltage, and power oscillations. Generally, the imbalance problem in AC-MGs can be evaluated based on the MG operation mode, either in islanded or grid-connected mode. In islanded mode, the main challenges are the overloading of DERs because of overcurrent, unbalanced voltage, high circulating current, and power oscillation. In grid-connected mode, the key challenges are rapid fault detection, proper synchronization, fault ride-through control, stable ramping up of power after recovery, as well as controlling DER power and overcurrent [165].
- The adoption of the latest trends in AI approaches in MG-protection, such as physical-informed AI and explainable AI, to address the limitations of traditional AI methods, such as overfitting of training data, lack of interpretability, limited understanding of complex systems, and reliance on large amounts of data. Physical-informed AI enhances interpretability and accuracy by incorporating physical knowledge and constraints into AI models informed by physical laws and principles. Common physical-informed AI approaches include physics-based and data-driven physics models, and physics-informed neural networks. Explainable AI, on the other hand,

Table 8 Summary of investigated MGs in North America

MG project	Country	Voltage level (kV)	Mode of operation		Load (MWA)	DERs types and ratings (technical characteristics)								Protection scheme
			Grid-connected	Islanded		PV	ESS	Diesel	Fuel cell	Wind	Hydro	Steam	Gas	
Electric Power Board MG	USA	12.47	✓	✓	NR*	1.3 MW	*	NR						SEL-751 protection IntelliRupter (directional overcurrent protection)
Santa Rita Jail MG	USA	12.47	✓	✓	6.6	1.2 MW	4 MWh	2.4 MW	1 MW	11.5 kW				Over-/Under- voltage Over-/Under- frequency Directional overcurrent
Illinois Institute of Technology MG	USA	4.16	✓	✓	12	300 kW	500 kWh	4 MW		8				
kW			8 MW	*Hierarchical scheme* Over-/Under- voltage, Over-/Under- frequency, and Directional overcurrent Differential protection Adaptive overcurrent protection Traditional overcurrent protection										
Borrego Springs MG	USA	12	✓	✓	4.6	700 kW	1.5 MWh	3.6 MW						Voltage-restrained overcurrent protection
Guásimas del Metate MG	Mexico	0.22		✓	NR	45.9 kW								Inverters' self-protection Undervoltage protection Voltage balance protection Volts-hertz protection
Tierra Blanca del Picacho MG	Mexico	0.22		✓	NR	45.9 kW								Inverters' self-protection Undervoltage protection Voltage balance protection Volts-hertz protection

Table 8 (continued)

MG project	Country	Voltage level (kV)	Mode of operation		Load (MWA)	DERs types and ratings (technical characteristics)								Protection scheme
			Grid-connected	Islanded		PV	ESS	Diesel	Fuel cell	Wind	Hydro	Steam	Gas	
British Columbia Hydro MG	Canada	25	✓	✓	3						14 MW			Adaptive overcurrent protection
British Columbia Institute of Technology MG	Canada	12.47	✓	✓	17.9	300 kW	550 kWh			10 kW		250 kW		Differential protection

[*] *NR* Not Reported in references, : Not installed(provided) in this MG

focuses on making AI systems more transparent and understandable to human users through techniques such as LIME (Local Interpretable Model-Agnostic Explanations), counterfactual explanations, and saliency maps. This leads to better predictions, decision-making, and outcomes across a range of fields and the ability to handle uncertainty and incomplete data [166–169].

- In power systems, inertia refers to the stored energy in large rotating machines such as generators and some industrial motors. This can be tapped for a few seconds to give the grid time to detect and respond to system failures, thus enhancing system stability. Conversely, AC-MGs consist mainly of inverter-based resources, which reduce the amount of inertia available and can result in instability and security issues. This makes AC-MGs more vulnerable to faults [170].
- In MGs, it is crucial to carefully consider the type of inverters being used, as the characteristics of current source inverters (CSI) and voltage source inverters (VSI) can impact the protection schemes during both normal and abnormal conditions. CSI-based DERs maintain a constant current flow at near-rated levels during faults, requiring more advanced protection schemes for fault detection. In contrast, VSI-based DERs significantly contribute to fault current while maintaining constant voltage, which makes fault detection easier [171].
- MGs have recently emerged as a solution to traditional network challenges, combining DERs, ESSs, and load management systems to improve system reliability, promote sustainability, and reduce toxic emissions. Meanwhile, rapid developments in monitoring and measurement devices and communication capabilities have resulted in the acquisition of extensive data volumes (i.e., the status of circuit breakers, system currents, and voltages). Accordingly, using big data analysis tools for such recordings enables MGs to quickly identify defects and failures, highlighting the role of data science in power engineering.
- More research should be conducted on using the internet of things (IoT), Fog, and cloud platforms to improve system monitoring and data storage, for reliable decisions with reasonable timing. Such platforms, in turn, link all power system apparatus to the internet, permitting data interchange with the cloud. This online framework supports data gathering, evaluation, and processing to reveal distinct patterns for effective decisions. However, data security and privacy are challenging when using these online platforms.
- The development of communication frameworks to suit the needs of MG operation, control, and protection is critical to the behavior of such grids. Accordingly, these communication routes must have enough bandwidth to store and process the huge amounts of data gathered by intelligent devices in the MG. In addition, they should support plug-and-play applications for more flexible operation. Wired, fiber-optic, wireless, microwave, and satellite connections are all examples of communication methods.
- Again, communication channels are essential in MGs for data gathering for monitoring, control, management, and protection purposes. However, the widespread use of these networks threatens the security of MGs, exposing them to risky cyber-attacks, which impact the performance of the protective devices. These attacks may be classified into several forms, including malware, phishing, cryptojacking, SQL injection, DNS tunneling, denial of service attacks, etc. Consequently, it is essential to consider cyber security while designing protection strategies for MGs.
- Cloud computing adoption offers exceptional processing power and storage capacity, particularly in poor countries. This technology lowers hardware costs, delivers the most recent software, optimizes data processing timing, allows flexible data access, and improves dependability and security. However, cyber-attacks and losing control over sensitive information are significant challenges when moving to cloud computing.

8 Conclusion

This study has examined the challenges and solutions for protecting AC microgrids (MGs). Traditional protection techniques have been reviewed and a comprehensive examination of reported protection methods in the literature has been provided. The methods were categorized into five classes: traditional, signal processing, knowledge and learning, multi-agent, and assisting external devices-based techniques. The paper also examined some real MGs in North America and identified additional challenges for future research. It was found that adaptive and differential protection schemes can effectively protect AC-MGs when efficient and stable communication channels are available. Directional overcurrent relays (DORs) are also a possible alternative, but variations in fault current can affect the selection of their operating characteristics, such as pickup current and time-delay settings. Multi-agent systems for protecting MGs depend on the performance of individual agents and communication platforms. Artificial intelligence and learning-based frameworks are suggested to address operational concerns, but they also make the system vulnerable to cyber-attacks, resulting in a decline in overall performance and access to sensitive information. In general, the protection of AC-MGs remains a crucial challenge for ensuring the reliability and stability of these systems, where further research and development are necessary considering emerging challenges and trends, so as to provide more viable and sustainable solutions.

Abbreviations

AC-MG	Alternating current microgrid
ANN	Artificial neural network
AR	Auto recloser
CB	Circuit breaker
CPS	Central protection system
CT	Current transformer
CTI	Coordinating time interval
DC-MG	Direct current microgrid
DER	Distributed energy resource
DFT	Discrete Fourier transform
DOR	Directional overcurrent relay
DT	Decision tree
EMD	Empirical mode decomposition
ESS	Energy storage system
FCL	Fault current limiter
FL	Fuzzy logic
GA	Genetic algorithm
HHT	Hilbert–Huang transform
HSA	Hilbert spectral analysis
HV	High voltage
IED	Intelligent electronic device
IMFs	Intrinsic mode functions
IoT	Internet of Things
ITOCR	Inverse-time over current relay
LOM	Loss of main
LUT	Look-up table
LV	Low voltage
MG	Microgrid
OCR	Overcurrent relay
PCC	Point of common coupling
RES	Renewable energy source
RF	Random forest
SLG	Single line to ground fault
ST	Stockwell transform (S-Transform)
SVM	Support vector machine
T2FL	Type-2 fuzzy logic
TDS	Time-dial setting
THD	Total harmonic distortion
TMFs	Transient monitoring functions
TOV	Temporary overvoltage
TW	Traveling wave
VT	Voltage transformer
WiMAX	Worldwide interoperability for microwave access
WT	Wavelet transform

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