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Review

Review of Methods for Addressing Challenging Issues in the Operation of Protection Devices in Microgrids with Voltages of up to 1 kV That Integrates Distributed Energy Resources

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Abstract: With the large-scale integration of distributed energy resources (DER) into passive distribution networks with voltages of up to 1 kV, these networks are being converted into microgrids. When the topology and operating conditions change, several challenging issues arise related to the functioning of the protection devices (PD) that are in operation. Most DERs, including renewable generators, are integrated into microgrids by means of inverters. In the event of short circuits (SC) in microgrids, these DERs provide a fault current contribution of no more than 1.2–2.0 I_{rated} at the fault location. This makes it difficult to identify the fault location and to carry out the selective disconnection of the faulty element by means of conventional PDs. This article provides an overview of engineering solutions for improving conventional protection schemes that have been historically used in passive distribution networks, as well as for creating modern protection schemes based on innovative principles and new methods. The use of adaptive protections built on decentralized and centralized principles in most cases ensures the reliable protection of microgrids. Modern intelligent electronic devices (IEDs), where protection functions are implemented, rank higher with respect to their technical perfection in terms of reliability, sensitivity, selectivity, and speed performance. The use of multi-agent systems in the implementation of modern protection schemes requires the availability of broadband communication channels, which hinders their use because of the high cost. The combined use of fault current limiters (FCL) and energy storage systems (ESS) allows for the reliable operation of microgrid protections. The use of modern PDs ensures the reliable operation of DERs and power supply to consumers in microgrids, both in the case of grid-connected and islanded operation modes. Since there is no unified concept of designing protection schemes for microgrids with DERs, the choice of specific approaches to the design of protection schemes should be based on the results of a comparative technical and economic analysis of different options.

Keywords: microgrid; distributed energy sources; inverter; protection device; intelligent electronic device; islanded mode; fault current limiter; energy storage system

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1. Introduction

At the current stage of development of the electric power industry, when the trend towards the decentralization of generating capacities is still ongoing, DERs are being integrated at a large scale into passive distribution networks [1]. With the integration of DERs, distribution grids are transformed into microgrids, allowing them to actively participate in the management of power system power flows.

The various types of primary and secondary energy resources, including renewable ones, can be used to generate electricity based on DERs. Therefore, DERs include distributed generation (DG) facilities based on non-renewable energy sources (gas-fired reciprocating engine plants and diesel generating sets, microturbines, etc.) and RES (photovoltaic modules, wind turbines, etc.), as well as fuel cells and ESS.

The transformation of passive distribution networks into microgrids is accompanied by the emergence of new challenging issues related to ensuring the operation of PDs [2]. The main reason for the emergence of challenging issues related to the operation of PDs is that bidirectional power flows are allowed, depending on generation modes and power consumption at the nodes of the network. This leads to changes in the levels of fault currents, depending on the number and power of integrated DERs [3], which is especially evident when microgrids are operated in the islanded mode [4]. In microgrids, the efficiency of traditionally used PDs, i.e., overcurrent protections (OCP), is significantly compromised, since the design of passive distribution networks did not take into account the new topologies and operating conditions [5].

The network topology (radial, ring, mesh), on the basis of which a microgrid is formed, has a significant impact on the choice of protection schemes [6]. As a rule, passive distribution networks have a radial topology in which all consumers are fed from a single transmission line. With this network topology, the power flows from the substation to the consumers can be unidirectional if the DERs are connected to the substation busbars or as close as possible to the beginning of the transmission line. In this case, there are no issues with the design of microgrid protection schemes when integrating DERs. The ring (loop) network topology is a closed configuration of power transmission lines. At present, the ring topology is more often used in residential neighborhoods to increase the reliability of power supply to consumers. Under normal conditions, transmission lines in the ring network are operated as two parallel radial lines, except that they are mutually redundant. In some cases, open ring operation is allowed. The use of the closed ring network topology has advantages in the form of voltage stability and the minimization of power losses. The disadvantages of this topology are the higher level of fault currents and the increased need for more complex protection schemes than in the case of the radial topology because of bidirectional power flows. The mesh network is a distribution network with multiple (alternative) connections between nodes. To ensure operational reliability and the proper functioning of protections, in practice, of all those possible, only a few topologies are used. They are usually of the radial and ring types. Thus, the mesh network has many variants to its configuration, which allows it to adapt to almost any change that occurs during operation (faults, switching, abnormal conditions). However, this notably increases the requirements for the schemes and principles of the implementation of protections used in such networks. This is due to the fact that when the topology is changed, the directions of power flows, the values of transmitted power, the level of fault currents, and algorithms governing the operation of microgrid protections change.

The integration of DERs into microgrids requires the increase in PD speed and ensures the selectivity of fault identification. This is due to the use of DG facilities with generation units (GU), which have small values of the mechanical inertia constant T_J [7]. In addition, this is due to the integration of RES-based generation into microgrids through power electronics devices, i.e., inverters, which, in the event of a SC, provide a fault current contribution of no more than 1.2–2.0 I_{rated}. This value of current is much lower than the level of fault current from conventional synchronous GUs (more than 5.0 I_{rated}). Inverters are used in GUs based on high-speed direct-drive gas turbine engines and microturbines with permanent-magnet generators. The fuel cells and ESSs are also connected to microgrids via inverters.

In the course of microgrid operation, abnormal and faulty operating conditions may occur due to overloads and short circuits in microgrids. The identification of such operating conditions and the detection of faulty microgrid elements is a challenging task. Therefore, in microgrids with DERs, a detailed analysis of fault processes (which are unacceptable if sustained for a long time) is required to prevent tripping failures, as well as the excessive and nuisance tripping of PDs [8]. As a rule, this requires a change in the schemes of protection implementation, the principles of their operation, and tripping set points [9].

The analysis of key defining features of DERs shows that the value of fault current contributions of the fault location depends on design features of the inverter and the control algorithms implemented in the automatic control system (ACS), as well as the type of connection to the microgrid [10]. The magnitude of the fault current contribution from the inverter in the microgrid may be such that the inverter will be switched off by internal protections. The insignificant value of the fault current contribution in the event of a short circuit (no more than 1.2–2 I_{rated}) does not allow conventional PDs in microgrids to correctly identify the location of the short circuit and selectively disconnect the faulty section [2].

The neutral grounding mode of the step-down power transformer, powered by the medium voltage network, has a significant impact on the operation of PDs in microgrids with voltages of up to 1 kV. The neutral grounding mode affects the magnitude of fault currents in both 1 kV and medium-voltage networks. With this in mind, the requirements to the protection scheme are formed and the selection of PDs with algorithms capable of detecting the appropriate types of faults is carried out [11,12].

There are published reviews highlighting the main challenging issues that arise when building microgrid protections in the context of mass integration of DERs. Study [13] presented a generalized analysis of microgrid protections and the challenging issues associated with their implementation. The analysis proposed the use of the hierarchical coordination of protections. However, this review did not include a classification of the protections used. Studies [14–17] performed detailed reviews of the challenging issues arising with the functioning of protections and the principles of building protection schemes. These studies also presented recommendations for the use of different types of protections, listing their advantages and disadvantages. However, the above reviews failed to address the technical limitations related to the implementation of protection schemes. Study [18] discussed various microgrid protection schemes with a focus on preventing cyberattacks, but the technical aspects of implementing new protection schemes were not specified. In [19,20], it the use of combined protection schemes was proposed, implemented based on diverse principles. The studies also listed the factors constraining the introduction of adaptive protections: the need for reliable communication channels; increasing the number of PDs requires more time to identify fault locations; the need for high-performance computing resources; and the growing threat of cyberattacks on protection devices. The main emphasis was placed on building only adaptive protections without considering other conventional protection schemes (differential protection, distance protection, etc.). In [21], the authors presented the engineering solutions used in pilot microgrid projects (Nanji island, Dongao island) and the results of the analysis of the operation of protection schemes, as well as the application of the IEEE 1588 standard to data transmission. However, the main emphasis was on the application of adaptive centralized protections. Studies [22,23] reviewed all the challenging issues arising in microgrid protections: they contributed a systematization of protections and discussed the technical aspects of the adoption of new protection schemes; however, the preferred types of communications were not covered.

This article provides an overview of engineering solutions for improving conventional protections, as well as for creating modern protections based on innovative principles and new methods with such protections used in microgrids with voltages of up to 1 kV. Modern PDs are superior with respect to their technical perfection in terms of reliability, sensitivity, selectivity, and speed specifications. The use of modern PDs with innovative principles of protection scheme designs should ensure the reliable operation of DERs and power supply to consumers in microgrids.

2. Issues of Operation of PDs in Microgrids with DERs

2.1. Factors That Lead to Malfunctioning of PDs

Microgrids with DERs can operate both in grid-connected and islanded modes, while supplying power to electrical loads from different DERs [24]. Hybrid inverters used in

DERs allow the production of electricity regardless of the availability of the connection to the power grid [25].

The behavior of a hybrid inverter in the event of a fault in the microgrid is determined by the control algorithms implemented in its ACS [9]. As a rule, given the multi-circuit ACS structure, the choice of a specific control algorithm for the hybrid inverter depends on the mode of operation of DERs. If the hybrid inverter operates in the grid-connected mode, then the grid-following (current source) inverter algorithm is executed, whereas if it operates in the islanded mode, then the grid-forming (voltage source) inverter algorithm can be executed. The transition of microgrids from the grid-connected mode to the islanded mode poses problems for the operation of PDs. Nuisance tripping or failures in the tripping of PDs in this case are caused by the choice of tripping set points of PDs with respect to the current when executing the OCP algorithm [14]. The integration of DERs into microgrids violates the conditions for ensuring the time selectivity of the OCP. This is due to the fact that fault currents can flow in any direction, depending on the fault location, the locations of DERs and their types (the value of the fault current contribution of the fault location depends on the type of DER).

The integration of DERs into the microgrid poses other problems as well [23,26,27]:

- The blinding of protections;
- a significant change in the value of fault currents during the transition from the grid-connected mode of operation to the islanded mode and vice versa;
- bidirectional power flows, which depend on the operating conditions of generation and power consumption at microgrid nodes;
- the improper operation of PDs during the automatic reclosing (AR) of power lines between the microgrid and the power system [28].

2.2. Blinding of Protections

When microgrids transition to the islanded mode, the total fault current may be lower than the set point for the tripping of overcurrent protections. As a result, the faulty element cannot be identified and disconnected by PDs.

Connecting DERs by a lateral to the feeder supplying the consumer, when a fault occurs between the DER integration point and the consumer, leads to a decrease in the level of fault current flowing through the PD feeder circuits from the power system side. As a result, the current transfer ratio in the PD feeder decreases, becoming less than 1. This can lead to a significant increase in the tripping time of the PD (when using a time-dependent trip characteristic curve), as a result of which the selectivity of the PD is compromised. When integrating a large number of DERs into the microgrid, tripping failures of PDs with time-independent trip characteristic curves are possible [29].

2.3. Significant Change in the Magnitude of Fault Currents

Since DERs have much less power than the power grid, when they are disconnected from it, there is a dramatic change in the level of fault currents in the microgrid. This is due to the fact that in the microgrid fault mode equivalent circuit, the equivalent impedance of the power supply source in the islanded mode is much higher than during grid-connected operation. Thus, there are two maximum values of the design fault current: one for the grid-connected mode of operation and the other for the islanded mode of microgrid operation. When selecting the tripping set points of PDs in the grid-connected mode of microgrid operation and when a fault occurs while in the islanded mode, the PDs will fail to trip due to a sharp decrease in the fault current level. Additionally, vice versa, in case of selecting the tripping set points of PDs in the islanded mode and when the microgrid operates in the grid-connected mode, the selectivity of PD action is compromised. This causes microgrid elements that are not faulty to be disconnected. In order to eliminate this problem, it is necessary for the automatic adaptation of set points, depending on the mode of microgrid operation with the power system, to be implemented in the PDs [30,31].

2.4. Bidirectional Power Flows

The emergence of bidirectional power flows is a result of the integration of DERs, due to which the direction of currents under normal operating conditions can change several times during the day. With a centralized power supply, currents in the transmission lines flowed only in one direction: from the power system to electrical loads. Bidirectional power flows can cause the nuisance tripping of PDs in the absence of a fault.

2.5. Disruption of Tripping Selectivity of Protections

When integrating DERs into microgrids, the directions of fault currents can also change. In this case, the conventional OCP devices used in distribution networks are unable to identify the faulty element, which results in nuisance OCP tripping. The disruption of PD selectivity also occurs as a consequence of the disruption of the time selectivity of the main and backup protections of microgrid elements. As a result, there is a need to use protections with power directional elements, operating both in the grid-connected and islanded modes.

2.6. Nuisance Tripping of Protections

This issue is also referred to as "sympathetic tripping of protections", which manifests itself when a DER connected to a feeder contributes to the tripping of a protection on that feeder when a fault occurs on a neighboring feeder connected to the same bus section of the substation.

2.7. Incorrect Operation of Protections during AR on Power Transmission Lines

The incorrect operation of PDs, where an AR is additionally installed, in cases of faults on the branches (laterals) of the transmission line that they protect, is characteristic only of the radial topology of the distribution network. With this network configuration, the PDs of the transmission line, in addition to their main function (the identification and localization of faults) perform an additional function: preventing the tripping of PDs on its laterals, in particular, fusible links, in case of temporary faults. This is achieved by ensuring that the following condition is met: the tripping time of the PDs of the transmission line is less than the tripping time of the PDs of its laterals. In this case, temporary faults on transmission line laterals are self-healed during auto-reclosing open time, after which the power supply to consumers is restored within the AR operating cycle. When integrating DERs, there is a need to ensure the coordination of the tripping of the PDs of the transmission line with the PDs of its laterals. If this condition fails to be met, the PDs of laterals are tripped earlier than the PDs of the transmission line, which renders AR operation ineffective [32,33].

The AR devices are used to clear temporary faults on overhead power transmission lines. The reclosing times of ARs are coordinated with the tripping times of the PDs installed on the power transmission line, so that as the AR moves farther away from the power source, the reclosing time of the AR decreases. During the dead time necessary for deionization of the air gap, the temporary fault may self-heal. When integrating DERs into microgrids it is necessary to match the AR reclosing times with the tripping times of the protections in a network of up to 1 kV. In the event of partial fault clearing, due to contributing current from the DER and the voltage subsequently reapplied by AR to the transmission line from the power system side, a temporary fault in most cases will turn into a permanent fault with larger damage and detrimental impacts.

There is no unified concept of designing protection schemes in microgrids with DERs as they evolve on the basis of existing passive distribution networks with the incremental integration of DERs into them.

3. Issues of Using Conventional Types of Protections in Microgrids

The principles of designing protections in microgrids of up to 1 kV are the same as in medium-voltage distribution networks. The protections employed differ in the array of PDs used and the type of values monitored. Conventional types of protections include:

- overcurrent protection that uses current sensors and responds to a current value exceeding a specified set point (tripping device or relay);
- voltage protection that uses voltage sensors and responds to a drop in voltage relative to a specified set point (tripping device or relay);
- distance protection that uses current and voltage sensors and responds to changes in impedance value specified as a set point based on fault current calculations;
- differential protection that uses current sensors installed at the ends of the element to be protected, e.g., a power transmission line, and a communication link between them. This protection responds to an increase in the value of the current difference at the ends of the power transmission line [34].

Let us list the main issues limiting the application of specific types of protections in microgrids with DERs [15,16].

3.1. Overcurrent Protection

In [35], the challenges related to overcurrent protections were discussed, which include:

- inability to correctly identify the faulty element in the case of a bidirectional power flow during a short circuit;
- notable tripping time delay for short circuits that occur far away from the generator;
- low sensitivity at high fault impedances;
- disruption of the selectivity of the action of protections at increased values of the fault current, for example, in the event of a near-to-generator three-phase short-circuit.

3.2. Voltage Protection

The following issues arise with voltage protections [36,37]:

- significant dependence of protection operation on the configuration of the power grid and DER operation modes;
- decrease in the sensitivity of protection in the grid-connected mode of microgrids operation;
- failure of the protection to trip at significant fault impedance values.

3.3. Distance Protection

The following issues arise with distance protection schemes [38,39]:

- insufficient sensitivity when installing a protection scheme on short power transmission lines, as well as in case of faults accompanied by a significant fault impedance;
- improper operation of protections when integrating a large number of wind turbines (WT) into a microgrid (combining a group of WTs into one equivalent WT fails to capture the nature and characteristics of the individual WT);
- incorrect operation of protections due to the incorrect choice of parameters of their tripping resulting from the assumption that the resistance of the wind turbine is a constant value (wind turbine impedance is a variable value, depending on the value of electricity generation, which in turn depends on the value of wind head at a given moment of time).

3.4. Differential Protection

The following issues arise with differential protection schemes [40]:

- incorrect operation of protections in unbalanced systems due to a decrease in the magnitude of the fault current, as well as in faults accompanied by a significant fault impedance;
- the need for a backup communication channel in case of damage caused to the working communication channel, which leads to a significant increase in the cost of the project.

4. Overview of Innovative Principles of Design of PDs in Microgrids with DERs

Articles [13–23,41–44] share their unified approach to the analysis of existing engineering solutions for the design of PDs, which are aimed at the following:

- improvement of algorithms and the selection of tripping set points for conventional current, voltage, distance, and differential protections;
- transition to the use of adaptive protections based on decentralized and centralized principles;
- application of additional power equipment in microgrids, such as FCLs [45] and ESSs [46], which allow influencing the parameters of emergency operating conditions.

In [47], the authors proposed a combination of centralized protections, distance protections, and multi-agent protections into a class of wide-area protections using Wireless Application Protocol (WAP). Wide-area protection has great prospects for use due to the intensive development of switching infrastructure in microgrids, providing the exchange of large amounts of data [48]. There are two basic concepts for designing a wide-area protection scheme. One is based on the application of differential protection [49] or distance protection [50], which use both symmetrical and asymmetrical components of currents and voltages in the implementation of operation algorithms. The second is based on the use of an adaptive algorithm in the fault search matrix, which is necessary to determine the fault location, with its subsequent clearing by implementing control actions on the PDs in microgrids [51].

4.1. Issues of Implementing Innovative Principles of Protection

Each protection scheme has to meet certain technical requirements that enable ensuring the reliable protection of microgrids under all possible conditions of its operation. The application of innovative principles of building protection schemes based on the exchange of data between geographically dispersed PDs requires additional analysis.

For approaches aimed at improving conventional protection schemes, it is of utmost importance to determine whether new algorithms can be incorporated into existing PDs. This affects the investment outlays to be allocated for solving the technical compatibility issues of PDs. When building adaptive protection schemes, the key points are the availability of communication infrastructure in microgrids as well as the computational capabilities of the IED. This makes it possible to develop better engineering solutions than the improvement of conventional protections while the cost of their implementation is about the same. The use of additional equipment (FCL and ESS) is limited only by economic feasibility.

4.1.1. Issues of Improving Conventional Protections

The most cost-effective option for improving the efficiency of protections in microgrids with DERs is to improve conventional protections. This is due to their widespread use in the existing infrastructure of passive distribution networks, their simplicity, and their relative cheapness.

The presence of bidirectional power flows, including in the event of short-circuits, requires the mandatory presence of a directional element as part of the protection scheme. In addition, given the possibility of microgrid operation both in the grid-connected and islanded modes, it is necessary to ensure the possibility of changing the tripping set points of PDs with respect to current and time.

These requirements limit the possibilities for improving the protection functions of circuit breakers with electrodynamic, thermal, and electronic (independent) tripping units and fuses commonly used in networks with voltages up to 1 kV. Consequently, the possibilities of their application in microgrids with DERs are limited, as they do not allow the effective implementation of the necessary protection functions under different topologies and operating conditions.

The use of circuit breakers with electronic (independent) tripping units in microgrids with DERs is possible provided that the function of remote change of set points of protection tripping and remote control is implemented. Given the above, microgrids require the following:

- to implement remote control on circuit breakers;
- to install additional current and voltage sensors, together with circuit breakers and fuses [52];
- to install IEDs, which will implement more up-to-date protection algorithms.

To assess the possibility of improving conventional protections in microgrids with DERs, one should consider the technical readiness of the PDs and switching devices currently in use for the transition to the adoption of the new principles of designing a protection scheme. This necessitates the standardization of their requirements and verification of the readiness of the passive distribution network infrastructure to operate under new operating conditions.

Let us list the key standards of the International Electrotechnical Commission [53], which consider the principles of microgrid design with DERs and intelligent control systems:

- IEC 61499 "Function blocks for industrial-process measurement and control systems". The series of standards defines a distributed, event-driven architecture, and software tool requirements for the encapsulation, embedding, deployment, and integration of software in intelligent devices, machines, and systems;
- IEC 61508 "Functional safety of electrical/electronic/programmable electronic safety-related systems". The series of standards describes the features of various systems (electrical, electronic, programmable) that ensure the reliability, efficiency, and fault-free operation of microgrids with DERs;
- IEC 61850 "Communication networks and systems in substations". The series of standards defines the formats of data flows, types of information, rules for describing the elements of the energy facility, and a set of rules for establishing an event protocol of data transfer between IEDs. One of the standards is IEC 61850-7 deals with the issues of the organization of communication for substation equipment and feeder power transmission lines, which allows the standardization of the process of designing microgrids with DERs, as well as synthesizing new types of protections [54];
- IEC 61970 "Energy management system application program interface (EMS-API)"/ IEC 61968 "Application integration at electric utilities—System interfaces for distribution management". The IEC 61970 series of standards presents a general information model describing the equipment and other elements of the power system in the form of classes, their properties, and relationships. The IEC 61968 series of standards extends this model by describing other aspects of data exchange, such as asset management, work scheduling, and the billing of customers that operate as part of the microgrid;
- IEC 62056 "Electricity metering data exchange—The DLMS/COSEM suite". This series of standards establishes the requirements for the exchange of data from the results of the measurements of electrical quantities for electricity metering;
- IEC 62351 "Power systems management and associated information exchange—Data and communications security". This series of standards governs the issues of ensuring data and communications security;
- IEC/TP 62357 "Power systems management and associated information exchange". The series of standards specifies requirements for power system management processes and related information exchange.

Compliance with the requirements of the above standards enables the interaction of various elements in microgrids based on the plug-and-play principle. This greatly simplifies the process of integrating DERs into existing passive distribution networks, as well as improving conventional protection schemes and designing new protection schemes. Given that in microgrids with voltage up to 1 kV one traditionally uses circuit breakers with electrodynamic, thermal, and electronic (independent) trip units, as well as fuses, it is impossible to implement protective functions that meet current requirements without the use of IEDs.

4.1.2. Issues of the Switching Infrastructure

The adoption of information and communication technologies in power systems makes it possible to create cyber-physical systems, of which microgrids are an example. To ensure the reliable power supply to microgrid consumers, it is necessary to implement such protection schemes, which require extensive communications to exchange information between PDs.

Ensuring reliable communication between microgrid PDs is a challenging task due to a large number of influencing factors: microgrid topology, spatial extent, composition of communication interface components, the technologies of DERs (master/slave inverter, droop control), protection and control schemes, and reliability requirements. Study [55] demonstrated that several types of communications are most common: wired, optical fiber, wireless, Global System for Mobile Communications (GSM), Global Positioning System (GPS), eXtensible Markup Language (XLM), and their combinations. Classifying the types of microgrid communications with respect to their reliability and drawing on the results of the analysis from [55], we obtain the following:

- high reliability: optical cable; GSM; and the combination of local area network (LAN) with wireless and power line communication;
- low reliability: telephonic communications and GPS.

Here are the communication protocols most commonly used in the microgrid master controller: IEC 61850, Distributed Network Protocol (DNP 3.0), Modbus, Profbus, Wi-Fi, and Transmission Control Protocol/Internet Protocol (TCP/IP).

In [56], the use of the 5G cellular network as well as the IEC 61850 communication protocol was proposed as a type of communication. This could greatly simplify the process of creating a high-performance and reliable microgrid communication infrastructure with the possibility of its further expansion.

The use of communications when building protection schemes allows the implementation of fast and sensitive protections (differential current protection, adaptive centralized protections, multi-agent protections, etc.) but because of the different principles governing their operation, the disruptions of communication will have different impacts on their functioning. There are two main uses of communication technologies in protection schemes [57]. (1) Intensive: the provision of data exchange in real time, and (2) sporadic: data transfer when a fault occurs (estimation of fault current values) or changes in the network topology.

Protection schemes based on intensive data exchange, such as differential protection, are more sensitive to faults because they respond to the magnitude and direction of the current. The proper operation of such a protection is highly dependent on the reliability of the communication method through which the data are transmitted, because if it is broken (loss of connection, timestamp error), the protection loses its advantages and may even initiate a false trip, especially in a wireless information transmission environment, which is affected by noise and interference.

In adaptive centralized protections and multi-agent systems that use communication infrastructure, the algorithms of their operation are based on the evaluation of fault current levels. Data exchange between the PDs is performed only when certain events occur in the microgrid (fault, change of network topology). These protections have less stringent requirements on the communication infrastructure, since a delay in data transmission or a short-term communication disruption is not critical. This is due to the fact that data exchange serves to collect information about the topology of the microgrid in order to change the parameters of the PD setup. In the Modbus protocol, topology changes must be identified with a maximum delay of 1 to 10 s (depending on the size of the microgrid), while performing basic backup protection functions during the transition period. In the IEC 61850 protocol, changing the microgrid topology also triggers the process of changing the PD settings with acceptable time delays, as with the use of Modbus.

Due to the possibility of disturbances in communications, there are microgrid protection schemes that are supplemented by protection against faults in the communication channel [58]. Such solutions can reduce the damage from the interruption of data exchange between PDs, which is especially relevant for differential protections.

4.2. An Overview of Improved Conventional Protection Schemes

4.2.1. Improved Overcurrent and Voltage Protections

The most common method for improving overcurrent and voltage protections is to combine them, which enables creating a better type of protection. Other improvement methods mainly use machine learning and wavelet transform techniques.

In [59], the authors discussed a method for improving current protections based on the use of power directional elements and reverse sequence filters as well as a distributed reverse sequence control scheme based on VDE-AR-N-4120 Technical Connection Rules [60]. In [61], an improved overcurrent protection was considered, which enables detecting faults through large fault impedances. The protection was implemented using communication channels, wavelet packet transforms, and extreme machine learning. The wavelet transform allows one to isolate the high-frequency components of three-phase currents at both ends of the transmission line, and extreme machine learning, based on a neural network, makes it possible to identify the faulty phases. The proposed method uses the phenomenon of the occurrence of short-term asymmetry at the initial moment of the fault, characterized by the presence of odd harmonics. The method has several advantages: insensitivity to fault location in microgrids, fault impedance, power swings, and other interference.

In [62], a method of ensuring the selectivity of overcurrent protections in microgrids with DERs was proposed. As the objective function, the authors considered the minimization of the total tripping time of the dual setting overcurrent relay used for both primary and backup protection. The main problems with the application of the method are the limited values of the dual setting of the current relay that depends on the degree of fault current limit, as well as the need to align the protection with respect to the tripping time.

In [63,64], it was proposed to improve directional overcurrent relays by using time-current–voltage characteristic curves of tripping and dual overcurrent settings to improve the consistency of directional overcurrent relays. This approach was complemented by non-linear programming, which was implemented with a genetic algorithm, and to improve its performance, with the Grey Wolf optimization algorithm. Improved directional overcurrent protection was implemented in already installed IEDs, while ensuring the selectivity of the protections.

In [65], the use of smart meters to improve the efficiency of operation of overcurrent protections was proposed. Using information concerning voltages and currents from smart meters allows the solving of the problem of identifying the fault location. In this case, the switching capabilities of smart meters are used to adaptively change the set points of overcurrent protections with respect to current and trip times, as shown in Figure 1.

Study [66] discussed an approach to the implementation of directional overcurrent protections using resistive super conductor fault current limiters. This made it possible to obtain optimal set points of the tripping of overcurrent protections without violating the principle of selectivity of the already installed PDs. To achieve the task, an optimization method (the particle swarm method) was used.

In [67,68], the use of an adaptive overcurrent protection was proposed together with a thyristor circuit that determined the state of the microgrid connected to the power system where the current protection is installed. The adaptive current protection scheme allows the estimation of the equivalent impedance of the microgrid, which had different values in the grid-connected mode and the islanded mode. Based on this, it is possible to change the tripping set points of overcurrent protections in the microgrid. This engineering solution is simple enough and does not require additional communication channels, which makes it much cheaper.

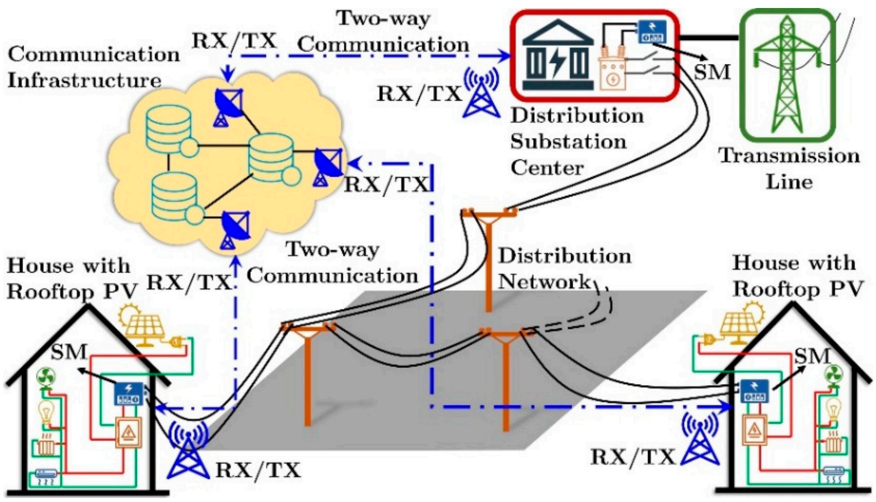

Figure 1. Effective use of smart meters in microgrids with DERs [65].

In [69], the use of voltage protections was proposed, employing a new type of voltage relays. The algorithm for this protection scheme uses voltage phasor measurements to identify fault locations in the microgrid. A schematic diagram of the Phasor Measurement Unit (PMU) voltage relay arrangement in the microgrid is shown in Figure 2.

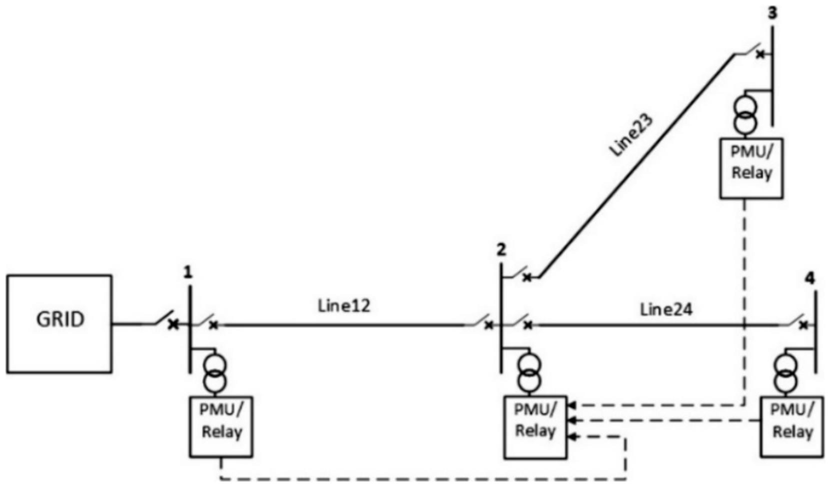

Figure 2. Application of a new type of voltage relays based on PMU [69].

This method makes it possible to identify the fault location by calculating the changes in active power and sensitivity in a particular protection zone, which includes the substation busbars and all outgoing feeders.

4.2.2. Improved Distance Protection Schemes

In [70], it was proposed to use improved distance protection schemes as protections of microgrids with DERs, with the algorithm of such protections additionally taking into account the zero-sequence impedance.

In [71], the protection of a microgrid with DERs based on the use of the apparent impedance of the power line was considered. The authors proposed the identification of any short circuit in the transmission line by the value of the deviation of the calculated apparent impedance from the real value of the single-phase impedance of the transmission line. The method uses only the voltage component along the d-axis from the remote end, which does not require accurate synchronization between measurements from both ends of the power transmission line. A time delay (up to 80 ms) was introduced, as it was required for the proper identification of the fault of the protected microgrid element and the faults of adjacent elements, including when the microgrid configuration is changed.

In [72,73], a method of improving distance protection by using impedance and phase angles was considered. Since the tripping time of this protection was chosen to be as short as possible, it ensured that the stability of the DER GU operation in the microgrid was maintained.

4.2.3. Improved Differential Protections

In [74], it was proposed that differential busbar protections based on symmetrical components in a microgrid with DERs be used. This method of designing protection is insensitive to changes in DER operation modes, which is an obvious advantage. In [58], it the application of differential protections with optical fiber communication lines was proposed, augmented with wavelength routing modules, in order to implement the clockwise protection of outgoing feeders (Figure 3).

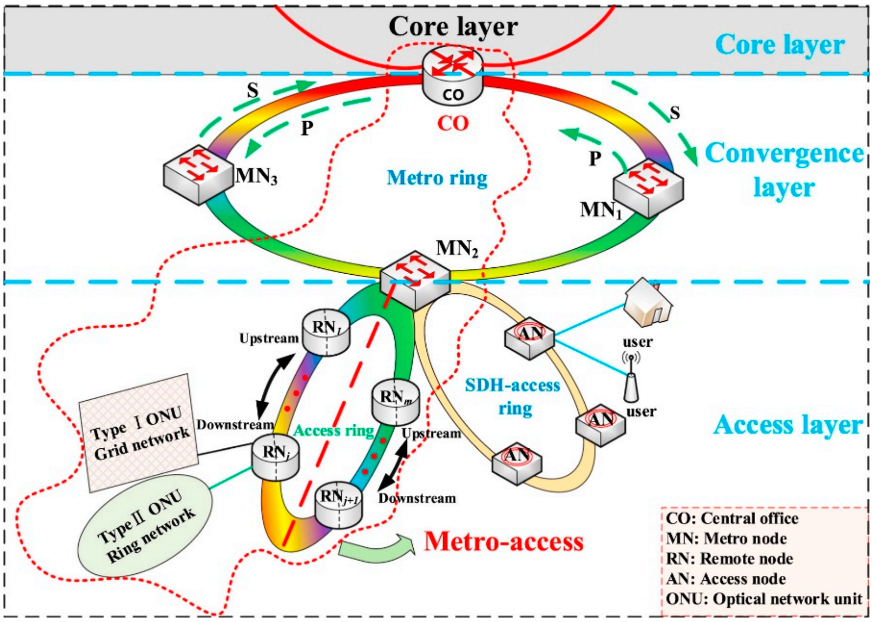

Figure 3. Diagram of network architecture of differential protection with optical fiber communication lines [58].

The implementation of the protection scheme requires the redundancy of the main communication channels, which can be used later when expanding microgrids. The authors of the article additionally suggested installing the protections of optical fiber communication lines.

Study [75] introduced an improved differential protection using a nonlinear signal transformation method referred to as "mathematical morphology". This method uses features that are based on three filtering operators: "erosion", "dilation", and "opening-closing-difference-filter". The use of filtering operators allows the extraction of a differential feature vector from the symmetrical current components, which initializes the tripping of the protection. The differential feature vector is also used as an input signal for training and testing when implementing machine learning to determine the most optimal set points for the main and backup current protections.

Studies [76,77] presented an improved differential protection algorithm that uses the S-Transform. The transform analyzes the time dependence of the fault signal energy, which allows the identification of the faulty microgrid element.

Study [78] introduced an improved differential protection scheme with a hybrid time–frequency transform based on the decomposition of the signal into functions, which are called "variational modes," and used the Hilbert transform to overcome the existing limitations of differential protection application (data window duration). The hybrid algorithm is highly tolerant to noise, allowing the faulty microgrid element to be detected and disabled in a timely manner.

4.3. Designing Adaptive (Decentralized and Centralized) Protection Schemes

One of the main elements of microgrids is IEDs, through which the control of its modes of operation is carried out. The introduction of IEDs allows one to abandon the use of conventional protections (overcurrent protections, voltage protections, distance protections, differential protections) in order to create adaptive protection schemes. Adaptive protection schemes must meet various requirements, such as selectivity and speed in identifying and disconnecting a faulty microgrid element. This makes it possible to implement the rapid self-healing of the microgrid after the localization of fault, as well as to restore power supply to consumers in the shortest possible time.

It is possible to create better protections by using the following:

- machine learning and artificial intelligence methods;
- Wide-Area Monitoring, Protection and Control (WAMPAC) devices;
- data exchange protocols compliant with IEC 61850 [79].

The use of the communication protocol compliant with IEC 61850 allows the implementation of adaptive protection schemes. In [54], an analysis of modern adaptive protection schemes is given, highlighting the main approaches:

- an approach based on computational intelligence whose actions are close to human reasoning;
- an adaptive approach based on modifications (combinations) of known approaches to improve the efficiency and reliability of protection schemes.

In [80–83], the authors highlighted the basic approaches to the design of adaptive protections and their modifications (combinations), which are based on the use of the following:

- artificial neural networks;
- metaheuristics;
- fuzzy logic;
- multi-agent systems.

The use of adaptive protections allows a relatively flexible and simple protection of a microgrid with DERs, taking into account the short-term imbalances of active and reactive power, grid reconfiguration, the changes of impedance directed from the microgrid, and microgrid operating modes (the grid-connected mode, the islanded mode).

There are two main approaches to building adaptive protection schemes: decentralized and centralized.

A decentralized adaptive protection scheme implies two-way communication between PDs in the microgrid. The tripping decision is made by each PD according to the preliminary check log. The data on the results of the pre-check of individual PDs (changes in the conditions of PD operation, the message on failures of operation) thus formed are sent to other PDs of the microgrid. As a rule, the decentralized approach to the design of adaptive protection schemes is implemented in multi-agent protection schemes [84].

The basis for designing a centralized adaptive protection scheme is the availability of communication channels between each PD in the microgrid and the central protection unit placed in the substation [85]. The central protection unit collects current and voltage measurements from microgrid elements, issues control actions to be applied to the PDs [86], and recalculates and issues new tripping set points of PDs when the microgrid operating conditions change.

4.3.1. Decentralized Adaptive Protections

The majority of research on adaptive protection schemes has focused on the use of intelligent analytical methods (e.g., the agent-based method), which allow significant amounts of data to be processed [87].

A system combining individual agents with a common objective, where information from each agent is used to find a solution, is called a multi-agent system (MAS). The improvement of microgrid protection schemes with DERs is possible through the use of MAS, as it uses new methods to find solutions to the objective function in order to improve their selectivity and speed.

In [88], the authors considered a possibility of augmenting the MAS with a fault location device on the power transmission line, with the subsequent partitioning of the faulty section in order to restore power supply to consumers on the non-faulted sections of the power transmission line.

One of the main disadvantages of MAS is the need for broadband communication channels, which hinders the application of such systems to implement protection algorithms [89], as it leads to a significant increase in the cost of PDs.

In [90–92], the protection of microgrids with DERs based on MAS with a dual action strategy was considered. The protection architecture was based on the use of IED agents as well as three additional agents (sensitivity, selectivity, and configuration) implemented in a single controller. The strategy for designing a multi-agent protection scheme was based on two complementary approaches: online and offline. The online approach allows the implementation of a fast protection through the collection of key information and the selection of protection actions based on expert systems. This requires communication infrastructure and the ability to control circuit breakers. With the application of the offline approach, backup protections are implemented to ensure fault localization in case of communication channel failures and longer-than-normal delay in the tripping of fast-acting online protections. In this case, the relevance check and adaptation of tripping set points of the backup protections is carried out in real time.

Study [93] presented an automatic adaptive protection scheme using a hybrid heuristic automation algorithm for selecting overcurrent and distance relay tripping set points. The hybrid algorithm was implemented in two stages. The first step was to perform a system analysis with a simulation of various faults, using, to this end, a database of relay measurement results. At the second stage, fuzzy sets were used to evaluate the correctness of the choice of tripping set points of overcurrent and distance relays.

Study [94] considered a design of a combined intelligent adaptive microgrid protection scheme based on a deep belief network and time–time transform. The time–time transform was used as a tool for fault identification because it amplified the high-frequency components of fault signals. Moreover, the time–time transform proved immune to interference, which was intrinsic to the discrete wavelet transform. Based on the time–time transform, information was extracted from the current measurements and then transferred to the deep belief network for fault identification and classification. This method requires the availability of the synchronized measurement of the currents at both ends of the transmission line, which was realized through the use of high-speed communication channels.

A decentralized uncoupled adaptive protection scheme is an adaptive protection scheme implemented without communication channels, which uses only local measurements of currents and voltages. Taking into account the fact that such PDs must make decisions on tripping without having information about the state of the other PDs in microgrids, the application of intelligent algorithms based on the use of artificial neural networks, metaheuristics, and fuzzy logic is required to improve their performance [95,96].

Studies [97,98] introduced a methodology for creating a decentralized adaptive protection scheme based on intelligent fault identification through the use of an intelligent fault detector in an unbalanced microgrid. The intelligent detector is used in the PDs installed at the ends of the element to be protected and does not require a communication channel between them. Each PD records current parameters of operating conditions to create a database for training each PD's local classifier using machine learning techniques. Since the PDs must distinguish between normal and fault operating conditions, the fault identification is treated as a binary classification problem: the sampling of fault and no-fault data. There are four steps in the proposed methodology: database creation, input data wrangling, parametrization, and the training of PDs by machine learning methods, and fault identification. In this case, the protection scheme takes advantage of machine learning, which greatly increases its effectiveness.

In [99], the use of a decentralized adaptive protection scheme without communication channels was proposed, which significantly reduces its cost. The protection scheme is based on the use of an artificial neural network to train IEDs that identify faults, as well as the use of a metaheuristic cuckoo search algorithm (a swarm intelligence algorithm) to determine the quasi-optimal protection setting. Using an artificial neural network makes it possible to identify faults with only the local measurements of currents and voltages available.

4.3.2. Centralized Adaptive Protection Schemes

Study [100] discussed the issue of designing a centralized fault management system based on the use of real-time ethernet information transmission technology. The authors noted the advantages of the cyclic structure of information transfer, and the centralized control system implemented through it provides high speed in fault localization due to a predetermined mis-synchronization error. In this case, the percentage differential protection was employed using instantaneous values of currents instead of their RMS values, which allows the localization of any fault within a time period not exceeding a sub-cycle overall fault clearance time.

In [46], the combination of centralized, distance, and multi-agent protection schemes into a class of Wide Area Protections (WAP) was proposed. Wide-area protection requires the development of a switching infrastructure in microgrids to enable large-scale information exchange [101].

There are two known basic concepts for designing wide-area protections. The first is based on differential [102] or distance protection [103], using the symmetrical and unbalanced components of currents. The other is based on the adaptive algorithm in the fault search blocking matrix used for fault identification and its subsequent clearing by implementing control actions in microgrids [104].

Study [105] discussed an adaptive centralized protection scheme that uses communication channels based on the IEEE 802.16 WiMAX technology, which makes it cheaper to implement this protection scheme. In [105], a centralized I-protection based on information and communication technologies of the Internet of Energy (IoE) was proposed, as shown in Figure 4.

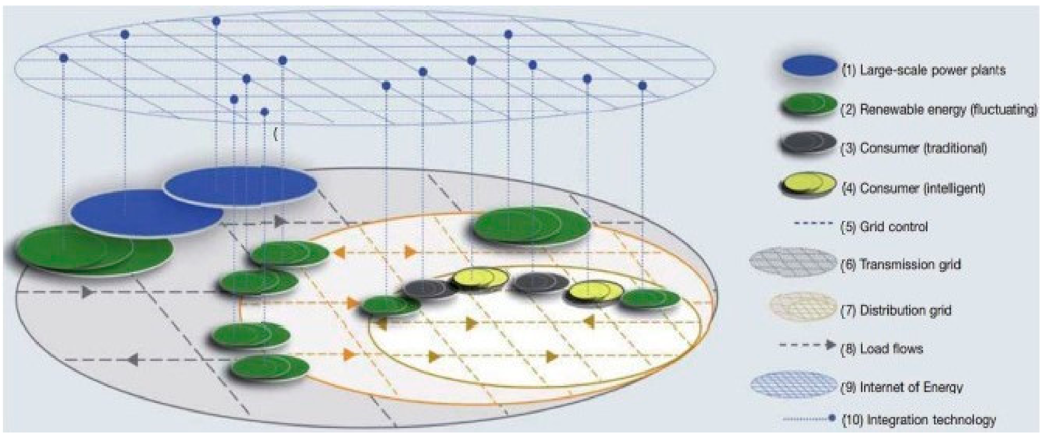

Figure 4. Application of IoE for transmission and sub-transmission of data at two levels of protection [105].

The proposed protection scheme uses the IEDs of different levels as the transmission medium (level 2) and sub-transmission medium (level 1) of information, which are part of the adaptive centralized protection scheme, as shown in Figure 5.

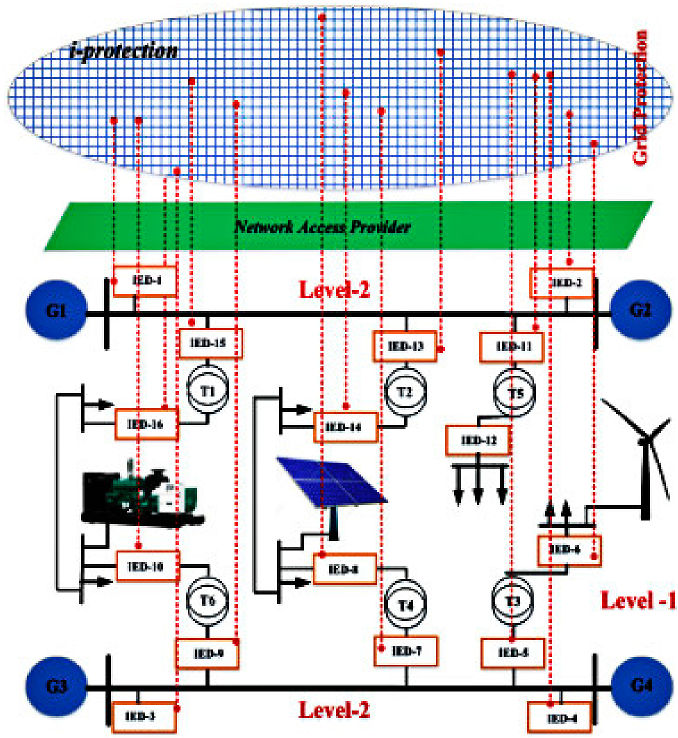

Figure 5. New relay topology based on *i*-protection [105].

The exchange of information between IEDs of all levels (transmission and sub-transmission) ensures the selectivity of the action of protections. Thus, an adaptive centralized protection scheme allows the provision of the reliable protection of microgrids with DERs in any of its configurations.

Adaptive protections, for all their functional advantages, also have significant disadvantages:

- the need for communication channels;
- the need to install high-performance IEDs;
- the need to take into account the various topological and operational situations;
- the complexity of fault current calculations in the presence of different types of DERs [106].

The improvement of conventional protection schemes through the use of machine learning, artificial neural networks, metaheuristics, and fuzzy logic can raise effectiveness to a new level. However, higher requirements are imposed on the IEDs in which these methods are implemented. In some cases, it is necessary to install additional compatible equipment, which reduces the technical reliability of such solutions.

The improvement of conventional protections or the use of innovative protections based on modern IEDs in microgrids with DERs should allow the reliable identification of fault locations, as well as their rapid and selective disconnection. This is necessary to ensure the reliable operation of DERs and power supply to consumers in the microgrid. The choice of specific approaches to the design of protection schemes in the microgrid with DERs should be based on the results of a comparative technical and economic analysis of different options.

4.4. Installation of Auxiliary Devices

The installation of auxiliary devices, such as FCL and ESS in microgrids, allows the mitigation of the negative effects of DER integration.

4.4.1. Fault Current Limiters

The FCL devices make it possible to reduce both the magnitude of fault currents within microgrids and fault current contributions from the power system [107]. Under normal operation, some types of FCLs have minimum impedance in order to reduce electricity and power losses, voltage losses, and the level of unwanted interference. When a fault occurs in a microgrid, the FCL sharply increases impedance to its maximum value to reduce the magnitude of the fault current.

The use of FCLs is the most practical method for solving the problem of selectivity of protections in microgrids. When a fault occurs in the power system, the FCL operates under normal conditions, and when a fault occurs in a microgrid, the FCL switches to the current limitation mode and ensures the selective action of overcurrent protections [108]. Since the FCL has a high speed, it makes it possible to reduce the magnitude of fault current contributions.

There are two concepts for designing FCLs: inductive and resistive. The inductive concept assumes that FCLs are connected in parallel to the power transmission line, and the resistive concept assumes that FCLs are connected in series to the power transmission line. The use of the inductive FCL is less efficient, since it uses a steel core, which, in addition to the weight and size disadvantages, creates additional power losses. Furthermore, common problems in the application of FCL in the microgrid include:

- the need to install an additional power device;
- ensuring the cooling requirements for FCLs, failure to comply with which may result in thermal breakdown of FCLs;
- difficulties in determining the magnitude of the FCL impedance due to the mutual influence of DERs in microgrids under different modes of operation;
- the need for availability of an accurate transient characteristic curve of FCLs.

4.4.2. Energy Storage Systems

Increasing the share of DERs connected to microgrids through inverters leads to a decrease in the level of fault current, which leads to a decrease in the sensitivity of protections, especially overcurrent protections. In order to ensure the necessary level of sensitivity, ESSs should be used, which allow increasing the magnitude of fault current to the tripping set points of the protections [109].

Since ESSs have a high speed, this allows a short-term increase in the fault current, which, when used in combination with FCLs, produces a synergistic effect. The effect is to limit the magnitude of the fault current contribution from the power system to a specified value by using a FCL, as well as to increase the level of the fault current in microgrids with DERs due to the output of the reactive component of current from ESSs [110].

The use of ESSs as an additional source of fault current contribution reduces the calendar life of the energy storage, which is due to its undesirable heating and degradation.

5. Conclusions

The trend of the last decade is the pervasive integration of heterogeneous DERs into microgrids, which has led to challenging issues related to the operation of protection devices. The article presents an overview of engineering solutions that allow both the increase in the effectiveness of conventional protection schemes and creating up-to-date microgrid protection schemes based on innovative principles and new methods.

The availability of broadband communication channels in microgrids allows the implementation of adaptive protection schemes that are more advanced relative to conventional protections. In addition, due to the synthesis with the algorithms of conventional protections, it is possible to create wide-area protections that allow the determination of the optimal tripping set points for all IEDs included in a microgrid.

The development of information and communication technologies (IEEE 802.16 WiMAX), based on the use of IoE, allows developing the most advanced centralized adaptive protection schemes, providing communication between different voltage classes. However, this requires the implementation of a unified approach to the design of protection schemes in microgrids with voltages of up to 1 kV and above 1 kV.

One of the ways to address the challenging issues of the operation of protections in microgrids with DERs is to use auxiliary devices: FCLs and ESSs. However, this significantly increases the cost of implementing protections in microgrids, but the approach can be employed when it is impossible and impractical to use other methods of protection design.

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Abbreviation

DER	distributed energy resources
PD	protection device
SC	short circuit
IED	intelligent electronic devices
FCL	fault current limiter
ESS	energy storage system
RES	renewable energy source
OCP	overcurrent protection
GU	generation unit
ACS	automatic control system
AR	automatic reclosing
WT	wind turbine
WAP	Wireless Application Protocol
GSM	Global System for Mobile Communications
GPS	Global Positioning System
XLM	eXtensible Markup Language
DNP	Distributed Network Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
PMU	Phasor Measurement Unit
WAMPAC	Wide-Area Monitoring, Protection, and Control Device
MAS	multi-agent system
WAP	Wide Area Protections
IoE	Internet of Energy

References

1. Filippov, S.P.; Dilman, M.D.; Ilyushin, P.V. Distributed Generation of Electricity and Sustainable Regional Growth. *Therm. Eng.* **2019**, *66*, 869–880. [CrossRef]
2. The Hoang, T.; Tuan Tran, Q.; Besanger, Y. An advanced protection scheme for medium-voltage distribution networks containing low-voltage microgrids with high penetration of photovoltaic systems. *Int. J. Electr. Power Energy Syst.* **2022**, *139*, 107988. [CrossRef]
3. Ilyushin, P.V.; Pazderin, A.V.; Seit, R.I. Photovoltaic power plants participation in frequency and voltage regulation. In Proceedings of the 17th International Ural Conference on AC Electric Drives (ACED), Yekaterinburg, Russia, 26–30 March 2018. [CrossRef]

4. Soshinskaya, M.; Crijns-Graus, W.H.J.; Guerrero, J.M.; Vasquez, J.C. Microgrids: Experiences, barriers and success factors. *Renew. Sustain. Energy Rev.* **2014**, *40*, 659–672.
5. Shushpanov, I.; Suslov, K.; Ilyushin, P.; Sidorov, D. Towards the flexible distribution networks design using the reliability performance metric. *Energies* **2021**, *14*, 6193. [CrossRef]
6. Pasonen, R. Community Microgrid—A Building Block of Finnish Smart Grid. Master's Thesis, Tampere University of Technology, Tampere, Finland, 2020; 119p.
7. Ilyushin, P.; Filippov, S.; Kulikov, A.; Suslov, K.; Karamov, D. Specific Features of Operation of Distributed Generation Facilities Based on Gas Reciprocating Units in Internal Power Systems of Industrial Entities. *Machines* **2022**, *10*, 693. [CrossRef]
8. Gadanayak, D.A. Protection algorithms of microgrids with inverter interfaced distributed generation units—A review. *Electr. Power Syst. Res.* **2021**, *192*, 106986. [CrossRef]
9. Suslov, K.; Shushpanov, I.; Buryanina, N.; Ilyushin, P. Flexible power distribution networks: New opportunities and applications. In Proceedings of the 9th International Conference on Smart Cities and Green ICT Systems, Prague, Czech Republic, 2–4 May 2020; Volume 1, pp. 57–64.
10. Pinto, J.O.C.P.; Moreto, M. Protection strategy for fault detection in inverter-dominated low voltage AC microgrid. *Electr. Power Syst. Res.* **2021**, *190*, 106572. [CrossRef]
11. Bui, D.M.; Chen, S.L.; Lien, K.Y.; Chang, Y.R.; Lee, Y.; Jiang, J.L. Investigation on transient behaviours of a uni-grounded low-voltage AC microgrid and evaluation on its available fault protection methods: Review and proposals. *Renew. Sustain. Energy Rev.* **2017**, *75*, 1417–1452. [CrossRef]
12. Bui, D.M.; Chen, S.L. Fault protection solutions appropriately proposed for ungrounded low-voltage AC microgrids: Review and proposals. *Renew. Sustain. Energy Rev.* **2017**, *75*, 1156–1174. [CrossRef]
13. Dehghanian, P.; Wang, B.; Tasdighi, M. New Protection Schemes in Smarter Power Grids with Higher Penetration of Renewable Energy Systems. *Pathw. A Smarter Power Syst.* **2019**, 317–342. [CrossRef]
14. Zheng, D.; Zhang, W.; Netsanet Alemu, S.; Wang, P.; Bitew, G.T.; Wei, D.; Yue, J. Key technical challenges in protection and control of microgrid. *Microgrid Prot. Control* **2021**, 45–56. [CrossRef]
15. Mirsaeidi, S.; Mat Said, D.; Wazir Mustafa, M.; Hafiz Habibuddin, M.; Ghaffari, K. Progress and problems in micro-grid protection schemes. *Renew. Sustain. Energy Rev.* **2014**, *37*, 834–839. [CrossRef]
16. Mirsaeidi, S.; Mat Said, D.; Wazir Mustafa, M.; Hafiz Habibuddin, M.; Ghaffari, K. An analytical literature review of the available techniques for the protection of micro-grids. *Int. J. Electr. Power Energy Syst.* **2014**, *58*, 300–306. [CrossRef]
17. Sinsel, S.R.; Riemke, R.L.; Hoffmann, V.H. Challenges and solution technologies for the integration of variable renewable energy sources—A review. *Renew. Energy* **2020**, *145*, 2271–2285. [CrossRef]
18. Sharma, N.K.; Samantaray, S.R. Issues and challenges in microgrid protection. *Microgrid Cyberphys. Syst.* **2022**, 233–254. [CrossRef]
19. Khalid, H.; Shobole, A. Existing Developments in Adaptive Smart Grid Protection: A Review. *Electr. Power Syst. Res.* **2021**, *191*, 106901. [CrossRef]
20. Telukunta, V.; Pradhan, J.; Agrawal, A.; Singh, M.; Srivani, S.G. Protection challenges under bulk penetration of renewable energy resources in power systems: A review. *CSEE J. Power Energy Syst.* **2017**, *3*, 365–379. [CrossRef]
21. Li, R. Protection and control technologies of connecting to the grid for distributed power resources. *Distrib. Power Resour.* **2019**, 121–144. [CrossRef]
22. Zheng, D.; Zhang, W.; Alemu, S.N.; Wang, P.; Bitew, G.T.; Wei, D.; Yue, J. *Microgrid Protection and Control*; Elsevier: Amsterdam, The Netherlands, 2021. [CrossRef]
23. Chandra, A.; Singh, G.K.; Pant, V. Protection of AC microgrid integrated with renewable energy sources—A research review and future trends. *Electr. Power Syst. Res.* **2021**, *193*, 107036. [CrossRef]
24. Ilyushin, P.V.; Sukhanov, O.A. The Structure of Emergency-Management Systems of Distribution Networks in Large Cities. *Russ. Electr. Eng.* **2014**, *85*, 133–137.
25. Majumder, R.; Dewadasa, M.; Ghosh, A.; Ledwich, G.; Zare, F. Control and protection of a microgrid connected to utility through back-to-back converters. *Electr. Power Syst. Res.* **2011**, *81*, 1424–1435. [CrossRef]
26. Ilyushin, P.V. Emergency and post-emergency control in the formation of micro-grids. *E3S Web Conf.* **2017**, *25*, 02002. [CrossRef]
27. Saad, S.M.; El-Naily, N.; Mohamed, F.A. A new constraint considering maximum PSM of industrial over-current relays to enhance the performance of the optimization techniques for microgrid protection schemes. *Sustain. Cities Soc.* **2019**, *44*, 445–457. [CrossRef]
28. Ilyushin, P.V. The analysis of dispersed generation influence on power system automatics settings and function algorithms. In Proceedings of the Methodological Problems in Reliability Study of Large Energy Systems (RSES), Irkutsk, Russia, 2–7 July 2018. [CrossRef]
29. Kulikov, A.L.; Sharygin, M.V.; Ilyushin, P.V. Principles of organization of relay protection in microgrids with distributed power generation sources. *Power Technol. Eng.* **2020**, *53*, 611–617. [CrossRef]
30. Sharygin, M.V.; Kulikov, A.L. Statistical methods of mode recognition in relay protection and automation of power supply networks. *Power Technol. Eng.* **2018**, *52*, 235–241.
31. Ilyushin, P.V. Analysis of the specifics of selecting relay protection and automatic (RPA) equipment in distributed networks with auxiliary low-power generating facilities. *Power Technol. Eng.* **2018**, *51*, 713–718. [CrossRef]
32. Kumpulainen, L.; Kauhaniemi, K. Analysis of the impact of distributed generation on automatic reclosing. In Proceedings of the IEEE PES Power Systems Conference and Exposition, 2004, New York, NY, USA, 10–13 October 2004.

33. Kulikov, A.L.; Anan'ev, V.V.; Vukolov, V.Y.; Platonov, P.S.; Lachugin, V.F. Modelling of wave processes on power transmission lines to improve the accuracy of fault location. *Power Technol. Eng.* **2016**, *49*, 378–385. [CrossRef]
34. Dubey, K.; Sanat; Jena, P. Protection schemes in microgrid. *Microgrid Cyberphys. Syst.* **2022**, 255–276. [CrossRef]
35. Saldarriaga-Zuluaga, S.D.; López-Lezama, J.M.; Muñoz-Galeano, N. Optimal coordination of over-current relays in microgrids considering multiple characteristic curves. *Alex. Eng. J.* **2021**, *60*, 2093–2113. [CrossRef]
36. Bogarra, S.; Rubión, X.; Rolán, A.; Córcoles, F.; Pedra, J.; Iglesias, J. Small synchronous machine protection during voltage sags caused by MV grid faults. *Electr. Power Syst. Res.* **2018**, *156*, 1–11. [CrossRef]
37. Lei, X.; Duan, J. Wind Farm tie-line protection setting based on adaptive current voltage protection principles. In Proceedings of the 2012 Asia-Pacific Power and Energy Engineering Conference (APPEEC), Shanghai, China, 27–29 March 2012. [CrossRef]
38. Ekanayake, J.B.; Holdsworth, L.; Wu, X.G.; Jenkins, N. Dynamic modeling of doubly fed induction generator wind turbines. *IEEE Trans. Power Syst.* **2003**, *18*, 885–895. [CrossRef]
39. Sadeghi, H. A novel method for adaptive distance protection of transmission line connected to wind farms. *Electr. Power Energy Syst.* **2012**, *43*, 1376–1382.
40. Zhou, C.; Zou, G.; Du, X.; Zang, L. Adaptive current differential protection for active distribution network considering time synchronization error. *Int. J. Electr. Power Energy Syst.* **2022**, *140*, 108085. [CrossRef]
41. Oudalov, A.; Fidigatti, A. Adaptive network protection in microgrids. *Int. J. Distrib. Energy Resour.* **2009**, *5*, 201–226.
42. Eissa, M.M. New protection principle for smart grid with renewable energy sources integration using WiMAX centralized scheduling technology. *Int. J. Electr. Power Energy Syst.* **2018**, *97*, 372–384. [CrossRef]
43. Pradhan, J.D.; Hadpe, S.S.; Shriwastava, R.G. Analysis and design of overcurrent protection for grid-connected microgrid with PV generation. *Glob. Transit. Proc.* **2022**, *3*, 349–358. [CrossRef]
44. Hallemans, L.; Ravyts, S.; Govaerts, G.; Fekriasl, S.; van Tichelen, P.; Driesen, J. A stepwise methodology for the design and evaluation of protection strategies in LVDC microgrids. *Appl. Energy* **2022**, *310*, 118420. [CrossRef]
45. Sotelo, G.G.; Santos, G.; Sass, F.; França, B.W.; Nogueira Dias, D.H.; Fortes, M.Z.; Polasek, A.; de Andrade, R., Jr. A review of superconducting fault current limiters compared with other proven technologies. *Superconductivity* **2022**, *3*, 100018. [CrossRef]
46. Habib, H.F.; Lashway, C.R.; Mohammed, O.A. A review of communication failure impacts on adaptive microgrid protection schemes and the use of energy storage as a contingency. *IEEE Trans. Ind. Appl.* **2018**, *54*, 1194–1207. [CrossRef]
47. Patnaik, B.; Mishra, M.; Bansal, R.C.; Jena, R.K. AC microgrid protection—A review: Current and future prospective. *Appl. Energy* **2020**, *271*, 115210. [CrossRef]
48. Anandan, N.; Sheeba, P.; Sivanesan, S.; Rama, S.; Bhuvaneswari, T.T. Wide area monitoring system for an electrical grid. *Energy Procedia* **2019**, *160*, 381–388. [CrossRef]
49. Namdari, F.; Jamali, S.; Crossley, P.A. Power differential based wide area protection. *Electr. Power Syst. Res.* **2007**, *77*, 1541–1551. [CrossRef]
50. Mousavi, S.A.E.; Chabanloo, R.M.; Farrokhifar, M.; Pozo, D. Wide area backup protection scheme for distance relays considering the uncertainty of network protection. *Electr. Power Syst. Res.* **2020**, *189*, 106651. [CrossRef]
51. Abd el-Ghany, H.A. Optimal PMU allocation for high-sensitivity wide-area backup protection scheme of transmission lines. *Electr. Power Syst. Res.* **2020**, *187*, 106485. [CrossRef]
52. Kulikov, A.L.; Loskutov, A.A.; Mitrovic, M. Improvement of the technical excellence of multiparameter relay protection by combining the signals of the measuring fault detectors using artificial intelligence methods. In Proceedings of the 2019 International Scientific and Technical Conference Smart Energy Systems (SES), Kazan, Russia, 18–20 September 2019; Volume 124, p. 01039.
53. SMB Smart Grid Strategic Group (SG3). *IEC Smart Grid Standardization Roadmap*; Tech. Rep. Ed. 1.0; International Electrotechnical Commission (IEC): Geneva, Switzerland, 2010.
54. Kaur, G.; Prakash, A.; Rao, K.U. A critical review of Microgrid adaptive protection techniques with distributed generation. *Renew. Energy Focus* **2021**, *39*, 99–109. [CrossRef]
55. Cagnano, A.; de Tuglie, E.; Mancarella, P. Microgrids: Overview and guidelines for practical implementations and operation. *Appl. Energy* **2020**, *258*, 114039. [CrossRef]
56. Demidov, I.; Melgarejo, D.C.; Pinomaa, A.; Ault, L.; Jolkkonen, J.; Leppa, K. IEC-61850 Performance Evaluation in a 5G Cellular Network: UDP and TCP Analysis. In *Handbook of Smart Energy Systems*; Springer: Cham, Switzerland, 2022; pp. 1–33. [CrossRef]
57. Kumar, S.; Islam, S.M.; Jolfaei, A. Microgrid communications—Protocols and standards. *Var. Scalab. Stab. Microgrids* **2019**, 291–326. [CrossRef]
58. Li, X.; Gan, C.; Liu, Z.; Yan, Y.; Qiao, H.B. Novel WRM-based architecture of hybrid PON featuring online access and full-fiber-fault protection for smart grid. *Opt. Commun.* **2018**, *407*, 69–82. [CrossRef]
59. Haddadi, A.; Kocar, I.; Mahseredjian, J.; Karaagac, U.; Farantatos, E. Negative sequence quantities-based protection under inverter-based resources Challenges and impact of the German grid code. *Electr. Power Syst. Res.* **2020**, *188*, 106573. [CrossRef]
60. Technical Connection Rules for High-Voltage (VDE-AR-N 4120). Available online: https://www.vde.com/en/fnn/topics/technical-connection-rules/tar-for-high-voltage (accessed on 20 October 2022).
61. Etingov, D.A.; Zhang, P.; Tang, Z.; Zhou, Y. AI-enabled traveling wave protection for microgrids. *Electr. Power Syst. Res.* **2022**, *210*, 108078. [CrossRef]

62. Asl, S.A.F.; Gandomkar, M.; Nikoukar, J. Optimal protection coordination in the micro-grid including inverter-based distributed generations and energy storage system with considering grid-connected and islanded modes. *Electr. Power Syst. Res.* **2020**, *184*, 106317. [CrossRef]
63. Dadfar, S.; Gandomkar, M. Augmenting protection coordination index in interconnected distribution electrical grids: Optimal dual characteristic using numerical relays. *Int. J. Electr. Power Energy Syst.* **2021**, *131*, 107107. [CrossRef]
64. Alam, M.N. Overcurrent protection of AC microgrids using mixed characteristic curves of relays. *Comput. Electr. Eng.* **2019**, *74*, 74–88. [CrossRef]
65. Chakraborty, S.; Das, S.; Sidhu, T.; Siva, A.K. Smart meters for enhancing protection and monitoring functions in emerging distribution systems. *Int. J. Electr. Power Energy Syst.* **2020**, *127*, 106626. [CrossRef]
66. Hatata, A.Y.; Ebeid, A.S.; El-Saadawi, M.M. Application of resistive super conductor fault current limiter for protection of grid-connected DGs. *Alex. Eng. J.* **2018**, *57*, 4229–4241. [CrossRef]
67. Ferreira, R.R.; Colorado, P.J.; Grilo, A.P.; Teixeira, J.C.; Santos, R.C. Method for identification of grid operating conditions for adaptive overcurrent protection during intentional islanding operation. *Int. J. Electr. Power Energy Syst.* **2018**, *105*, 632–641. [CrossRef]
68. Khatua, S.; Mukherjee, V. Adaptive overcurrent protection scheme suitable for station blackout power supply of nuclear power plant operated through an integrated microgrid. *Electr. Power Syst. Res.* **2020**, *192*, 106934. [CrossRef]
69. Manditereza, P.T.; Bansal, R.C. Protection of microgrids using voltage-based power differential and sensitivity analysis. *Int. J. Electr. Power Energy Syst.* **2020**, *118*, 105756. [CrossRef]
70. Ma, K.; Chen, Z.; Liu, Z.; Leth Bak, C.; Castillo, M. Protection collaborative fault control for power electronic-based power plants during unbalanced grid faults. *Int. J. Electr. Power Energy Syst.* **2021**, *130*, 107009. [CrossRef]
71. Mohammadi, S.; Ojaghi, M.; Jalilvand, A.; Shafiee, Q. A pilot-based unit protection scheme for meshed microgrids using apparent resistance estimation. *Int. J. Electr. Power Energy Syst.* **2021**, *126*, 106564. [CrossRef]
72. Eissa, M.M.; Mahfouz, M.M.A.; Sowilam, G.M.A. A new developed smart grid protection technique with wind farms based on positive sequence impedances and current angles. *Electr. Power Syst. Res.* **2020**, *178*, 106020. [CrossRef]
73. George, S.P.; Ashok, S. Adaptive distance protection for grid-connected wind farms based on optimal quadrilateral characteristics. *Comput. Electr. Eng.* **2021**, *93*, 107300. [CrossRef]
74. Jena, S.; Paladhi, S.; Pradhan, A.K. Bus protection in systems with inverter interfaced renewables using composite sequence currents. *Int. J. Electr. Power Energy Syst.* **2022**, *136*, 107665. [CrossRef]
75. Mishra, M.; Panigrahi, R.R.; Rout, P.K. A combined mathematical morphology and extreme learning machine techniques-based approach to micro-grid protection. *Ain Shams Eng. J.* **2019**, *10*, 307–318. [CrossRef]
76. Langarizadeh, A.; Hasheminejad, S. A new differential algorithm based on S-transform for the micro-grid protection. *Electr. Power Syst. Res.* **2022**, *202*, 107590. [CrossRef]
77. Maali Amiri, E.; Vahidi, B. Integrated protection scheme for both operation modes of microgrid using S-Transform. *Int. J. Electr. Power Energy Syst.* **2020**, *121*, 106051. [CrossRef]
78. Chaitanya, B.K.; Yadav, A.; Pazoki, M. An improved differential protection scheme for micro-grid using time-frequency transform. *Int. J. Electr. Power Energy Syst.* **2019**, *111*, 132–143. [CrossRef]
79. Alvarez de Sotomayor, A.; della Giustina, D.; Massa, G.; Dedè, A.; Ramos, F.; Barbato, A. IEC 61850-based adaptive protection system for the MV distribution smart grid. *Sustain. Energy Grids Netw.* **2018**, *15*, 26–33. [CrossRef]
80. Blaabjerg, F.; Yang, Y.; Yang, D.; Wang, X. Distributed Power-Generation Systems and Protection. *Proc. IEEE* **2017**, *105*, 1311–1331. [CrossRef]
81. Dagar, A.; Gupta, P.; Niranjan, V. Microgrid protection: A comprehensive review. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111401. [CrossRef]
82. Zheng, D.; Zhang, W.; Netsanet Alemu, S.; Wang, P.; Bitew, G.T.; Wei, D.; Yue, J. Protection of microgrids. *Microgrid Prot. Control* **2021**, 121–168. [CrossRef]
83. Barra, P.H.A.; Coury, D.V.; Fernandes, R.A.S. A survey on adaptive protection of microgrids and distribution systems with distributed generators. *Renew. Sustain. Energy Rev.* **2020**, *118*, 109524. [CrossRef]
84. Liu, Z.; Su, C.; Høidalen, H.K.; Chen, Z. A multiagent system-based protection and control scheme for distribution system with distributed generation integration. *IEEE Trans. Power Deliv.* **2017**, *32*, 536–545.
85. Brearley, B.J.; Prabu, R.R. A review on issues and approaches for microgrid protection. *Renew. Sustain. Energy Rev.* **2017**, *67*, 988–997. [CrossRef]
86. Ilyushin, P.V.; Kulikov, A.L.; Filippov, S.P. Adaptive algorithm for automated undervoltage protection of industrial power districts with distributed generation facilities. In Proceedings of the 2019 International Russian Automation Conference (RusAutoCon), Sochi, Russia, 8–14 September 2019. [CrossRef]
87. Shobole, A.A.; Wadi, M. Multiagent systems application for the smart grid protection. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111352. [CrossRef]
88. Kiani, A.; Fani, B.; Shahgholian, G. A multi-agent solution to multi-thread protection of DG-dominated distribution networks. *Int. J. Electr. Power Energy Syst.* **2021**, *130*, 106921. [CrossRef]
89. Rameshrao, A.G.; Koley, E.; Ghosh, S. An optimal sensor location based protection scheme for DER-integrated hybrid AC/DC microgrid with reduced communication delay. *Sustain. Energy Grids Netw.* **2022**, *30*, 100680. [CrossRef]

90. Dos Reis, F.B.; Pinto, J.O.C.P.; dos Reis, F.S.; Issicaba, D.; Rolim, J.G. Multi-agent dual strategy based adaptive protection for microgrids. *Sustain. Energy Grids Netw.* **2021**, *27*, 100501. [CrossRef]
91. Ghadiri, S.M.E.; Mazlumi, K. Adaptive protection scheme for microgrids based on SOM clustering technique. *Appl. Soft Comput.* **2020**, *88*, 106062. [CrossRef]
92. Hussain, A.; Aslam, M.; Arif, S.M. N-version programming-based protection scheme for microgrids: A multi-agent system based approach. *Sustain. Energy Grids Netw.* **2016**, *6*, 35–45. [CrossRef]
93. Meyer, G.J.; Lorz, T.; Wehner, R.; Jaeger, J.; Dauer, M.; Krebs, R. Hybrid fuzzy evaluation algorithm for power system protection security assessment. *Electr. Power Syst. Res.* **2020**, *189*, 106555. [CrossRef]
94. Gashteroodkhani, O.A.; Majidi, M.; Etezadi-Amoli, M. A combined deep belief network and time-time transform based intelligent protection Scheme for microgrids. *Electr. Power Syst. Res.* **2020**, *182*, 106239. [CrossRef]
95. Shen, S.; Lin, D.; Wang, H. An Adaptive Protection Scheme for Distribution Systems with DGs Based on Optimized Thevenin Equivalent Parameters Estimation. *IEEE Trans. Power Deliv.* **2017**, *32*, 411–419.
96. Saldarriaga-Zuluaga, S.D.; López-Lezama, J.M.; Muñoz-Galeano, N. Adaptive protection coordination scheme in microgrids using directional over-current relays with non-standard characteristics. *Heliyon* **2021**, *7*, e06665. [CrossRef]
97. Marín-Quintero, J.; Orozco-Henao, C.; Percybrooks, W.S.; Vélez, J.C.; Montoya, O.D.; Gil-González, W. Toward an adaptive protection scheme in active distribution networks: Intelligent approach fault detector. *Appl. Soft Comput.* **2020**, *98*, 106839. [CrossRef]
98. Chakraborty, S.; Das, S. Communication-less protection scheme for AC microgrids using hybrid tripping characteristic. *Electr. Power Syst. Res.* **2020**, *187*, 106453. [CrossRef]
99. Marín-Quintero, J.; Orozco-Henao, C.; Velez, J.C.; Bretas, A.S. Micro grids decentralized hybrid data-driven cuckoo search based adaptive protection model. *Int. J. Electr. Power Energy Syst.* **2021**, *130*, 106960. [CrossRef]
100. Liu, X.; Cai, Z.; Fan, H.; Yu, M. Experimental studies on the rtEthernet-based centralized fault management system for smart grids. *Electr. Power Syst. Res.* **2019**, *181*, 106163. [CrossRef]
101. Adamiak, M.; Apostolov, A.; Begovic, M.; Henville, C.; Martin, K.E.; Michel, G.L.; Phadke, A.G.; Thorp, J.S. Wide Area Protection—Technology and Infrastructures. *IEEE Trans. Power Deliv.* **2006**, *21*, 601–609. [CrossRef]
102. Hong, Q.; Kawal, K.; Paladhi, S.; Zhang, G.; Booth, C.; Terzija, V. Wide Area Monitoring, Protection and Control (WAMPAC). *Ref. Modul. Mater. Sci. Mater. Eng.* **2022**, 278–293. [CrossRef]
103. Li, Z.; Wan, Y.; Wu, L.; Cheng, Y.; Weng, H. Study on wide-area protection algorithm based on composite impedance directional principle. *Int. J. Electr. Power Energy Syst.* **2020**, *115*, 105518. [CrossRef]
104. Brahma, S.; Kavasseri, R.; Cao, H.; Chaudhuri, N.R.; Alexopoulos, T.; Cui, Y. Real-Time Identification of Dynamic Events in Power Systems Using PMU Data, and Potential Applications—Models, Promises, and Challenges. *IEEE Trans. Power Deliv.* **2017**, *32*, 294–301. [CrossRef]
105. Eissa, M.M.; Awadalla, M.H.A. Centralized protection scheme for smart grid integrated with multiple renewable resources using Internet of Energy. *Glob. Transit.* **2019**, *1*, 50–60. [CrossRef]
106. Fan, X.; Dudkina, E.; Gambuzza, L.V.; Frasca, M.; Crisostomi, E. A network-based structure-preserving dynamical model for the study of cascading failures in power grids. *Electr. Power Syst. Res.* **2022**, *209*, 107987. [CrossRef]
107. Farzinfar, M.; Jazaeri, M. A novel methodology in optimal setting of directional fault current limiter and protection of the MG. *Int. J. Electr. Power Energy Syst.* **2020**, *116*, 105564. [CrossRef]
108. Sadeghi, M.; Abasi, M. Optimal placement and sizing of hybrid superconducting fault current limiter for protection coordination restoration of the distribution networks in the presence of simultaneous distributed generation. *Electr. Power Syst. Res.* **2021**, *201*, 107541. [CrossRef]
109. Li, J.; Cornelusse, B.; Vanderbemden, P.; Ernst, D. A SC/battery Hybrid Energy Storage System in the Microgrid. *Energy Procedia* **2017**, *142*, 3697–3702. [CrossRef]
110. Adewole, A.C.; Rajapakse, A.D.; Ouellette, D.; Forsyth, P. Protection of active distribution networks incorporating microgrids with multi-technology distributed energy resources. *Electr. Power Syst. Res.* **2022**, *202*, 107575. [CrossRef]