Impact of Adaptive Protections in Electric Microgrids, Challenges and Future Trends

Eduardo Gómez-Luna¹, John E. Candelo², Eduardo Marrés³, Juan M. Guaridiola¹ and Jorge de la Cruz²

¹GITICAP Research Group. Potencia y Tecnologías Incorporadas S.A. Carrera 56 No. 2-50, Cali, Colombia. Santiago de Cali, Colombia.
²Applied Technology Research Group - GITA, Universidad Nacional de Colombia, Sede Medellín, Carrera 80 No. 65-223, Medellín, Colombia.
³High Voltage Research Group – GRALTA, Universidad del Valle, Calle 100 No 13-00, Cali, Colombia.

Received 21 May 2018; Accepted 14 December 2019

Abstract

This paper reviews and discusses the use of adaptive protections in microgrids. The main goal of the paper is to review the progress made in the last 10 years, to identify the challenges that are still present, and to note the current trends in the use of these protections in microgrids. The analysis is based on applications implemented since 2007, and on a wide bibliographical review of books, theses, patents, scholarly papers, conferences, technical reports, and experts’ experiences. The paper includes a comparative table that summarizes the reviewed literature and its findings. The paper is of interest to academics who do research on development and implementation of new robust and reliable protection schemes in microgrids, and to those in the industrial sector, who implement electric microgrids, and who want to understand the impact of their protection schemes.

Keywords: Centralized and decentralized adaptive protections, Microgrids (MG), distributed generation (DG), real-time simulation (RTS).

1. Introduction

Adaptive protections are a set of functions that allows the adjustment of their parameters according to modifications or new system requirements, making use of communication protocols [1]. The integration of distributed generation (DG), and the use of distributed energy resources (DER) on distribution networks (DN), have made power systems more complex [2]. This has changed the dynamics of the traditional networks [3], including bidirectional power flow, variable short circuit capabilities, and different fault paths on modern networks [2, 4–9]. As a result, several issues have risen in the operation of traditional protections [10–13] such as, loss of selectivity, false tripping, miss operation and faults of the anti-islanding protections [14]. These are caused by the type of source of DG, the nature of the energy resource (solar, wind, fuel) [15], the number of installed units, and the mode of operation of the microgrid (MG) (grid-connected or islanded mode) [3, 16–20].

These issues have led to the consideration of new strategies for the coordination and protection of the microgrids [21–33] that change and modify optimally the traditional protection schemes to ensure the correct operation of the MG in both connecting modes. Some authors propose to adapt and use traditional protections schemes [34–39]. For example, [34] proposes a method to coordinate different types of protections (over current relay (OCR), directional over current (OC) and differential) that ensures the operation of the MG on the faulty zone. This method demonstrated selectivity and an appropriate operation for a specific network topology; nonetheless, before generalizations can be made, this methodology will need to be evaluated in different scenarios and topologies.

Further, [35] shows that some of the issues about the integration of DG’s are resolved by using distance relays for protection of a distribution network. However, in [36] is shown that distance relays are inappropriate for applications in MGs, and a new directional element is proposed. This new element detects the direction of symmetrical faults by using the magnitude of the positive and negative sequence impedance, along with the positive sequence current and the torque angle, as well as the direction of asymmetrical faults by using the magnitude and angle of negative sequence impedance. Simulations showed that this new directional element is effective for different conditions and types of failures in the MG.

The authors in [37], propose a method to analyze and improve the response of a distance protection for a wind power DG unit connected to the distribution system. By compensating the wind intermittence, the proposed scheme changes dynamically in accordance to the variations of the power network. In [38] the authors propose a relay protection scheme with two types of settings, assisted by a communication path for a MG, with the capability of working connected to the main grid or in islanded operation mode. To maintain the proper coordination, they use directional overcurrent relays with two sets of adjustments, with a communication path with low bandwidth. This method does not require adaptive and continuous modifications on the relay settings, and its primary functionality is completely independent of the communication signal.

A new technique is introduced in [39] to solve the problem of low fault current presented in a MG in islanded operation mode. The technique connects all the loads neutral
points of the MG to the grounding system, which results in an increase in the fault current in the islanded mode of operation and reduction of the step voltage in every node.

To guarantee a correct operation of the MG, other authors recommend protection schemes that adapt to the MG operational conditions [40–50]. For example, in [40], the concept of agents for a DG anti-islanding protection is introduced, where multi-agent systems are used to coordinate the connection status of the DG unit. The authors in [41] suggest a protection scheme with digital relays based on a differential protection with a communication network applied to a distribution system with high penetration of alternative energy resources.

On the other hand, [42] brings into the discussion, the concerns of the protections in low voltage MG. The author presents an assessment of the use of communication protocols and the application of the standard IEC 61850, and suggests how to make the operation of the communication-based protections more reliable. In [43], the authors applied communication based protection schemes with differential relays to islanded systems, and test their efficacy and accuracy via real-time simulations.

In 2011, [44] proposed the use of an adaptive overcurrent protection, based on local information, with no need of a communication system, that allows to detect faults and the state of operation of the DG unit, by updating the relay tripping characteristics and their operational status. In [45], an adaptive scheme and a adaptable protection architecture is suggested for the new digital substations. The authors in [46] considered a hierarchical protection strategy based in digital overcurrent relays with communication assistance, that responds with adaptive settings according to the network topology, and differential control schemes, that protects the specific MG efficiently.

The authors in [47], describe how the use of the standard IEC 61850 and their logical nodes allow to update the protection settings, to locate and isolate a fault, and to restore a distribution network. The authors in [48], present and adaptive overcurrent protection, integrating both, the economic and technical advantages of fuses and relays on a MG. The relays are coordinated with the maximum nominal current of the fuses at the nodes, obtaining selectivity, reliability and speed in the operation when simulated. The authors in [49], discuss other configurations for the MG, specifically, ring microgrids, that emphasizes the protection and load adaptive behavior as a way to improve the detection of faults.

In 2018, the authors in [50], present an adaptive reclosing scheme, formed by a protective relay, two circuit breakers located at the side of the source and the load, and a battery energy storage system as an uninterruptible power supply. The scheme uses the neutral current in radial distribution network with unbalanced loads, determining the neutral current characteristics at the time a fault occurs, through the transformed wavelet analysis.

In view of the above, it is noticeable, how the concept of adaptive protection begins to be relevant, and how it has become one of the best options to protect a distribution network with MG integration.

Based on the review and analysis of the literature (sources shown in Fig.1), the next section, summarizes the adaptive protections, with an emphasis on ongoing implementations, challenges, and the impact of these types of protection. Section III discusses the current trends, and section IV offers some conclusions.

2. Adaptive Protections

Adaptive protections are characterized for storing several settings groups, and for applying them in the protection devices, in accordance with their operation topology. Through the implementation of communication protocols, [51,52][51,52] adaptive protections are able to modify their relay operation parameters [51,52].

Nowadays the advantages of the adaptive protection schemes are recognized over the traditional ones [53]. First, they are able to incorporate the changes in the status of the DG’s and breakers in order to adjust the protective relays, and more importantly, they operate correctly.

According to [1,3,54], the adaptive protection schemes used in MGs, can be divided into two types of protections: centralized and decentralized –multi-agent - adaptive protections. A Graphical representation of each of these can be seen in [17] and [12], respectively.

2.1 Centralized adaptive protections

A centralized protection structure has the particularity of containing remote control units or central protection units that store all the information about the MG. This stored information relates to the number and type of DG units, existing loads, and the status of the breakers. The main purpose is to establish links and monitor the equipment thru communication protocols that allow sending control signals to the protection devices.

Once the control units detect a change on the system’s characteristics, be the connection or non-connection of the DG, or a failure, using local or remote data, they produce new calculations to update the operational conditions of the microgrid, and to adjust their parameters to finally isolate the failure in the best possible way [1,2].

The main components in a centralized protection scheme and its characteristics are as follows:

**Centralized Control:** The centralized control is located at the point of common coupling or at the station of the main reconnecter; it counts with communication protocols of type IEC 61850 and IEC 61870-5-104. It incorporates all the DG’s information, and carries over the control function. Common types of Centralized Controls, are the Programmable logic controllers, PLC’s, which are used for decision making processes, the selection of pre-calculated setting groups, and control of the DG units, either remotely or locally, through a communication protocol based on IEC 61131-3 ([55,56][57,58]).
**Grid automation controller:** The grid automation controller is responsible for establishing the modes of operation of the MG automatically or manually. It takes into account all of the changes, topology modifications, protection settings, and remote control of the DG’s. The signal is taken to the PLC’s through the main server, where all the settings to be implemented are stored [56][59].

**Information management servers:** these collect and store the information obtained throughout the communication protocols from every relay, detect the system changes and gather the data when faults occur [60].

**Supervisory Control And Data Acquisition:** The SCADA/DMS behaves as the control center of the entire red in a centralized scheme, and performs the evaluation of all the components in the red. From this evaluation, the mode of operation of the Smart Substation Controller (SSC) is determined. This controller has the ability to modify the relay connection groups, and collect local data using sensors to determine the actual state of the network [61].

**Microgrid central protection unit (MCPU):** The MCPU performs the communication operation with all the relays in the MG and DG units. In accordance with status of the units, i.e., connection or non-connection, the protection equipment will update its settings and, ultimately, detect a fault in the system. Simultaneously, the control unit counts with a communication and control module (CCM), where time delays for selectivity are calculated and embedded into the protective relays. The communication scheme is achieved by a TCP/IP protocol, based on Ethernet network for instant communication [54].

### 2.2 Decentralized adaptive protections

A decentralized adaptive protection structure groups multiple intelligent entities named agents, which allow autonomy in the system decision-making processes [9]. These agents, which are distributed throughout the network, consist of hardware and smart software entities, including expert algorithms for task execution. The communication between the agents is achieved through protocols, which allow them to act in response to a specific assignment, and to establish communication with the other agents, as a way to fulfill a common objective [62,63]. Adaptive protections are inserted in the DG units in the protection and control schemes [64–68], identifying and acting according with the system necessities.

According to [62], the principal elements that conform a multi-agent protection scheme are layers, and each layer is formed by several agents. The following lists the agents most commonly used:

- **Measurement agents:** the measurement agents are located in the measurement devices of the MG; these include the current, voltage transformers, and phasor measurement units.
- **Protection agents:** these agents use digital relays or Intelligent Electronic Devices (IED’s) and overcurrent relays.
- **Mobile agents:** these agents exchange information with the upper layers.
- **Performance agents:** performance agents determine the relay settings incorporating the topological changes of the network.
- **System agents:** these agents monitor the network using communication protocols.
- **Evaluator agents:** these agents validate the settings information, selectivity and the operation of the relays.

In what follows, we will discuss the operational conditions, applications, the challenges, and the impacts of the decentralized and centralized adaptive protections:

#### 2.3. Operational Conditions and applications

**Operational conditions for the selection of a centralized protection:** The operational conditions of a protective scheme in a MG, and the system protection needs will determine the more suitable choice between centralized or decentralized type of adaptive protection. The following are the conditions needed for the selection of a centralized protection:

- **Selectivity:** it requires the implementation of more sensitive methods than those made for overcurrent protections, in order to detect faulty zones, without being affected by the generation units intermittence [69].

**Communication and data transfer in short distances:** a centralized protection requires short-distance communications in order to reduce the delays on data transfers. This is necessary to increase the reliability of the centralized protections in the process of data exchange [69].

**Coordination in the operation of protective equipment:** a centralized protection requires coordination in the operation of the protection devices. In this way it is possible to identify the location of a fault inside the MG through the tripping signals from the circuit breakers; hence, isolate the faulty zone without losing continuity in the network [69].

**Optimal operation in the presence of dynamic changes of the MG:** this guarantees that the adjustment and operational parameters from the protective devices are updated optimally [54,69].

**System structure and protection hierarchy:** due to the dynamic state of the MG, it is required to know its status continuously, to identify the connection mode of the generation units, and their protection coordination [54].

**Simplicity:** given that the data processing and control are directed from the central unit, the network elements like the circuit breakers, the controllers in the loads, and the generators need to be constructively simple [55].

**Applications of centralized protections:** Implementation of centralized adaptive protections have been reported in [56,61,70–77]. The authors of [56], report a pilot case of a MG integrated to a medium voltage distribution network, DN, in isolated mode of operation, which was implemented in Hailuoto – Finland. The system counted with a 20 kV feeder with a recloser, a 0.5 MW wind turbine, and a 1.5 MW diesel generator. The grid automation controller was located in the recloser to execute the control over the generation units, and to allow the communication process through the IEC 61850 protocol.

In [61], the adaptability of the protective relay for the DG unit is verified through real-time simulation (RTS). The
authors in [70], propose an adaptive protection scheme with a microgrid central protection unit (MCPU), and 15 Intelligent Electronic Devices (IED’s), which were distributed in the nodes, loads and DG units, with communications happening through a wide range wireless network, based on WiMAX technology. Its behavior was validated throughout simulations that showed the system complied with the latency requirements and protected the proposed MG.

In [71], an adaptive protection algorithm was verified in the IEEE 13 node modified model, by adjusting the protection settings in response to changes in the generation units. In [72], a Denmark 10 kV network was modified by adding loads and several DG units (1 PV, 5 wind turbines, 4 combined cycle plants). In addition, the authors test an online detection algorithm for an overcurrent adaptive protection, and a decentralized communication system to detect changes in the topology of the MG.

Using RTS, the authors in [73], report the effectiveness of an adaptive protection system for overcurrent relays for a countryside MG with DG units, changing their modes of operation using the IEC 61850 protocol. In [74], a centralized adaptive scheme with phasor measurement units (PMU’s) and a control protection unit (CPU) was designed. This protection system was based on positive sequence components that were able to detect the incident and the affected zones, and protect against different types of faults and topologies in the MG.

In [75] the authors used a microprocessor relay model with a digital communication system instead of a CPU, able of detecting different type of faults and the faulty phase. Similarly, the system blocks the signal that flags the problem, protecting the MG in both modes of operation. In [76], an adaptive protection coordination scheme based in the algorithm of the Artificial Bee Colony (ABC) is presented. This protection allows an optimal directional overcurrent relay (DOCR) coordination in the IEEE 30 node with multiple DG units, where a master server is used as central unit, enabling communication with the relays as a way to select the proper settings for each device and monitoring the network changes.

In [77] a MG is modeled with distributed energy resources, electronically coupled with an adaptive protection scheme. This model ensures the MG protection for different types of contingencies, independently of its operation mode. It uses reclosers, overcurrent relays based on microprocessors, and a microgrid communication path between all the relays and the DG units. The novelty of the proposed scheme is its capacity to monitor the MG, and instantaneously update the relay fault current, according to the variations in the system.

The authors in [78], work with a patented adaptive overcurrent protection method on a pico grid formed by a MCPU, updating its mode of operation and the protection settings, in response to the location and type of fault

**Operational conditions for the selection of a decentralized protection:** The following are the conditions needed for the selection of a decentralized protection:

**Selectivity:** selectivity in a decentralized protection is achieved throughout the intelligence incorporated in the local devices, and the cooperation between agents, which allow the identification of faulty zones with great accuracy and reliability, avoiding false tripping.

**Decentralized architecture:** the decentralized architecture requires that the decision making and local information exchange be adjustable to the distributed characteristics of the MG [79].

**Flexibility:** a decentralized protection must be able to adapt to the conditions of the system, independently of the type of generation or load in the system [79].

**Resilience:** a decentralized protection must have the capacity to respond and isolate a fault, without interrupting its operation and objectives [79,80].

**Communication and data transfer at different distances:** A decentralized protection must be able to transfer data at different distances. Depending on the communication system, and on its speed, a decentralized protection system can communicate its information and monitor the system locally or remotely, offering robustness.

**Local operation of protective devices:** A decentralized protection must be able to perform self-validation, self-correction, and act quickly in response to a contingency [81].

**Simplicity:** decentralized protections must have simple agent platforms with precise algorithms that ensure an optimal use of the MG resources [82].

The use of decentralized adaptive protections for analysis, protection, isolation and restoration of the energy service after a contingency, using different methodologies have been reported in [59,83–87]. In [59], relays settings are modified off-line through simulations and the faults are cleared on-line, maintaining the selectivity of the protective devices. In [83], an expert algorithm that mimics the human cellular behavior of the immune system is adopted for the agents, improving the reliability in the equipment response and avoiding the use of the central controllers.

According to [84], multi-agent systems (MAS) are applied to achieve an efficient power management and fault restoration, forming dynamic groups for the administration of the agents, with a flexible structure. The authors in [85] propose a multi-agent system based on the magnitude and direction of the sequence current to locate and isolate a fault in a MG. The authors in [86] use the Ybus algorithm, defining Ip currents as initial conditions for the modes of operation of the MG. The communication among agents is achieved using TCP/IP protocols.

In [87], the phase angle of a current signal is compared and a communication assisted method is implemented using the protocol IEEE std. C37.118.

In [88], a decentralized adaptive protection development based on distributed logic was patented. The system divides the distribution network (DN) into multiple areas, which are composed of a busbar, an area controller, and a protective device. This method allows for the detection of any local changes in the network, and re-calculation of level of the short circuit in the specific area.

### 2.4. Challenges

Despite finding several examples of applications of adaptive protections with clear significant operative advantages, they are still in the process of research and development. One of the main challenges identified in the reviewed literature is the operative speed of the protection, the re-adjustment of its settings, and the minimization of the number of users affected from contingencies that can be caused by the connection and disconnection of big DG units, or by the change in the operation mode of the MG [56]. Other challenges include the
improvement of the delay times and sensitivity of the adaptive protections to guarantee a correct coordination in their operation [89].

Due to all the possible scenarios in a MG, it is complicated to calculate and consider settings and adjustments in an infinite number of cases. As a result, to ensure a complete protection, the most representative and significant cases are selected [73]. Similarly, when considering different distributed energy resources, it is necessary to define the criteria for the relay settings [90].

On the other hand, like smart grids, adaptive protections depend heavily on communication systems. Therefore, all the issues that are inherent to any communication system also affect them [91]. In addition, they are vulnerable to the problems of interoperability and exchangeability [92], and to cyber-attacks [93–95]. All these are external issues that affect their operational integrity [91].

Decentralized schemes also present many challenges that need to be addressed and resolved before they become a popular alternative [96]. These challenges include portability, security, and emerging behavior of the multi-agent systems [79]. Similarly, delay times in data transfer and communications [82,86,97], and delays on the circuit breakers operations [98] need to be improved. Furthermore, it is necessary to develop more economically efficient schemes with PMU’s [87].

Additional challenges include addressing information security, [99]; obtaining standardization of the agent modules, [62], [79], [81], [99]; dealing with the impact of government regulations and achieving economic efficiency [100,101]. Furthermore, the MAS need to be implemented in real settings, and tested in systems that are more complex [101–103].

2.5. Impacts

According to the authors in [104], adaptive protections are seen as a necessary element in a smart grid and are currently among the best options for protection of MGs.

As discussed above, centralized adaptive protections rely on the network paths, and communications to detect changes in the system and adjust parameters. Therefore, events that lead to a loss of information and communication between the units will greatly affect the MG. These include cyberattacks carried out throughout the system’s communication network that can cause distortions in the IED’s units and transmit malicious codes that lead to buffer overflows that create inconveniences for the control of the system’s data. Similarly, of importance are cyberattacks that occur in the data transmission systems like the Generic Object Oriented Substation Event (GOOSE), and the Sampled Measured Valued systems SMV, which are both part of the IEC 61850 protocol [93,105]. Because these carry vital information (alarm, status, and control) between devices, alterations of these values could create an automation breakdown, causing a circuit breaker to miss an operation. The authors in [106] summarize the cyber security standards and privacy for smart grids.

Selecting decentralized adaptive protections in accordance to the application will reduce costs (due to the fact that voltage transformers are not used [87]); it will shorten the data transfer process and reduce the delay time while isolating a fault [86]. In addition, it will guarantee protective selectivity, offering robustness to the system [59,82,107], and accuracy and reliability in the operation of the MG [108].

Furthermore, the coordination among agents and artificial intelligence articulation [83,109,110] provide autonomy to the devices used for decision making processes, in response to the changes of the MG. This leads to an optimal use of energy resources with better reasoning times [82]. In addition, this allows to modify the system architecture, determine with precision and restore the faults dynamically [84,111], analyzing, validating, acting and managing the daily system operation [81,112,113]. Additionally, the local decision making process improves the communication system response and the errors related to them [114].

3. Future Trends of Adaptive Protections in Electric MG

As the development and implementation of micro-grids increase around the world, so will the use of adaptive protections in MGs. It is clear then that validating their operation schemes in real-time, becomes a necessary step in order to guarantee a reliable operation. Some studies have begun using real-time simulation (RTS) [69,115–119] with hardware in the loop configuration (HIL). Optimal coordination adjustments have been determined for an adaptive protective scheme before its physical implementation. Tests performed with real-time (RTS) and non-real-time simulation (NRTS) has been also compared [120], validating the selectivity, reliability and speed for the adaptive overcurrent protection systems.

Other research has shown the use of Real Time Simulations (RTS) as a way to test communication protocols [121], like the IEC 61850 and the third generation of the Distribution Network Protocol (DNP3). Their integration into smart grids in real-time will be for sure in continuous development. The authors of [122], provide a comprehensive summary of RTS in applications in MG, outlining the test techniques, and existing methodologies in regards to the quality of power, stability, control and protections of the MG.

According to [123], the future of adaptive protections, points to the development of new and novel methods, that will address improvements in the communication systems [123–125]. Developments that make adaptive protections suitable to protect any type of fault, for example, capable of detecting high impedance faults [126], and that are capable of optimizing the protective relay capacity [126], in order to maintain the security in any type of MG (AC, DC, AC/DC) [127]. Similarly, [128] and [129] propose schemes that are more robust for hybrid, and islanded MGs, respectively, as solutions to some of the impacts discussed above.

Currently, IEEE 1547 and IEEE 2030 specifications do not include standards for the interconnection and interoperability of distributed energy resources by adaptive protections, [130], [131–133]. Therefore, progress needs to happen in the development of standards and regulations that allow for the unification of the design, planning, and operation of MGs with adaptive protections. Tab.1 and Tab.2 summarizes, the applications, challenges, and trends for a centralized and decentralized adaptive protection respectively, discussed in the reviewed references.
Table 1. Applications, challenges, and future trends of a centralized adaptive protections

| IMPACT OF ADAPTIVE PROTECTIONS IN MG | REFERENCES |
|-------------------------------------|------------|
| **Applications**                   | **Challenges** | **Trends** |
| Analysis, monitoring and fault diagnosis | Fault location | Communication speed | - | [69],[72] |
|                                    | Fault isolation | Improve the operative speed | - | [54,56,69] |
|                                    | Information management and system status | Improve the communication links with the central control unit in long distances | - | [54,69,72] |
|                                    |                  | Change in the configuration of the DG’s | - | [71,73] |
| Protection coordination            | Relay settings modification (off-line) | - | - | [54,55,69,71] |
|                                    | Reorganization of the protections hierarchy | - | - | [54,89] |
|                                    | Limited fault scenarios | Calculation of settings in Real-time | [89] |

Table 2. Applications, challenges, and future trends of a decentralized adaptive protections

| IMPACT OF ADAPTIVE PROTECTIONS IN MG | REFERENCES |
|-------------------------------------|------------|
| **Applications**                   | **Challenges** | **Trends** |
| Analysis, monitoring and fault diagnosis | Fault location | - | - | [83,85–87,99,108] |
|                                    | Fault isolation | - | - | [83,86,87,100,108]; [83,84,86,87,108,111] |
|                                    | System restoration | - | - | [59] |
|                                    | Clearing faults on-line | - | - | [59,81,98,103,112] |
| Protection coordination            | Relay settings modification (off-line) | - | - | [59,81,98,103,112] |
| Power and demand management        | Load ejection | - | - | [82,84,103,114] |
|                                    | Efficient power management | - | - | [82,84,103,114] |
|                                    | Improve delay times in data transfer | - | - | [79,82,86,98] |
|                                    | Economical protection schemes and less sensitives | - | - | [87,100,101,111] |
|                                    | Information security | - | - | [79,99] |
|                                    | Standardization of the agent technology | - | - | [62,79,81,99,101,108] |
|                                    | Real and complex systems implementations | - | - | [79,84,102,103,112] |
|                                    | Validate the information delay times with simulation software’s and expert algorithms software’s development of more simulation software’s and expert algorithms software’s implementation of intelligent devices, sensors, optimal measurements in different sections of the network | - | - | [59,86,98] | [86] | [87] |
|                                    | Prove the efficiency of the protection schemes in different | - | - | [84,108,123] |
4. Conclusions

The current state and future trends of adaptive protections in MGs were presented, as well as their applications, the impacts from their implementation, and the challenges that lie ahead. It was observed that more efficient schemes and reliable communication systems still need to be developed, and that research and development needs to focus on the development of systems that are less vulnerable to contingencies and cyber-attacks. The progress in decentralized adaptive schemes will need to provide protections that are more dynamic. These need to be equipped with artificial intelligence to guarantee decisions and operation autonomy, to monitor and diagnose faults, and ultimately, accomplish the correct protection coordination. In order to ensure their reliability in real-life settings, it is necessary to carry over tests and detailed validations of adaptive protections that include tests of their communication systems using real-time simulations. Adaptive protections were shown to have a positive impact on MGs, specifically in regards to selectivity, speed, and sensitivity. According to the reviewed literature, as the number of applications of adaptive protections in real and more complex settings grows, evidence on their effectiveness and reliability will be clear. As a result, adaptive protections will be seen as the proper scheme for protection of any type of microgrid.

Acknowledgments

The authors would like to thank Potencia y Tecnologias Incorporadas, PTI, S.A for the support during this research. We also thank the GITICAP group from the same company, for their contributions during the development of the innovation project 54558-2016 approved by the CNBVT from Colciencias. Further, we thank the Universidad del Valle and Universidad Nacional for their participation, and support with this research project.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License

References

[1] Hosseini SA, Abyaneh HA, Sadeghi SHI, Razavi F, Nasiri A. An overview of microgrid protection methods and the factors involved. Renew Sustain Energy Rev 2016;64:174–86. doi:10.1016/j.rser.2016.05.089.

[2] Memen AA, Kauhaniemi K. A critical review of AC Microgrid protection issues and available solutions. Electr Power Syst Res 2015;129:23–31. doi:10.1016/j. EPSR.2015.07.006.

[3] Brearley BJ, Prabu RR. A review on issues and approaches for microgrid protection. Renew Sustain Energy Rev 2017;67:988–97. doi:10.1016/j.rser.2016.09.047.

[4] Stadler M, Cardoso G, Mashayekh S, Forget T, DeForest N, Agarwal A, et al. Value streams in microgrids: An overview. Energy Procedia 2016;12:137.

[5] Hooshayar A, Iravani R. Microgrid Protection. Proc IEEE 2017;105:1332–53. doi:10.1109/JPROC.2017.2669342.

[6] Mumtaz F, Bayram IS. Planning, Operation, and Protection of microgrids: An Overview. Energy Procedia 2017;105:1332–40. doi:10.1016/j.egypro.2016.12.137.

[7] Muruganantham B, Gnanadass R, Padhy NP. Challenges with renewable energy sources and storage in practical distribution systems. Renew Sustain Energy Rev 2017;73:125–34. doi:10.1016/j.rser.2017.01.069.

[8] Yoldag Y, Onen A, Muyeem SM, Vasilakos A V., Alan I. Enhancing smart grid with microgrids: Challenges and opportunities. Renew Sustain Energy Rev 2017;72:205–14. doi:10.1016/j.rser.2017.01.064.

[9] Teimourzadeh S, Amini far F, Davarpanah M. Microgrid dynamic security: Challenges, solutions and key considerations. Electr J 2017;30:43–51. doi:10.1599/ej.2017.04.015.

[10] Gabbar HA, Islam R, Isham MU, Trivedi V. Risk-based performance analysis of microgrid topology with distributed energy generation. Int J Electr Power Energy Syst 2012;43:1363–75. doi:10.1016/j.ijepes.2012.05.061.

[11] Eissa MM. Protection techniques with renewable resources and smart grids - A survey. Renew Sustain Energy Rev 2015;52:1645–67. doi:10.1016/j.rser.2015.08.031.

[12] Manditereza PT, Bansal R. Renewable distributed generation: The hidden challenges - A review from the protection perspective. Renew Sustain Energy Rev 2016;58:1457–65. doi:10.1016/j.rser.2015.12.276.

[13] Akhtar Z, Saqib MA. Microgrids formed by renewable energy integration into power grids pose electrical protection challenges. Renew Energy 2016;99:148–57. doi:10.1016/j.renene.2016.06.053.

[14] Guo X, Xu D, Wu B. Overview of anti-islanding US patents for grid-connected inverters. Renew Sustain Energy Rev 2014;40:311–7. doi:10.1016/j.rser.2014.07.190.

[15] Hare J, Shi X, Gupta S, Bazzi A. Fault diagnostics in smart microgrids: A survey. Renew Sustain Energy Rev 2016;60:1114–24. doi:10.1016/j.rser.2016.01.122.

[16] Coni S. Analysis of distribution network protection issues in presence of dispersed generation. Renew Sustain Energy Res 2009;79:49–56. doi:10.1016/j.ijepesr.2008.05.002.

[17] Basak P, Chowdhury S, Halder Nee Dey S, Chowdhury SP. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew Sustain Energy Rev 2012;16:5545–56. doi:10.1016/j.rser.2012.05.043.

[18] Ju ST, Mwasilu F, Lee J, Jung JW. AC-microgrids versus DC-microgrids with distributed energy resources: A review. Renew Sustain Energy Rev 2013;24:387–405. doi:10.1016/j.rser.2013.03.067.

[19] Palizban O, Kauhaniemi K, Guerero JM. Microgrids in active network management - Part II: System operation, power quality and protection. Renew Sustain Energy Rev 2014;36:440–51. doi:10.1016/j.rser.2014.04.048.

[20] Yang J, Wang Y. Review on protection issues of low-voltage distribution network with multiple power-electronic-converter-interfaced distribution energy resources. Int Conf Renew Power Gener (RPG 2015) 2015:1–6. doi:10.1049/cp.2015.0327.

[21] Coni S, Nicotra S. Procedures for fault location and isolation to solve protection selectivity problems in MV distribution networks with dispersed generation. Electr Power Syst Res 2009;79:57–64. doi:10.1016/j.epsr.2008.05.003.

[22] Tuittemwong K, Premrudeepreechacharn S. Expert system for protection coordination of distribution system with distributed generators. Int J Electr Power Energy Syst 2011;33:466–71.
Li XL, Dysko A., Burt GM. Application of communication based distribution protection schemes in islands systems. Univ Power Eng Conf (UPEC), 2010 45th Int.  

Mahat P, Chen Z, Bak-Jensen B, Bak CL. A simple adaptive overcurrent protection of distribution systems with distributed generation. IEEE Trans Smart Grid 2011;2:428-37. doi:10.1109/TSG.2011.2149550.  

Abdulhadi I, Coffele F, Dysko A, Booth B, Curt G. Adaptive protection architecture for the smart grid. IEEE PES Innov Smart Grid Technol Conf Eur 2011. doi:10.1109/ISGTEurope.2011.6165000.  

Che L, Khodayar ME, Shahidehpour M. Adaptive protection system for microgrids: Protection practices of a functional microgrid system. IEEE Electrif Mag 2014;2:66–80. doi:10.1109/MELE.2013.2297031.  

Giustina Della A., De A., De Sottomayor AA, Ramos F. Toward an adaptive protection system for the distribution grid by using the IEC 61850. Proc IEEE Int Conf Ind Technol 2015;June:2374–8. doi:10.1109/ICT.2015.7254485.  

Plesciorskiy EC, Schulz NN. Fuse relay adaptive overcurrent protection scheme for microgrid with distributed generators. IET Gener Trans Distrib 2017;11:540–9. doi:10.1049/iet-gtd.2016.1144.  

Orji U, Schantz C, Leeb SB, Kirlley JL, Sievenpiper B, Gerhard K, et al. Adaptive Zonal Protection for Ring Microgrids. IEEE Trans Smart Grid 2017;8:1843–51. doi:10.1109/TSG.2017.2590918.  

See H-C, Rhee S-B. Novel adaptive reclosing scheme using wavelet transform in distribution system with battery energy storage system. Int J Electr Power Energy Syst 2018;97:186–200. doi:10.1016/j.ijepes.2017.11.009.  

Ho Q-D, Le-Noeg T. Smart Grid Communications Networks: Wireless Technologies, Protocols, Issues, and Standards. Elsevier Inc., 2013. doi:10.1016/B978-0-12-451584-3.00005-X.  

Alizadeh SM, Ozansoy C. The role of communications and standardization in wind power applications - A review. Renew Sustain Energy Rev 2016;54:944–58. doi:10.1016/j.rser.2015.10.061.  

Voima S, Laaksonen H, Kauhaniemi K. Adaptive protection scheme for smart grids. Dev Power Syst Prot (DPSP 2014), 12th IET Int Conf 2014:1–6. doi:10.1049/cp.2014.0139.  

Ustun TS, Ozansoy C, Zayegh A. Modeling of a centralized microgrid protection system and distributed energy resources according to IEC 61850-7-420. IEEE Trans Power Syst 2012;27:1560–70. doi:10.1109/TPWRS.2012.2185072.  

Degner T, Li R, Jenkins N, Oudalov a. MoreMicrogrids - DC2 - Novel protection systems for microgrids 2009:1–168.  

Laaksonen H, Iishchenko D, Oudalov A. Adaptive protection and microgrid control design for Hailuoto Island. IEEE Trans Smart Grid 2014;5:1486–93. doi:10.1109/TSG.2013.2287672.  

Kheredzadeh M. Adaptive setting of protective relays in microgrid-connected and autonomous operation. 11th IET Int Conf Dev Power Syst Prot (DPSP) Birmingham 2012:P14–P14. doi:10.1049/iet-dpssp.2012.0076.  

Kaur A, Kaushal J, Basak P. A review on microgrid central controller. Renew Sustain Energy Rev 2016;55:338–45. doi:10.1016/j.rser.2015.10.141.  

Do Nascimento LL, Rolim JG. Multi-Agent system for adaptive protection of microgrids. IEEE PES Conf Innov Smart Grid Technol ISGT LA 2013 2013. doi:10.1109/ISGTEurope.2013.6554435.  

Kawano F, Baber GP, Beaumont PG, Fukushiga K, Miyoshi T, Shono T, et al. Intelligent protection relay system for smart grid. 10th IET Int Conf Dev Power Syst Prot (DPSP 2010) Manag Chang 2010:13–13. doi:10.1049/978-0-85613-193-3.  

Almeida, E. Leite, H. Silva N. Real-time Closed-Loop Test to Adaptive Protection in a Smart-Grid Context. 13th Int Conf Dev Power Syst Prot 2016;2014:1–5. doi:10.1049/cp.2016.0061.  

McArthur SDJ, Davidson EM, Catteron VM, Dimeas AL, Hatzigarigou NB, Ponci F., et al. Multi-Agent Systems for Power Engineering Applications -- Part I and Part II. IEEE Trans Power Syst Vol 22, Issue 4, pp 1743–1759 2007.  

Moradi MH, Razi N, Mahdi Hosseini S. State of art of multiagent systems in power engineering: A review. Renew Sustain Energy Rev 2016;58:814–24. doi:10.1016/j.rser.2015.12.007.  

Pipattanasomporn M, Feroza H, Rahman S. Multi-agent systems in a distributed smart grid: Design and implementation. IEEE/PES Power Syst Conf Expo 2009 PSCE '09 2009:1–8. doi:10.1109/PSCE.2009.4840807.  

Jian Z, Ai Q, Jiang C, Wang X, Zheng Z, Gu C. The application of Multi Agent System in Microgrid coordination control. 1st Int Conf Sustain Power Gener Supply, SUPERGEN '09 2009.
Habib HF, Youssef T, Cintuglu MH, Mohammed OA. Ananda SA, Gu JC, Yang MT, Wang JM, Chen J Da, Centralized coordination & control of future power systems. Intell Ind Syst 2015;1:255

Farid AM. Multiagent systems for microgrid control. Eng Appl Artif Intell 2016;3:320

Hyun K, Kang H, Kim J, Lee G, Goh S, Kim J. Multi-agent system fault protection with topology identification – A comprehensive survey. Comput Stand Interfaces 2017;58:62–73. doi:10.1016/j.csi.2017.09.005.

Kato T, Takahashi H, Sasai K, Kitagata G, Kim HM, Kinoshita T. On the communication failure impacts on adaptive microgrid protection schemes and the use of energy storage as a contingency. IEEE Trans Ind Appl 2017;9994:1–10. doi:10.1109/TIA.2017.2776858.

Habib HF, Lashway CR, Members S, Mohammed OA. On the Adaptive protection of Microgrids: A Review on How to Mitigate Cyber Attacks and Communication Failures. Ind Appl Soc Annu Meet 2017 IEEE 2017:33174–1.

Jin D, Li Z, Hannon C, Chen C, Wang J, Shahidehpour M, et al. Toward a Cyber Resilient and Secure Microgrid Using Software-Defined Networking. IEEE Trans Smart Grid 2017;8:2494–504. doi:10.1109/TSG.2017.2703911.

Vrba P, Mark V, Siano P, Letato P, Zhablova G, Výkytník V, et al. A review of agent and service-oriented concepts applied to intelligent energy systems. IEEE Trans Ind Informatics 2014;10:1890–93. doi:10.1109/TII.2014.2326411.

Perkonigg F, Bruijc D, Ristic M. MAC-Sim: A multi-agent and communication network simulation platform for smart grid applications. 5th International Conference on Future Electric Energy Systems and Technologies. 2013 IEEE Int Conf Smart Grid Commun 2013:570–5. doi:10.1109/SmartGridComm.2013.6710450.

Habib HF, Lashway CR, Mohammed OA. A Review of Communication Failure Impacts on Adaptive Microgrid Protection Schemes and the Use of Energy Storage as a Contingency. IEEE Trans Ind Appl 2017;53:9994:1–10. doi:10.1109/TIA.2017.2776858.

Habib HF, Lashway CR, Members S, Mohammed OA. On the Adaptive protection of Microgrids: A Review on How to Mitigate Cyber Attacks and Communication Failures. Ind Appl Soc Annu Meet 2017 IEEE 2017:33174–1.

Jin D, Li Z, Hannon C, Chen C, Wang J, Shahidehpour M, et al. Toward a Cyber Resilient and Secure Microgrid Using Software-Defined Networking. IEEE Trans Smart Grid 2017;8:2494–504. doi:10.1109/TSG.2017.2703911.

Vrba P, Mark V, Siano P, Letato P, Zhablova G, Výkytník V, et al. A review of agent and service-oriented concepts applied to intelligent energy systems. IEEE Trans Ind Informatics 2014;10:1890–93. doi:10.1109/TII.2014.2326411.

Shang J, Tai N, Liu Q, Multi-agent based protection system for distribution system with DG 2013:8.

Perera N, Rajapakse AD. Agent-Based Protection Scheme for Distribution Networks with Distributed Generators. 2006 IEEE Power Eng Soc Gen Meet 2006:1–6. doi:10.1109/PES.2006.1709528.

Cintuglu MH, Martin H, Mohammed OA. An intelligent multi-agent framework for active distribution networks based on IEC 61850 and IEC standards. 2015 18th Int Conf Intell Syst Appl to Power Syst 2015:1–6. doi:10.1109/ISAAP.2015.7325577.

Kulasekera A L, Gopura R a RC, Hemapala KTMU, Perera N, Pallegedara A. Dual layer multi agent system for intentional islanding operation of microgrids. Proceeding … 2012:2012:994–7.

He Y, Wang W, Wu X, Xu L, Li R. An overview of applications of MAS in smart distribution network with DG. 2015 IEEE 2nd Int Futur Energy Electron Conf IFEEC 2015 2015:1–6. doi:10.1109/IFEEC.2015.7361567.

Strasser T, Andrén F, Kathar J, Cecati C, ... A review of architectures and concepts for intelligence in future electric energy systems. IEEE Trans … 2015:1–12. doi:10.1109/TSG.2017.2703911.

Kato T, Takahashi H, Sasai K, Kitagata G, Kim HM, Kinoshita T. Priority-based hierarchical operational management for multiagent-based microgrids. Energies 2014;7:2051–78. doi:10.3390/en7012051.

Hussain A, Aslam M, Arif SM. N-version programming-based protection scheme for microgrids: A multi-agent system based approach. Sustain Energy, Grids Networks 2016:6:35–45. doi:10.1109/ISGT.2016.202.001.

Goebel R, Siekmann J, Wahster W. Lecture Notes in Artificial Intelligence Subseries of Lecture Notes in Computer Science LNAI Series Editors. 2012. doi:10.1007/978-3-642-34182-3.
[110] Cintuglu MH, Mohammed OA. Multiagent-based decentralized operation of microgrids considering data interoperability. 2015 IEEE Int Conf Smart Grid Commun SmartGridComm 2015 2016:404–9. doi:10.1109/SmartGridComm.2015.7436334.

[111] Meskina S Ben, Doggaz N, Khalgui M, Li Z. Multiagent Framework for Smart Grids Recovery. IEEE Trans Syst MAN Cybern Syst 2016;47:1–17. doi:10.1109/TSMC.2016.2573824.

[112] Wan H, Li KK, Wong KP. An adaptive multilayer approach to protection relay coordination with distributed generators in industrial power distribution system. IEEE Trans Ind Appl 2010;46:2118–24. doi:10.1109/TIA.2010.2059492.

[113] Boussaada Z, Cureau O, Camblong H, Bellalj Mrabet N, Hacala A. Multi-agent systems for the dependability and safety of microgrids. Int J Interact Des Manuf 2016;10:1–13. doi:10.1007/s12288-014-0257-9.

[114] Dinneas AL, Hatzigiourov ND. A multiagent system for microgrids. IEEE Power Eng Soc Gen Meet 2004 2004:2:55–8. doi:10.1109/PES.2004.1372752.

[115] Papaspiliotopoulos VA, Korres GN, Klefaksis VA, Hatzigiourov ND. Hardware-in-the-loop Design and Optimal Setting of Adaptive Protection Schemes for Distribution Systems with Distributed Generation. IEEE Trans Power Deliv 2017;32:393–400. doi:10.1109/TPWRD.2015.2509784.

[116] Muda H, Jena P. Real time simulation of new adaptive overcurrent protection for microgrid protection. 2016 Natl Power Syst Conf NPSC 2016 2016:3:78. doi:10.1109/NPSC.2016.7858897.

[117] Cr??ciu O, Florescu A, Munteanu I, Bratcu AI, Bacha S, Radu D. Hardware-in-the-loop simulation applied to protection devices testing. Int J Electr Power Energy Syst 2014;54:55–64. doi:10.1016/j.ijepes.2013.06.031.

[118] Logenthiran T, Srinivasan D, Khambandkone AM, Aung HN. Multiagent system for real-time operation of a microgrid in real-time digital simulator. IEEE Trans Smart Grid 2012;3:925–33. doi:10.1109/TSG.2012.2189028.

[119] Monadi M, Zamani MA, Koch-Cibotaru C, Candela II, Rodriguez P. A communication-assisted protection scheme for direct-current distribution networks. Energy 2016;109:578–91. doi:10.1016/j.energy.2016.04.118.

[120] Piesciorovsky EC, Schulz NN. Comparison of non-real-time and real-time simulators with relays in-the-loop for adaptive overcurrent protection. Electr Power Syst Res 2017;143:657–68. doi:10.1016/j.epsr.2016.10.049.

[121] Dufour C, Belanger J. On the use of real-time simulation technology in smart grid research and development. 2013 IEEE Energy Convers Congr Expo 2013;50.2982–9. doi:10.1109/ECCE.2013.6647090.

[122] Vijay AS, Doilla S, Chandorkar MC. Real-Time Testing Approaches for Microgrids. IEEE J Emerg Sel Top Power Electron 2015;5:1356–76. doi:10.1109/JESTPE.2015.2509486.

[123] Cintuglu MH, Ma T, Mohammed OA. Protection of Autonomous Microgrids Using Agent-Based Distributed Communication. IEEE Trans Power Deliv 2017;32:551–60. doi:10.1109/TPWRD.2016.2551368.

[124] Bui DM, Chen SL. Fault protection solutions appropriately proposed for ungrounded low-voltage AC microgrids: Review and proposals. Renew Sustain Energy Rev 2017;75:1156–74. doi:10.1016/j.rser.2016.11.097.

[125] J.A. Ocampo-Wilches, A.J. Ustariz-Farfan EAC-P. Modeling of a Centralized Microgrid Protection Scheme. Power Electron Power Qual Appl (PEPQA), 2017 IEEE Work 2017.

[126] Piesciorovsky EC, Schulz NN. Comparison of Programmable Logic and Setting Group Methods for adaptive overcurrent protection in microgrids. Electr Power Syst Res 2017;151:273–82. doi:10.1016/j.epsr.2017.05.035.

[127] Teimourzadeh S, Aminifar F, Davarpanah M, Shahidehpour M. Adaptive Protection for Preserving Microgrid Security. IEEE Trans Smart Grid 2017;3:3053–1. doi:10.1109/TSG.2017.2749301.

[128] Mirzaei D, Dong X, Shi S, Tzelepis D. Challenges, advances and future directions in protection of hybrid AC/DC microgrids. IET Renew Power Gener 2017;11:1495–502. doi:10.1049/iet-rpg.2017.0079.

[129] Lai K, Illindala MS, Haj-Ahmed MA. Comprehensive Protection Strategy for an Islanded Microgrid Using Intelligent Relays. IEEE Trans Ind Appl 2017;53:47–55. doi:10.1109/TIA.2016.2604203.

[130] Basso T. IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability with the Electricity Grid IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability with the Electricity Grid. Nrel 2014 2017.

[131] Kroposki B. Microgrid Standards and Protocols. DOE Microgrid Plan Meet 2013.

[132] IEEE STANDARDS. IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems IEEE Standards Coordinating Committee 21 Sponsored by the. 2011.

[133] 21 ISCC. IEEE Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary N etworks IEEE Standards Coordinating Committee 21 Sponsored by the. 2011. doi:10.1109/IEEESTD.2011.6022734.