Renewable and Sustainable Energy Reviews 118 (2020) 109524

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

A survey on adaptive protection of microgrids and distribution systems with distributed generators

P.H.A. Barra [a,*], D.V. Coury [a], R.A.S. Fernandes [b]

[a] Department of Electrical and Computer Engineering, São Carlos School of Engineering, University of São Paulo, 13566–590, São Carlos, São Paulo, Brazil
[b] Department of Electrical Engineering, Center of Exact Sciences and Technology, Federal University of São Carlos, 13565–905, São Carlos, São Paulo, Brazil

ARTICLE INFO

Keywords:
Adaptive protection
Bibliometric analysis
Distributed generation
Microgrid
Protection scheme
Renewable energy sources

ABSTRACT

Microgrids have emerged as a prospective framework that integrates renewable energy sources, energy storage systems, and loads. They can be addressed as a local distribution system with distributed generators (DGs) and have the potential to improve power quality, reliability, and energy efficiency to their consumers in a grid-connected or islanded mode. However, in order to implement microgrids or distribution systems with DGs, some challenges should be faced, especially concerning protection issues. The possible operating modes and the presence of distributed energy resources may make conventional protection schemes ineffective. Therefore, new protection schemes have been developed in the context of microgrids, including the cases of distribution systems with DGs. Thus, this paper presents a comprehensive survey aiming at studies considering this kind of protection. Emphasis has been given to studies associated with adaptive protection, considered by some researchers as a promising solution for microgrid protection. For this purpose, firstly, a microgrid structure is briefly presented. Afterwards, some challenges related to the protection of these systems are also addressed. Moreover, a brief overview of adaptive protection is provided, and then the newly developed schemes found in the technical literature are described. It is worth mentioning that a bibliometric analysis is also presented in this paper, highlighting a substantial growth in publications concerning adaptive protection. Nevertheless, it can be observed that more effort is still needed to obtain a complete solution for the protection of microgrids and distribution systems with DGs. Further attention to matters such as communication failures, cyberattacks, and the presence of energy storage systems should emerge in the next few years.

1. Introduction

A trend known as the “three Ds” has been observed in the world’s electricity systems in recent years, i.e., they are starting to “decentralize, decarbonize and democratize”. This trend is motivated by the need to improve resilience and reliability of power systems, reduce CO_2 emissions to mitigate climate change (based on the Paris Agreement), to rein in electricity costs, among other issues [1,2]. In order to meet these and other needs, the application of distributed energy resources, especially wind turbine (WT) and photovoltaic (PV) systems, have become more widespread at the distribution level [3]. While the application of these resources can potentially help with the needs that were pointed out, the control of a large number of distributed generators (DGs) creates a new challenge for operating and controlling networks. This challenge can be partially addressed by microgrids (MGs), which are entities that coordinate the distributed energy resources in a more decentralized way [4].

MGs are active systems and consist of DGs, energy storage systems (ESS), and different loads at the voltage level of distribution. The advantages of MGs can be highlighted from the perspectives of networks, customers, and the environment. The main benefit from the network point of view is that MGs are treated as a controlled entity and may be considered as an aggregated load [5]. Moreover, MGs provide minimization of line losses and interruption costs, such as those presented in Ref. [6]. From the customers’ perspective, MGs are beneficial since they can improve reliability and efficiency while reducing blackouts [5,6]. Regarding the environmental point of view, MGs may result in lower environmental pollution due to low-carbon technologies [5,6].

MG pilots have been successfully implemented in some countries, such as the USA, Japan, Korea, Spain, Finland and Germany [7]. Despite this fact and the presented advantages of MGs in the modern context of power systems, their widespread implementation is still limited due to technical challenges, such as protection, security, power quality, operation in normal and islanded modes, voltage and frequency control,

---

* Corresponding author.
E-mail addresses: pedrobarra@usp.br, pedrohenrique_ab@hotmail.com (P.H.A. Barra).

https://doi.org/10.1016/j.rser.2019.109524
Received 11 June 2019; Received in revised form 18 September 2019; Accepted 24 October 2019

List of abbreviations

ACL	agent communications language
ACO	ant colony optimization
ANM	active network management
ANN	artificial neural network
BESS	battery energy storage systems
CPC	central protection center
CT	current transformer
CWT	continuous wavelet transform
DE	differential evolution
DG	distributed generator
DS	distribution system
DSA	differential search algorithm
ELM	extreme learning machine
ESS	energy storage systems
FCL	fault current limiter
GA	genetic algorithm
HIF	high impedance faults
HIL	hardware-in-the-loop
HS	harmonic search
IBDG	inverter-based distributed generator
IED	intelligent electronic device
JADE	Java agent development framework
LP	linear programming
MBESS	mobile battery energy storage systems
MG	microgrid
MGCC	microgrid central controller
MLP	multilayer perceptron
OCR	overcurrent relay
PCC	point of common coupling
PLM	programmable logic method
PMU	phasor measurement unit
PSO	particle swarm optimization
PV	photovoltaic
RBFN	radial basis function network
SBDG	synchronous based distributed generator
SGM	setting group method
SOA	seeker optimization algorithm
SVM	support vector machine
VT	voltage transformer
WT	wind turbine

plug-and-play operation, energy management, and system stability. As one of the aforementioned challenges, protection has the crucial task of isolating, as quickly as possible, any element of the system when it is subjected to a short-circuit, or abnormal operation that can cause damage to it and/or to the rest of the system. However, in the protection of MGs or DSs with DGs, traditional schemes may not operate properly due to issues such as [7]:

- Changes in fault currents (strong dependence of operation mode);
- Bidirectional power flow;
- Presence of DGs and their dynamic behavior;
- Topological changes in the power grid due to the intermittent nature of DGs;
- Type of DGs (inverter or synchronous based DGs);
- Quantity, location, power rating and control type of DGs.

Considering the importance of reliable protection for supporting the widespread implementation of MGs, some researchers have been engaged in developing studies that address the above-mentioned issues. Thus, papers that present a literature review on the protection of MGs and DSs with DGs should be useful to researchers. Some papers [7–12] have also presented a literature review concerning MG protection. However, due to the quick progress of research on this topic, they do not show the most recent studies. Therefore, this paper presents an up-to-date survey related to the protection of MGs and DSs with DGs, emphasizing adaptive protection strategies, considered by some researchers as an interesting solution for MG protection. In addition, an important bibliometric analysis is carried out showing the most cited studies on adaptive protection and how the evolution of publications has occurred so far. This analysis also creates a data-driven vision of how the global collaboration on adaptive protection works.

2. Methods

This paper is organized as follows. After the introduction, Section 2 describes the method adopted for the literature review, as in Refs. [13–15]. Fig. 1 depicts the framework of this review study. Once the MGs structure is presented (Section 3), some challenges in their protection are shown (Section 4). In Section 5, a historical overview of adaptive protection is presented. Important information about the initial and most cited studies on adaptive protection is highlighted, and a bibliometric analysis on this topic is presented. Moreover, innovative schemes and strategies of adaptive protection for MGs and DSs with DGs are addressed and divided into two groups: (i) computational intelligence-based approaches; and (ii) other adaptive approaches. In Section 6, other non-adaptive methods for protecting MGs and DSs with DGs are briefly presented. Finally, a discussion and conclusion are provided, respectively, in Sections 7 and 8.

Regarding the bibliometric analysis carried out in Section 5, it is worth mentioning that, typically, it is carried out based on using one of the four widely popular databases, which include Web of Science, Google Scholar, PubMed, and Scopus [16,17]. In this study, the Scopus database was used to retrieve papers related to adaptive protection because it is considered the largest database and indexes more journals than other databases. It includes more than 70 million items and covers over 21,950 peer-reviewed journals (including 3600 full open access journals) [18]. In the electrical engineering field, this database covers Elsevier indexed journals (e.g., Electric Power Systems Research [5-Year Impact Factor: 3.135], International Journal of Electrical Power & Energy Systems [5-Year Impact Factor: 4.262] and Renewable &

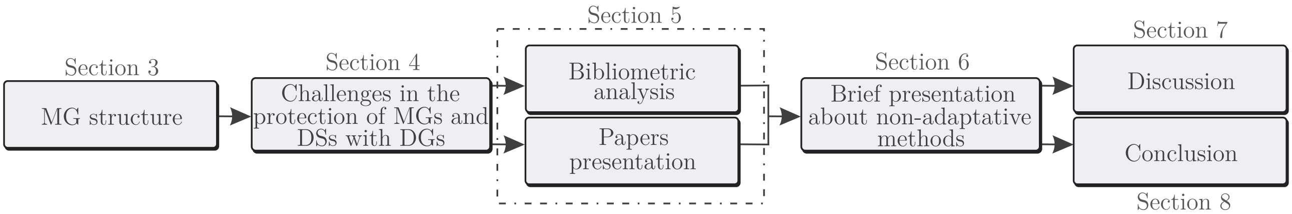


Fig. 1. Framework of the review study on adaptive protection.

Sustainable Energy Reviews [5-Year Impact Factor: 11.239]), IEEE indexed journals (e.g., IEEE Transactions on Power Delivery [5-Year Impact Factor: 4.695], IEEE Transactions on Smart Grid [5-Year Impact Factor: 10.607] and IET Generation, Transmission & Distribution [5-Year Impact Factor: 3.432]), as well as other important journals and relevant conferences.

Fig. 2a depicts the general procedure of the performed bibliometric analysis, which consists of 3 stages (S1, S2, and S3). Stage 1 (S1) is related to defining queries and obtaining the database of interest. Then, Stage 2 (S2) consists of importing and refining the database in VOSviewer (free software to construct and visualize bibliometric networks) [19]. Finally, in Stage 3 (S3), the networks of interest are obtained and analyzed.

Note in Fig. 2b that each stage has some steps. In S1, the first step is to identify the scientific field and the period of interest. In this study, the scientific field is the adaptive protection, and no time restrictions were imposed on the search regarding the starting year. The second step of S1 is related to database choice, where Scopus was selected, as mentioned before. Afterwards, two queries were defined as depicted in Fig. 2b and, subsequently, these databases were downloaded containing information such as the title, authors, year, affiliations, countries, abstract, keywords and the references of each paper. It is important to mention that this study considered only the documents classified as articles, review articles, conference papers, and conference review papers. In S2, these databases were imported in VOSviewer to visualize the results, where the data were refined by merging some keywords and authors (as illustrated in Fig. 2b). Finally, in S3, the bibliometric networks (for keywords, authors, and countries) were obtained and analyzed.

In order to clarify the bibliometric networks' concept, the hypothetical bibliometric network was considered, depicted in Fig. 3. This network consists of nodes and edges. The nodes represent publications, journals, researchers, or keywords. The edges indicate the relation and the strength of this association between a pair of nodes. For this study, the following networks were considered:

- Keywords – In the hypothetical keywords' network presented in Fig. 3, there are five keywords named as A, B, C, D, and E. The higher

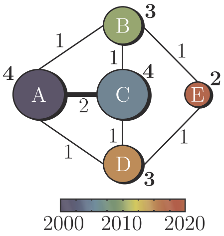


Fig. 3. Example of a bibliometric network.

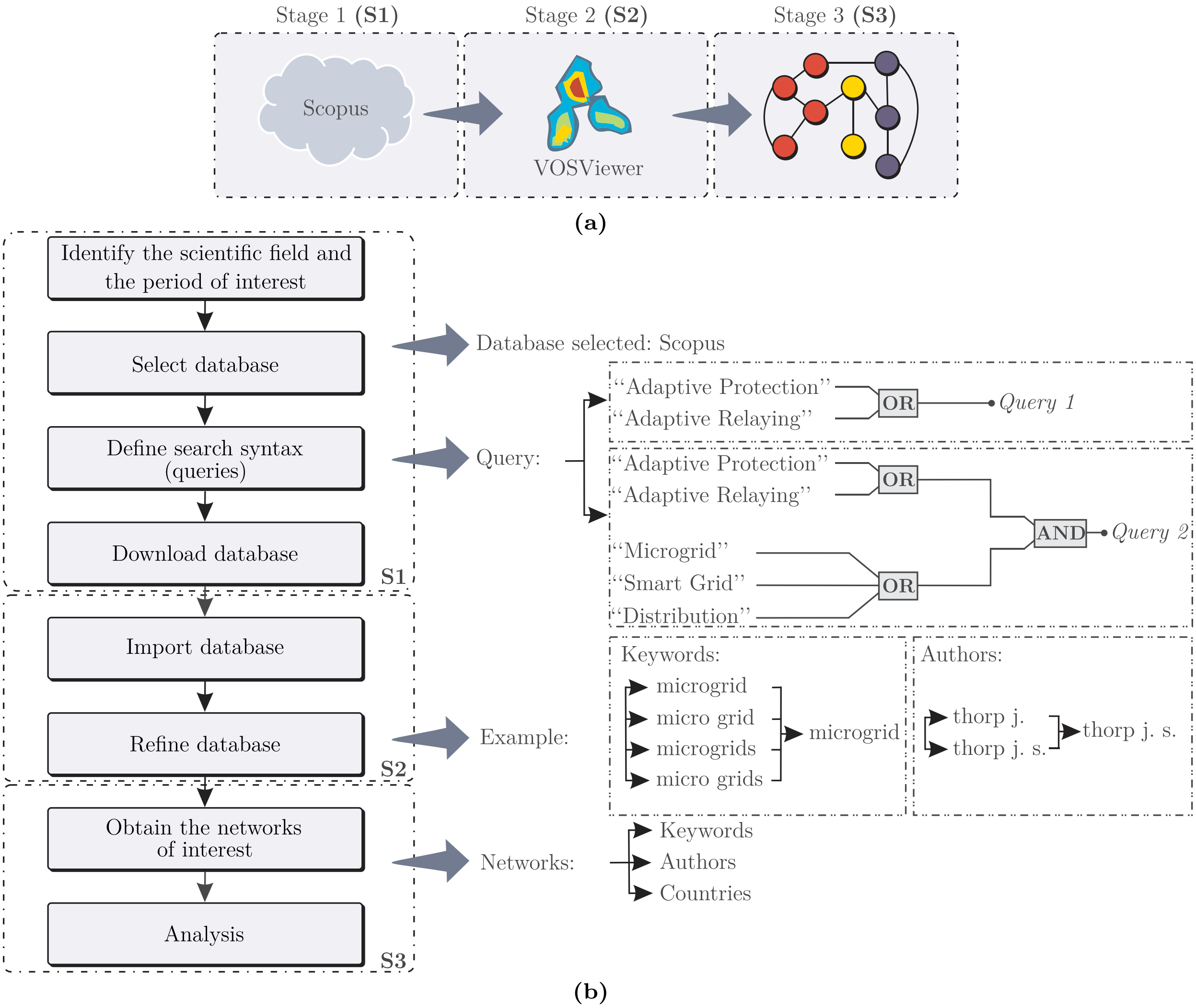


Fig. 2. Diagrams depicting the details of performed bibliometric analysis: (a) Basic stages of bibliometric analysis carried out and (b) Additional details of each stage in the analysis.

the diameter of the circles concerning a keyword, the more times this keyword was used by the papers in their abstract, title or keywords. The thicknesses of lines (the link between two nodes) are proportional to the number of times the keywords were used together. Additionally, the colors of the circles represent the average for the publication year of the documents that used a given keyword. For example, keyword A was used four times by the database; once with keyword B, twice with keyword C, and once with keyword D. It can also be inferred that the average of the publication year of the four papers that used this keyword is 2000;

- Authors – Fig. 3 can also represent an authors' network, with five authors named as A, B, C, D, and E. In this case, the higher the diameter of the circles concerning an author, the more the number of publications of this author. The thicknesses of lines, in this case, are proportional to the number of times they cite each other. The color of the circles represents the average for the publication year of the documents published by a given author. For example, author B has three publications, and was cited (or cited) once by author A, once by author C, and once by author E. Finally, it can be inferred that the average for the publication year of the three papers of this author is around 2010;
- Countries – In this case, the analysis is similar to the authors' network. For example, country E has two publications and was cited (or cited) once by country B, and once by country D. Finally, it can be inferred that the average for the publication year of four papers of country E is 2020.

Many review papers (for example [20–22]) have been using these bibliometric networks since they have the potential to generate a data-driven vision of scientific research activities across different research areas and can present evidence-based depictions, comparisons, and visualizations of research outputs. In the keyword network, for example, the evolution of research on adaptive protection until this date can be observed and some directions for the future can be foreseen. In the networks of authors and countries, the main contributors to the adaptive protection area, and what the leading countries regarding the quantity of publications are, can be seen. This information is meaningful and can help researchers improve their global collaboration on the topic and to search for partnerships with other authors and countries.

3. Microgrid structure

An MG can be addressed as a local system of power and energy delivery to individual consumers [4,23]. As illustrated in Fig. 4, an MG typically consists of a set of elements such as distributed generators (e.g., PV, WT and diesel generators), energy storage systems (e.g., supercapacitors, battery energy storage systems (BESS) and mobile battery energy storage systems (MBESS)), a communication infrastructure, loads and a central controller called as MGCC [24–26]. It is worth noting that the MGCC is usually installed at the substation and is responsible for the central control and management of the MG. The MGCC has several functions and heads the hierarchical control system, whose second hierarchical control level is composed of unit controllers located at loads and sources [27]. Additionally, an MG can be a single or three-phase system, connected to the medium or low voltage and can operate in both grid-connected or islanded modes [28]. An MG provides a solution to manage local generations and loads. Some authors [4,25,26] emphasize that MGs have the potential to improve the overall system power quality, reliability and efficiency, as well as energy surety for critical loads.

4. Challenges in the protection of microgrids and distribution systems with DGs

Traditional DSs, in most cases, are designed in a radial topology. Additionally, these systems are characterized by an unidirectional power flow, i.e., from generation to load. Nevertheless, the MG topology can be mixed, looped or meshed grids and the power flow is bidirectional [29]. These and other factors (dynamic characteristics of DGs, intermittent nature of the DGs, changes in fault current and grid-connected or islanded modes) may imply more complex fault current paths and impair classical protection schemes. Some challenges in MG protection should be highlighted [7,9,10]: i) changes in fault currents; ii) blinding of protection; iii) false tripping; and iv) unsynchronized and automatic reclosing, which are discussed next.

4.1. Changes in fault currents

A fault current depends on existing short-circuit sources. In fact, transmission/distribution systems have a higher short-circuit level than small DGs connected to MGs. Thus, when an MG is operating in islanded

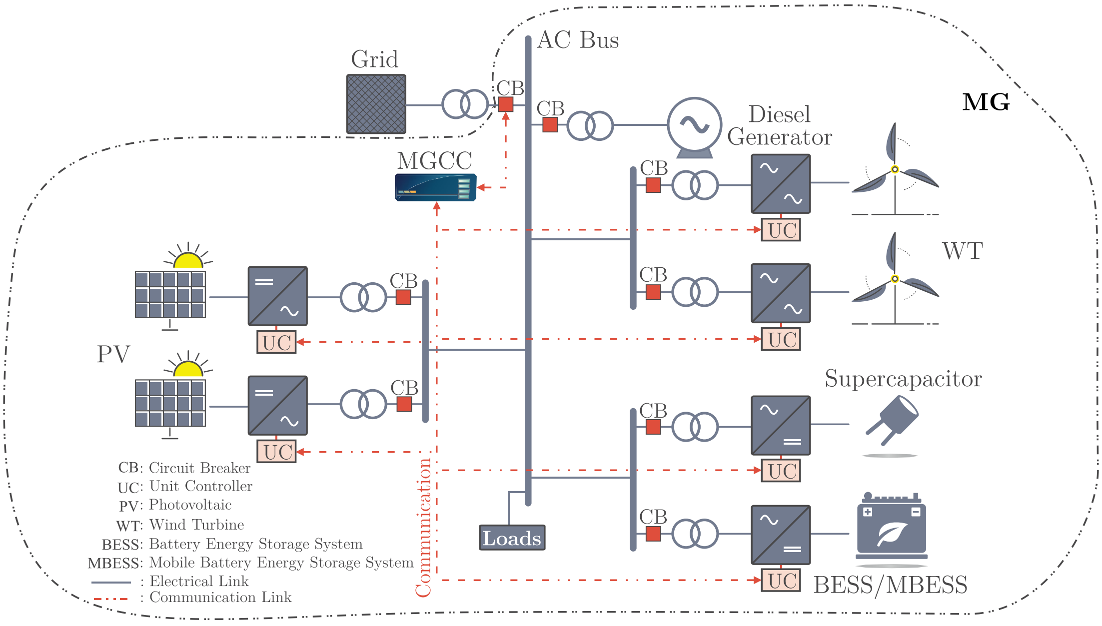


Fig. 4. Example of a microgrid structure.

mode, the fault current seen by protective devices will be much smaller than the fault current seen when the MG is operating in grid-connected mode [30]. In addition, for an MG, the fault current depends on the type, operation mode (ON/OFF), quantity, control type, placement and power rating of the DGs, as well as the MG topology [30–32].

4.2. *Blinding of protection*

Blinding of protection occurs when the fault current, seen by a relay, changes due to the DG connection, which can imply misoperation of protective devices (under-reach for the upstream relays and overreach for the downstream relays). Considering the grid presented in Fig. 5, for a fault F_1, the current seen by overcurrent relay (OCR) R_2 is increased, because of the DG at bus B_2 [33]. In this case, OCR R_2 can trip erroneously as the primary protection. In fact, OCR R_2 could trip for faults located out of its protection zone. In this case, relay R_2 is blinded to the fault.

4.3. *False tripping*

A false tripping situation occurs when a protective device connected to a given feeder responds to a fault in an adjacent feeder, due to the connection of the DGs. To demonstrate this event, consider again the grid presented in Fig. 5. For fault F_2, the contribution from the DG can overcome the pickup current of OCR R_1. If it occurs, depending on the settings of OCRs, R_1 and R_4, the OCR R_1 may lead to a false trip.

4.4. *Unsynchronized and automatic reclosing*

When a DG is connected to the grid by a recloser, the synchronism between the DG and the grid needs to be considered. If this connection occurs disregarding the synchronism, overvoltages, overcurrents, and large mechanical torques are likely to occur. These can cause damage to rotating generators and motors [34,35]. According to Ref. [35], other pieces of equipment connected to the grid (e.g., circuit breaker) are also vulnerable to extra stress. Moreover, there is the automatic reclosing issue. In fact, without DG, majority of transient faults may be cleared by automatic recloser in radially fed grids. Nevertheless, in the presence of DG, both the DG and the grid supply the fault current. Although the recloser disconnects the grid, the DG may sustain feeding fault current during the auto reclose open time, which prohibits the arc extinction. In this case, a potential transient fault changes into a permanent fault [10,36,37].

5. Adaptive protection of microgrids and distribution systems with DGs: An overview

5.1. *Adaptive protection*

Phadke and Thorp [38] define adaptive protection as a protection philosophy which permits and seeks to make adjustments to various protection functions, in order to make them more adequate for power system conditions. These dynamic adjustment changes are also used for recloser-fuse coordination, for example. The trip characteristic of a protective device changes as a function of the modifications in system conditions to maintain or improve the protection effectiveness.

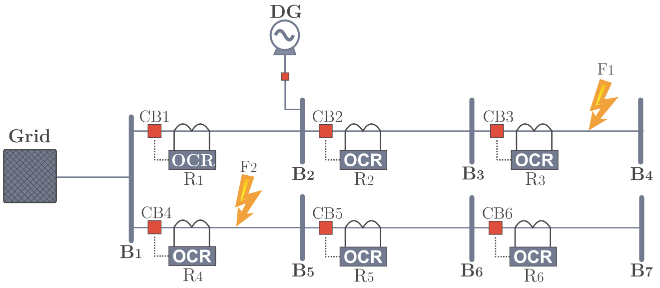


Fig. 5. Hypothetical electrical system.

The philosophy of adaptive protection is not new. More than three decades ago, Horowitz et al. [39] presented results of an investigation into the possibilities of using digital techniques to adapt the transmission system protection to power system changes. Phadke et al. [40] also presented some examples concerning adaptive protection and its advantages. However, even today, there is a niche regarding new developments on adaptive protection topics. In DSs, for example, the presence of DG, the use of energy storage systems, and the possible operation in grid-connected and islanded modes are new scenarios that require new protection schemes and studies.

A growing number of publications on adaptive protection have been observed. Fig. 6a presents the annual number of papers with citations of the terms "adaptive protection" or "adaptive relaying" in their title, keywords or abstract, obtained from Query 1. Therefore, Fig. 6b presents the cumulative annual number of these papers. Fig. 6 is designed based on a database obtained through Scopus [41], as previously detailed in Section 2.

From Fig. 6a, it is clear, therefore, that the adaptive protection approach is a current issue. In 2007, there was a significant increase in the number of publications. Furthermore, one notes from the graphs that the number of publications was the highest in 2018, which shows there is still a niche and a need to carry out more studies on adaptive protection.

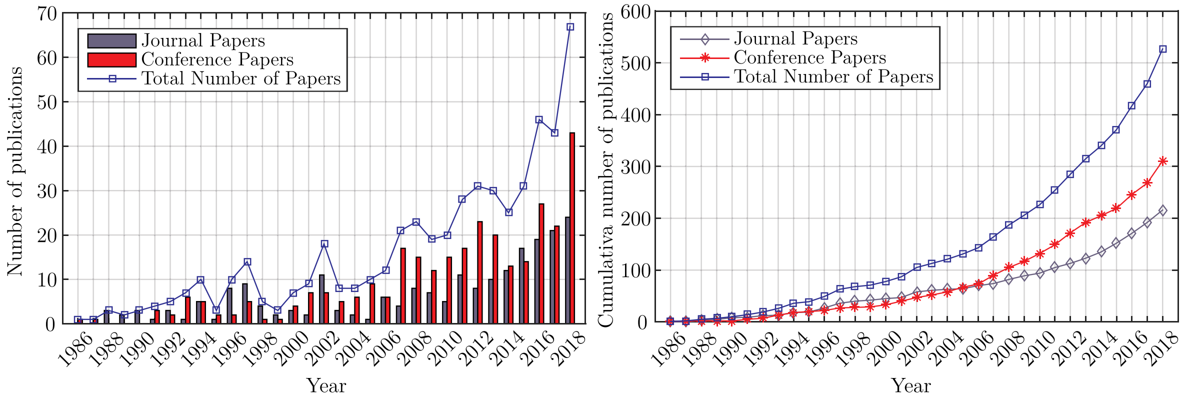
Note, however, that the term "adaptive protection" is very comprehensive, i.e., among the existing papers in the database obtained, a division can be made in subareas: some papers use adaptive protection in transmission lines, some in transformers and others in DSs/MGs. In this regard, Fig. 7 shows a map of the most used keywords in the papers analyzed. The presented map was created using the database of the aforementioned papers through the VOSviewer [19], and the characteristics of this map (diameter of the circles, thicknesses of lines and the color) are according to the explanation provided in Section 2. In order to include a keyword in this map, it has to appear at least 20 times in papers obtained from Query 1. An important aspect observed in Fig. 7 is that, since 2014, papers on adaptive protection, related to topics such as MGs, distributed generation, smart grids, renewable energy resources, among others, have increased considerably.

Fig. 8 presents the results of the bibliometric analysis, which shows a collaborative network containing the main authors on adaptive protection. In order to include authors in this network, they must have at least 120 accumulated citations in their papers, with the aforementioned conditions, i.e., papers with citations of the terms "adaptive protection" or "adaptive relaying" in their title, keywords or abstract. It can be observed that Phadke and Thorp are the most productive authors. However, Bak-Jensen, Chen and Bak are productive authors with a more recent average year of publication.

Moreover, the database also allows for extracting the countries of origin of all the research. Thus, Fig. 9 shows a collaborative network between countries. For a country to be included in this network, it must have at least 20 accumulated citations in all papers. Regarding the number of publications, one can note that China, the United States, India, Canada and the United Kingdom are the countries which dominate the publication production.

Based on the database of the papers, Table 1 lists the five most cited papers related to adaptive protection. Noteworthy here is that only [42] is not aimed at the DS. Thus [30,43,44], and [45] have been utilized by all the authors as a theoretical basis for developing other studies on adaptive protection, and hence they are discussed next.

Brahma and Girgis [43] emphasized that conventional DSs are characterized by a radial topology. The traditional protection schemes for DSs consisting of fuses, reclosers, and relays have been adjusted/designed considering this radial topology. However, from connecting DGs, part of the system may no longer be radial, affecting the



(a) (b)

Fig. 6. Published papers with citations of the terms “adaptive protection” or “adaptive relaying” in the titles, keywords or abstracts: (a) annual quantity and (b) cumulative annual quantity.

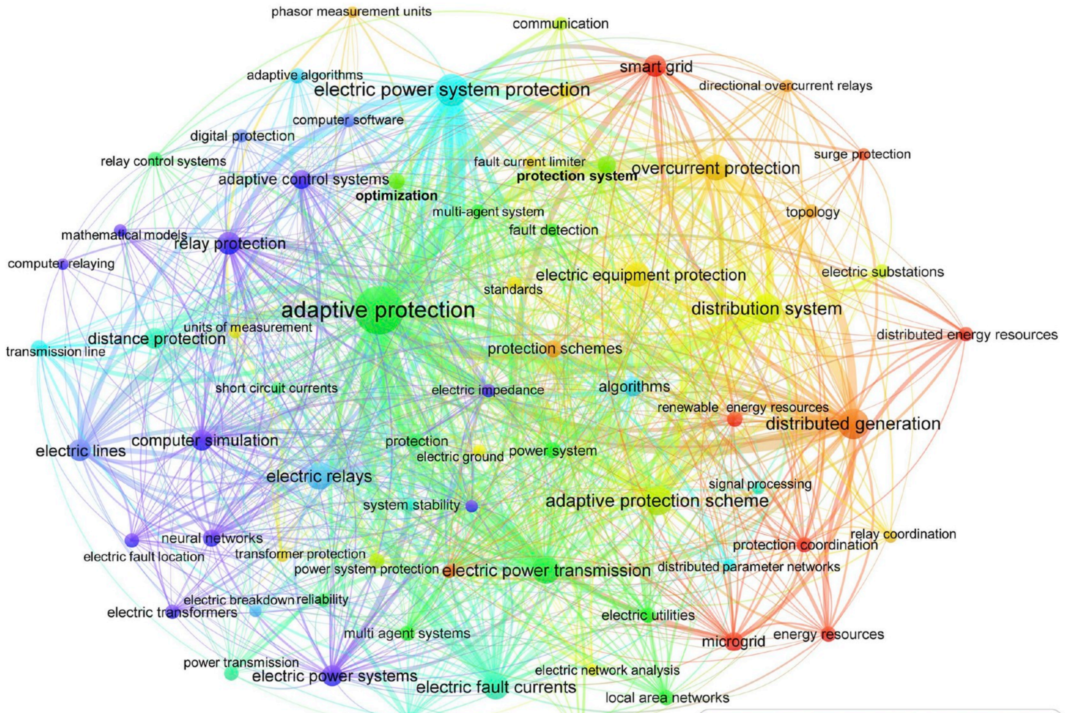


Fig. 7. Map of keywords used by authors concerning time.

coordination of the protection. The authors also highlight that coordination depends on size, type and placement of DGs. Thus, this paper shows some effects of high DG penetration on protective device coordination, proposing an adaptive protection scheme as a solution. Tests were carried out on a distribution feeder to verify the performance of the proposed adaptive scheme for all types of faults (LLL, LL, LLG, and LG). It is worth mentioning that a phasor measurement unit (PMU) is recommended for this scheme. Moreover, this scheme does not work well for low DG penetration cases.

In the second most cited paper, Brown [44] discussed the potential impact that issues related to smart grids will have on DS design. In the context of protection, the author recalls that traditional DSs use time-current coordination devices. Then, these devices assume that faster trips occur in devices topologically further from the substations. However, in a smart grid context, topology is flexible, and this assumption can be problematic. Therefore, the protection system, as well as system topology must be planned together to provide good coordination for all possibilities.

In Mahat et al. [30], an overcurrent adaptive protection for DSs with DGs is presented. In this paper, the trip characteristic of protective devices is updated depending on operating states, i.e., grid-connected or islanded, and the faulted section. Thus, by using state detection algorithms, the relays detect the system status and select the tripping characteristics accordingly. The simulations were carried out in DigSILENT PowerFactory, considering a radial DS under only LLL faults. The authors considered the following test scenarios: i) normal operation of DGs in a grid-connected mode; ii) islanded mode; and iii) $n-1$ contingency, with DG disconnection. Among the five most cited papers, this study can be highlighted because it shows an analysis including island and contingency situations.

Finally, in the fifth most cited paper, Chattopadhyay et al. [45] proposed an algorithm for adaptive protection in meshed DSs. From

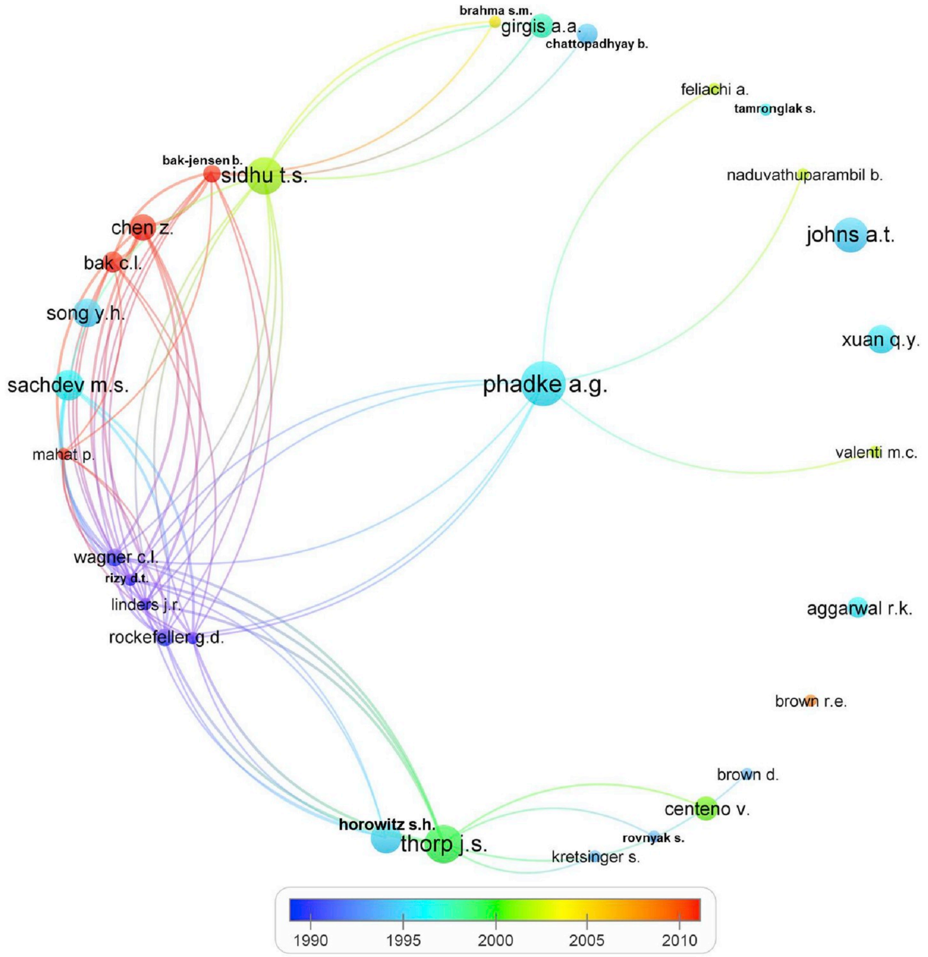


Fig. 8. Authors' collaborative network on adaptive protection concerning time.

changes in system topology, the authors proposed a technique for determining coordinated relay settings, using the Simplex two-phase method. At first, the method determines the constraints selected for maintaining good coordination between primary and backup relays. Then, the second phase finds the optimal relay settings. Tests were conducted for load variations and topology changes in a meshed DS.

The aforementioned studies have been the most cited papers until now. However, other papers on adaptive protection are also important, and can be useful for developing new strategies and schemes. Some of the main and latest papers are discussed further in the present paper.

5.2. Adaptive protection in the context of microgrids and distribution systems with DGs

After an overview showing adaptive protection, the remainder of this section presents a comprehensive survey concerning useful protection studies for DSs/MGs/smart grids, where Fig. 10(a) and (b) show, respectively, the annual quantity and the cumulative annual quantity of published papers in this context. The number of papers concerning time, pointed out in Fig. 10, was obtained from the database of Query 2, as mentioned earlier. Thus, these papers should now contain the citations of the terms "adaptive protection" or "adaptive relaying," and "distribution," "microgrid" or "smart grid" in the titles, keywords or abstracts. The studies aimed at protection of DSs with DGs are useful and are entirely in line with the grid-connected mode of MGs, and, thus, they were not neglected.

The main papers considered in Fig. 10 are discussed in the next subsections. In order to present these studies in an organized manner, they are subdivided into two major topics: i) computational intelligence-based approaches; and ii) other adaptive approaches. Note that the first major topic is again subdivided into subgroups, since the papers are based on artificial neural network (ANN), fuzzy systems, metaheuristics, multi-agent systems, or other intelligent approaches. These subdivisions aim only to provide the reader with a more directed search for approaches of their interest.

5.3. Computational intelligence-based approaches

5.3.1. ANN-based approaches

A new adaptive protection scheme integrated with strategies for locating faults and coordinating protective devices was developed by Zayandehroodi et al. [46]. The authors developed a method for automatically locating the faults through a two-stage radial basis function network (RBFN). The distance of faults from each generation source is determined and, subsequently, the faulty line is identified. Afterwards, the backtracking algorithm is used to coordinate the protection system. Simulations were carried out using DIgSILENT software and the results indicate that the proposed scheme is accurate to identify the faulted line and to coordinate the relays in a DS with DGs. These simulations consider the four types of faults (LLL, LL, LLG and LG). Finally, the authors mention that the results obtained are advantageous compared with other studies that use multilayer perceptron (MLP) [47,48].

Strategies for the overcurrent protection for DSs with DGs and fault current limiters (FCLs) are explored by Tang and Yang [49]. In this approach, the relays with communication ability can determine their own operating states from the operation setting decision tree and

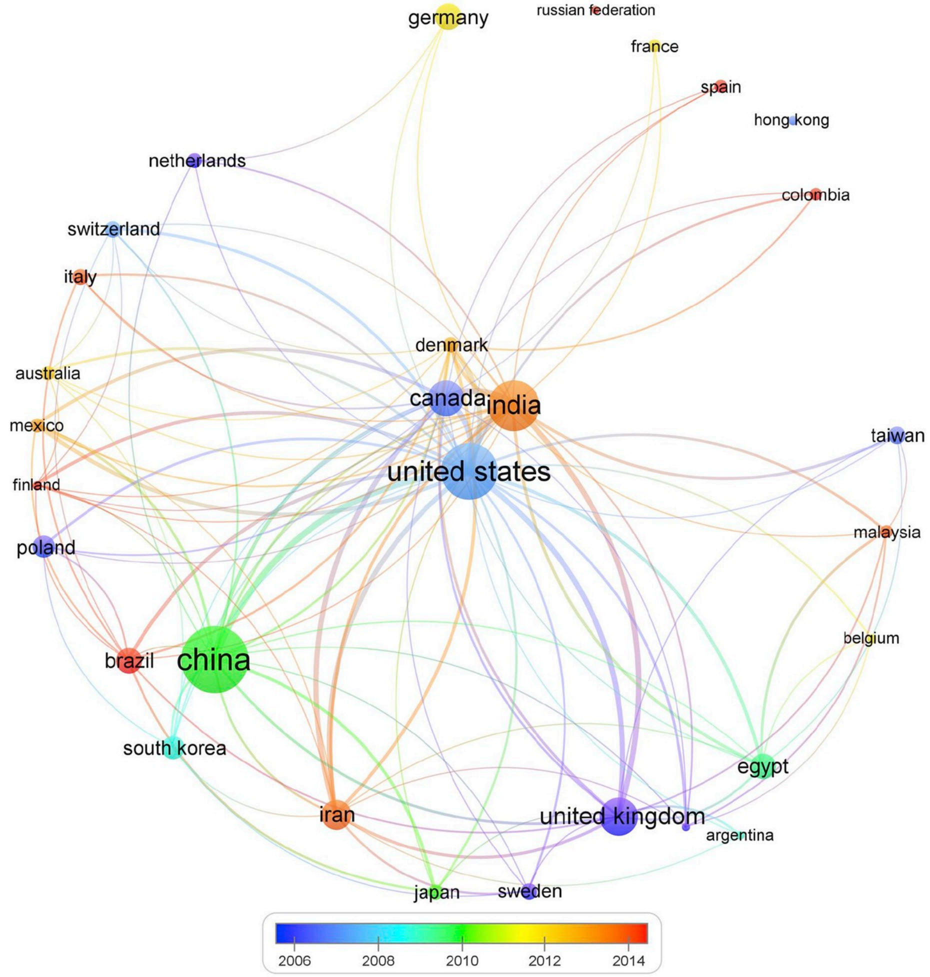


Fig. 9. Collaborative network between countries in terms of their publications.

Table 1
The five most cited papers related to adaptive protection (papers with citations of the terms "adaptive protection" or "adaptive relaying" in the titles, keywords or abstracts).

Position	Reference	Year	Number of citations	Is it about DS?
#1	Brahma and Girgis [43]	2004	435	✓
#2	Brown [44]	2008	294	✓
#3	Naduvathuparambil et al. [42]	2002	234	×
#4	Mahat et al. [30]	2011	192	✓
#5	Chattopadhyay et al. [45]	1996	192	✓

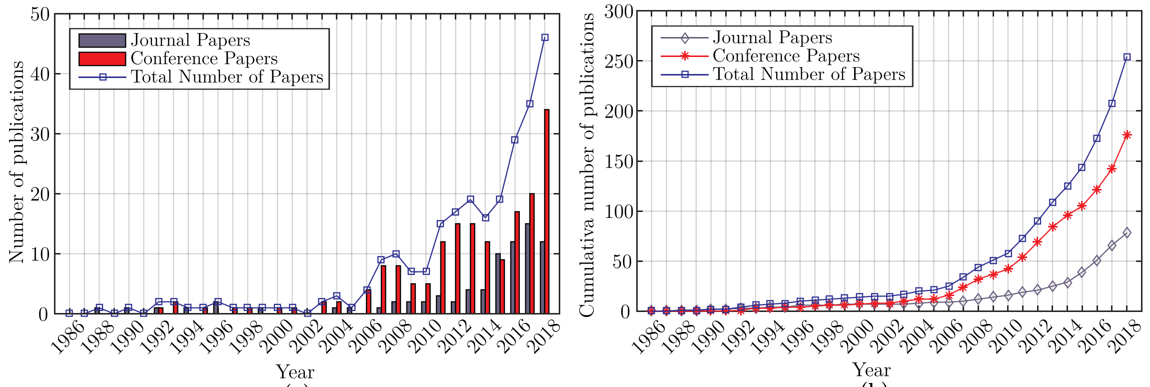
topology-adaptive neural network model based on data processed by the Fast Fourier Transform (FFT). The simulations were performed in DIgSILENT software, consisting of different scenarios, such as the DS with/without DGs, with/without FCLs, load profile and topology variation. From these simulations, the accuracy and efficiency of the proposed strategy are verified.

Lin et al. [50] presented a rule-based adaptive protection scheme combined with a machine learning methodology for MGs. In this study, the uncertain elements in an MG are analyzed quantitatively by Pearson correlation coefficients. Then, a hybrid model that uses an ANN and a support vector machine (SVM) is proposed for state recognition in MGs. Based on this recognition, the protective settings can be reconfigured automatically to ensure the reliability of the operation. Based on simulations carried out in DIgSILENT software, the effectiveness of the proposed method is demonstrated on two different test systems.

5.3.2. *Metaheuristic-based approaches*

Papaspiliotopoulos et al. [51] presented a paper concerning methods to obtain optimized coordination among overcurrent relays in adaptive protection schemes. This study uses particle swarm optimization (PSO) and nonlinear interior point trust region optimization algorithms to optimize the coordination. Simulations were carried out in RTDS and the efficiency of the proposed methods was evaluated on distribution grids with penetration of DGs. Moreover, by using PSO, an adaptive protection scheme is developed by Atteya et al. [52] to respond to the topological changes in power grids. In this study, a modified PSO version is presented as a solution for coordination problems of modern DSs. The proposed scheme is effective for the analyzed scenarios, which includes disconnection of a DG or a line.

An idea of adaptive protection by formulating the coordination problem using ant colony optimization (ACO) is presented by Shih et al. [53]. In this paper, the authors introduce an adaptive protection scheme



(a) (b)

Fig. 10. Published papers with citations of the terms “adaptive protection” or “adaptive relaying” and “distribution” or “microgrid” or “smart grid” in the titles, keywords or abstracts: (a) annual quantity and (b) cumulative annual quantity.

and searching for alternative coordination solutions. To evaluate the obtained results, the performance of a genetic algorithm (GA) is used as a comparison reference, where it is concluded that ACO has faster convergence and better performance than the GA. Finally, one notes that the overall operation time, sensitivity and selectivity of relays were improved, also tolerating an $n-1$ contingency.

In Singh et al. [54], an adaptive protection coordination scheme is discussed. Based on changes in grid topology, the settings of overcurrent relays, as well as Zone 2 configurations of distance relays are updated. Selecting new adjustments is based on the pre-optimized relay group settings. Online selection of the relay settings is carried out using an adaptive fuzzy-based technique. The optimal relay settings are obtained offline using the DSA. Simulations were carried out in RSCAD (designed software specifically for interfacing RTDS), which demonstrates that the proposed approach is flexible in maintaining the coordination between overcurrent and distance relays.

Investigations made by Shih et al. [55] indicate mitigation of DG impact on directional overcurrent relay coordination by using adaptive protection scheme with the differential evolution (DE) algorithm. Noteworthy here is that the DE was selected by the authors for coordination studies since it has been reported to be very efficient in different areas, according to Refs. [56,57]. The authors highlight the study carried out by Alam et al. [58], which compares GA, PSO, DE, the harmonic search (HS) and the seeker optimization algorithm (SOA), indicating that DE outperformed these algorithms in the coordination study. The results show the following advantages concerning the proposed scheme: automatic online coordination, fulfilment of selectivity requirement, and overall sensitivity improvement.

An adaptive protection scheme, which incorporates real-time simulations, multifunction protection, centralized control, and optimal calculation of protection settings has been proposed by Papaspiliotopoulos et al. [59]. The proposed scheme is based on determining the optimal relay setting groups, and then on the online self-adjustment of these setting groups of relays. Two solvers were used by the authors to attain a better assessment of the obtained results, namely Ipopt and Baron. Thus, simulations were performed in RSCAD, considering two distribution test feeders with DG, indicating the efficiency of the proposed solution.

Alam et al. [60] proposed an adaptive protection coordination scheme for MGs using micro-phasor measurement units (μPMUs) and numerical directional overcurrent relays. In this study, the measurements acquired by the μPMUs are used to estimate the existing network topology, power contributed from the DGs, and the status of the point of common coupling. Thus, if a significant change in the MG is identified, the protection coordination settings of the relays are updated. The coordination problem in this work was formulated as an optimization problem and solved using the OPTI Toolbox based IPOPT solver. Finally, the proposed approach was validated on a 7-bus MG system, derived from the IEEE 14-bus system.

5.3.3. *Fuzzy-based approaches*

Naily et al. [61] presented an online adaptive protection scheme based on fuzzy systems, which update and optimize the coordination of the protection when grid topology has been changed. The algorithm depends on some parameters, such as circuit breaker status of the main feeder and the pre-fault power flow. Through simulations in ETAP software, the results show the two main consequences of DG insertion in DSs: the blinding of protection and the false tripping. The authors also show that this impact depends on DG capacity and its location. Finally, one notes from the results that the suggested approach leads to correct coordination for studied scenarios (only LLL faults). Other papers based on a similar approach were published by the same research group [62,63].

A numerical protection strategy with adaptive protection settings, considering the stochastic nature of DGs, is suggested by Kumar and Srinivasan [64]. In this paper, an adaptive fuzzy inference module works with GA in order to determine the appropriate current settings and a heuristic algorithm is used to calculate the time settings of the relays. This algorithm was tested on a DS fed by different types of DGs. Some simulations were carried out in Simulink software, concerning different grid conditions and types of faults. The results show the ability of this approach to find optimal protection settings with minimal relay operating time.

In Momesso et al. [65], an adaptive protection system based on the Fuzzy logic for adjusting pick-up currents of overcurrent relays with instantaneous and current-voltage based inverse-time is proposed. The authors proposed a methodology that considers two variables: the pre-fault current and the variation of current. These variables define the various classes of the pick-up current. Simulations were carried out in ATP-EMTP, considering the IEEE 13-bus test feeder with a DG. The proposed approach was tested considering different fault types and fault resistances. In addition, the influence of a motor starting and transformer energization on the protection was also evaluated.

5.3.4. *Multi-agent system-based approaches*

Nascimento and Rolim [66] described a multi-agent system for adaptive protection of MGs using the Java agent development framework (JADE). This paper highlights that main tasks of the proposed strategy consist of updating the relay characteristics in order to adapt the protection to system changes, in an offline mode. Afterwards, the proposed scheme eliminates the faults, in an online mode. The fault simulation performed in PSCAD software was utilized to define the agent parameters, as well as to validate the multi-agent system-based protection.

George and Ashok [67] highlighted that the previously existing relay parameters may not be effective when the DS is integrated with DG. Thus, the authors proposed multi-agent based adaptive protection. Different agents were defined, such as the measurement agent, relay agent, breaker agent, optimal coordination agent and protection agent. Noteworthy here is that these agents can communicate with each other. The simulations were performed in ETAP software, considering changes in fault currents due to DG status, problems associated with blinding of protection, as well as the bidirectional power flow issue.

A multi-agent system-based protection and control scheme for DSs with DGs is presented by Liu et al. [32]. The scheme deals with the possible modes of operation of a DS with DGs. Based on the cooperation between relays and the DG control, the adaptive protection and the control algorithm are developed on the WT converter to mitigate its influence on fault currents. Based on hardware-in-the-loop simulations, some operation conditions, such as changes in the topology system and DG status were evaluated. Considering case studies, the feasibility of the proposed strategy was verified.

In the context of MG integration with PV, Faria et al. [68] showed the viability of multi-agent based adaptive protection. Some agents were defined by the authors, e.g., for load profile, the point of common coupling, relays and circuit breakers, in which all these agents were situated at the substation. This paper presents simulations performed in RSCAD, indicating positive results for studied scenarios: presence and absence of the DG and some changes in fault resistance. Considering decentralized communication, an adaptive protection scheme using a multi-agent system was presented by Daryani and Karkevandi [69]. In this approach, every relay has sufficient intelligence to dynamically calculate and update its settings based on online identification of prevailing grid mode of operation (grid-connected or islanded). Moreover, all the protection relays are considered as intelligent agents, and they are composed of three sub-agents: measurement, communication and operation. The measurement sub-agent measures the current and voltage signals at the relay location and sends these signals to the operation sub-agent. Besides, the operation sub-agent in addition to the local measurement sub-agent receives signals from all relays and DG agents and a point of common coupling (PCC) agent, and finally, by using this information it detects the MG mode of operation. Simulations were carried out in Simulink, considering some scenarios and the results indicate that protection settings of all relay agents are appropriately adapted for these cases.

5.3.5. *Other computational intelligence-based approaches*

A method that uses a decision tree after each fault to ensure a robust protection coordination is developed by Hosseini et al. [70]. The authors mention that uncertainties in MG topology, protection systems and communication links involve accidental variables that affect the protection coordination. Regarding this issue, the proposed method enables an adaptive protection to make a decision considering MG topology and also the probability of correct operation of the protection system and communication links. Simulations were carried out in DIgSILENT software, and the results indicate that this method can be considered effective for solving MG protection coordination problems. In addition, the authors emphasize that as decision trees are used in an online mode, it is not necessary to store a considerable amount of offline settings.

Some publications related to adaptive protection are based on SGM, i.e., they use the available setting groups of relays (in general is limited between 2 and 8). Nevertheless, this available number is much lower than the possible topologies of a power grid, as shown by Ojaghi and Mohammadi [71]. Thus, the authors propose a *k*-means clustering technique to classify the topologies into some clusters, whose number is equal to the number of available setting groups (a limit of four groups was adopted in this paper). Noteworthy here is that for each cluster, the topologies are close to each other regarding coordination of the relays. In order to obtain optimal setting groups, linear programming (LP) is used in this paper due to its simplicity and certain global optimum results. The studies show that using the proposed technique, the coordination can be preserved under all the topologies with considerably lower time dial settings and time delays of the relays.

5.4. *Other adaptive approaches*

A communication-less overcurrent protection based on local information is developed by Liu et al. [72]. Measuring only the local information, this method aims to adapt the protection settings to the grid states, such as the change of operation mode, the change of grid topology and the disconnection of some DGs. In the same way, as the other papers, the relay settings are calculated offline and updated in an online mode. Symmetrical fault simulations were performed in DIgSILENT software, and the results indicate that this methodology is effective for the studied system and scenarios.

Ma et al. [73] described a new adaptive voltage protection scheme for DSs with DGs. In this research, intelligent electronic devices (IEDs) are used to acquire, in real-time, the current and voltage measurements, as well as to facilitate the communication among IEDs. The proposed scheme is based on the relationship between the pre and post-fault phase voltage difference and the phase current. From simulations in PSCAD software, the proposed scheme was tested and shows advantages in relation to traditional voltage protection schemes for the following studied scenarios: different fault types, fault locations, presence and absence of DGs, as well as variations in power output of DGs.

Investigations were made by Hussain et al. [74] to show the loss of coordination between reclosers and fuses in a DS with DG insertion. In fact, when temporary faults occur, an appropriate coordination between a recloser and a fuse can save the fuses (a practice known as fuse saving). However, due to limitations of reclosers, fuse saving may not occur in DSs with DG presence. In this regard, the authors of this paper present an adaptive relaying strategy to ensure fuse saving in this new scenario, under the most adverse conditions. The simulation results confirm that the settings selected adaptively are adequate, focusing on fuse saving.

Laaksonen et al. [75] show, firstly, the need to adapt the protection in cases of topological changes and insertion of DGs into MGs. Secondly, the paper proposes an adaptive protection scheme for the Hailuoto island, a Finnish MG. The proposed scheme is based on a central control system, which operates and analyses, in real-time, the data received from the IEDs considering IEC 61850. Some scenarios have been tested using simulations, and the proposed scheme was developed and is currently being installed on Hailuoto island for a practical demonstration.

An adaptive overcurrent protection scheme which automatically configures the protection settings considering the impact of DG, active network management (ANM) and islanding operation is developed by Coffele et al. [76]. The proposed scheme calculates and makes adjustments in real-time, which differentiates this proposal among others that calculate the adjustments previously. In order to do this, the paper uses commercially available protective devices and IEC 61850-based communication. The simulations were performed in RTDS for some scenarios, such as changes of fault level, islanded operation, change of grid topology and connection/disconnection of the DG units under LL and LG faults. Based on comparisons with a conventional overcurrent protection, the authors verify a reduction in false operations and in the mean operating time of devices.

Bhattarai et al. [33] proposed a combination of local adaptive and communication assisted central protection. In this paper, the local adaptive protection updates relay settings based on DG status (ON/OFF) using locally acquired information, whereas the centralized protection updates the relay settings during major changes in grid topologies, such as switching between grid-connected and islanded modes. Simulations were carried out in RTDS, showing the effectiveness of the proposed algorithm and ability to overcome issues such as protection blinding and false tripping.

A strategy for adaptive protection and coordination between relays, which takes into account the dynamic characteristics of the DG, is proposed by Ates et al. [77]. The study considers different scenarios (e.g., island and status of DGs) and shows three possible protection schemes, namely adaptive, semi-adaptive and conventional. The simulations performed in Simulink compare these schemes in terms of the protection effectiveness, indicating that the proposed adaptive protection outperformed the other schemes in both grid-connected and islanded operating modes and active DG status changes. A similar study was carried out in Ref. [78], considering, however, a more compact test system.

An adaptive protection scheme for MGs with electronically coupled distributed generators was presented by Sitharthan et al. [79]. The proposed scheme provides a suitable protection for operating modes of an MG and also uses auto-reclosures in the scheme, which leads to a faster recovery of the fault. An MG communication medium (MCM) for communication between relays and DGs is used in this paper. Simulations were carried out in PSCAD software considering both grid-connected and islanded modes and the results indicate that the proposed protective relay performs adequately and provides suitable protection.

In Swathika and Hemamalini [80], a central protection center (CPC) is incorporated whose function is to monitor the MG continuously, identify fault events and locate the exact faulty branch. The proposed Prims-Aided Dijkstra algorithm is executed continuously in the CPC, and firstly, it is responsible for identifying the current system topology and the shortest route from the faulted point to the nearest operating source. Secondly, the CPC is also responsible for adaptively adjusting the settings of relays. The proposed algorithm is validated in two test systems, considering possible topologies and faults. The obtained results show the capability of this strategy in clearing the fault by disconnecting a minimum portion of the grid.

An adaptive directional overcurrent protection approach for DSs with DGs, based on sequence currents, is proposed by Muda and Jena [81]. The authors highlight that due to changes in the operating mode of power grids, the magnitude and direction of fault currents are modified. Then, these modifications may imply in the protection failure, as well as a loss of coordination between the primary and backup relays. The authors consider that the fault current from inverter-based distributed generator (IBDG) is in the range of 2 pu. In this context, the protection coordination is achieved by the adapting relay settings for each operating mode of DGs, using the stored conventional relay settings. The protection coordination is further improved by using negative-sequence overcurrent-based backup directional overcurrent relays. Moreover, the direction of fault is determined using the phase change in superimposed and pre-fault positive-sequence currents. Through simulations in the real-time digital simulator (RTDS), the results obtained for several operating modes indicate that the adaptive approach implies in an accurate operating time for both primary and backup relays, considering LG and LLL faults. Another paper based on superimposed adaptive sequence currents is presented by the same authors in Ref. [82]. In this paper, the authors evaluate the performance of the proposed technique in the IEEE 34-bus test feeder instead of 4- and 8-bus systems, considering all fault types, and also high impedance faults (HIF).

In order to mitigate the DG influence on the protective devices, Shen et al. [83] presented an online calculation method of fault currents under some system operation conditions. By sampling locally available measurements in the buses, a proposed optimized estimation method is used to dynamically calculate the Thévenin equivalent parameters of the system. Thus, the fault current can be calculated and the relays are adjusted taking into account the behavior of DGs during the fault. The performance of the proposed method was tested over extensive simulations on a sample DS in PSCAD software. The sensitivity and selectivity of the proposed scheme are satisfied under different system operation conditions, fault types and locations.

Piesciorovsky and Schulz [84] pointed out that recent publications related to adaptive protection were based on SGM. Thus, these recent papers use the limited functions preexisting in relays. This paper, however, shows that SGM has a limited quantity of setting groups, and disable the relays for a fixed amount of time in re-setting cases, reducing the relay's availability. Thus, the programmable logic method (PLM) was developed for an adaptive overcurrent protection system, using programmable logic and math operators instead of the functions found in the relay. Besides, the paper reinforces that PLM increases the capacity of relays, requiring only one setting group, leaving other groups for additional and seasonal protection settings.

A two-stage algorithm for an adaptive protection scheme focusing on DSs with high penetration of PV is proposed by Fani et al. [85]. In the offline mode, the most appropriate group settings are calculated based on the voltage profile obtained using short-circuit and power flow studies. Afterwards, an online algorithm applies the predefined group settings to the protective devices. Simulation results indicate the effectiveness of the proposed method in a practical DS.

A new application of μPMUs for adaptive coordination of overcurrent relays was proposed by Zanjani et al. [86]. The authors mention that power grid uncertainties, such as line and power plant outages can imply in miscoordination due to a variation of the relay fault current. Thus, this paper proposed an algorithm to detect these uncertainties in online operation by monitoring the Thévenin impedance, and then, the MG overcurrent relay coordination is optimized again. Based on simulations in DIgSILENT software, the results indicate that this method is able to detect the aforementioned uncertainties to reconfigure the relays and to adapt the relay settings.

A method for identify grid operating conditions for adaptive overcurrent protection during intentional islanding operation is presented by Ferreira et al. [87,88]. This method is based on using a local scheme installed near the protective device, which consists of a thyristor that is fired during a short waveform interval of voltage. By monitoring the voltage and current signals, the grid equivalent is calculated. Thus, the mode of operation (grid-connected or islanded) can be determined. The results show that the proposed method can be used to update the protection settings without using a communication system.

A novel approach based on IEC 61850 GOOSE messages in order to perform the MG protection was presented in Gu et al. [89]. This approach is different from the conventional methods since this is not based on inverse-time characteristic curves for power system protection. By monitoring the operating status of the electrical equipment and determining the operating mode of the MG, the management system can adjust the IEDs. Thus, the management system reassigns the IEDs' parameters to adapt to the dynamic changes in the MG. Simulations were performed in ETAP software to verify the feasibility and effectiveness of the proposed approach.

Singh and Basak [90] describe that the dynamic behavior of an MG makes adaptive protection a general necessity for reliable MG operations. In this study, a new adaptive protection scheme is proposed based on operation modes of MGs. The proposed scheme is based on quadrature and zero sequence components ($q0$ system) of fault current considering the impact of X/R ratio of DGs. The authors highlight that the MG system has a low X/R ratio compared to the existing power system. Thus, any change in X or R of DGs or lines may imply in an important detectable role in fault detection. Simulations were carried out in Simulink considering different fault types and locations, and the results show that the time derivative of quadrature and zero-axis components of fault currents were sufficient to detect the fault location and fault nature in the MG system.

Some other papers have also been published under this same context. A compact algorithm that uses the existent setting groups of relays is proposed by Purwar and Choudhary [91], and Nascimento et al. [92,93]. Besides, Singh and Reddy [94] and Ma et al. [95] presented an adaptive protection scheme that uses a communication network for distribution grids with DGs. Another possible adaptive protection scheme is proposed by Buque et al. [96], where simulations were carried out to test the protection effectiveness in both operation modes of MGs (grid-connected or islanded) under fault scenarios. Other papers can be found aiming to show the DG impact on overcurrent protection of a feeder, such as Baran and El-Markabi [97] and Cheung et al. [98]. Noteworthy here is that there are other studies concerning methods for protecting MGs. A brief review of these methods and studies is presented in Section 6.

6. Non-adaptive methods for protecting microgrids and distribution systems with DGs

Non-adaptive strategies for protecting MGs, and mitigating the impact of the DG penetration can be found in the technical literature. The disconnection of DGs immediately after fault detection is a possibility, such as discussed by Ref. [99]. The limitation of installed DG capacity is explored by Refs. [100,101]. Modifying the protection system by installing extra breakers or reclosers, as well as reconfiguring the power grids is addressed by Refs. [102,103]. A fault-ride-through control strategy of IBDGs is presented by Ref. [104], and a fault current control by solid-state-switch-based field discharge circuits for synchronous DGs is proposed by Ref. [105]. Besides, the installation of FCLs to preserve the relay settings is also an approach presented by Refs. [106–110], and the application of FCLs to reduce the fault current contribution from DGs is suggested by Refs. [111,112]. Finally, distance and differential protection schemes can be found in the literature as a solution for the MG protection issue, respectively, in Refs. [113–124].

Despite the fact that these methods can mitigate the impacts of DG presence on the performance of the protective devices, they have some disadvantages, such as those mentioned by Shih et al. [55]. Disconnecting large DGs immediately after the fault detection may lead to severe voltage sags throughout the system, especially in high DG penetration cases, as the contribution of reactive power from these DGs will be cut off. Note that voltage sag is a momentary decrease in the voltage magnitude that can cause extensive disruption to the industrial process sector in terms of production loss [125,126]. Limiting the DG capacity may not be recommended due to the low cost of renewable energy and the need to reduce CO_2 emission. One note here is that this limitation also occurs in the steady-state of the system, and not only under faults. Thus, the potential of renewable energy resources may not be fully used. Modifying the protection scheme by installing more protective devices and reconfiguring grids is costly. Installing FCLs to preserve the relay settings are practical, but leads to an additional cost for both utility and DG owners [55]. Despite these shortcomings, it is worth pointing out that various studies concerning these other methods for protecting MG are being developed, and more effort is needed to overcome them.

7. Discussion

An MG consists of elements such as DGs (e.g., PV, WT and diesel generators), energy storage devices (e.g., supercapacitors, BESS and MBESS), communication infrastructure, as well as lines and loads. The interaction among all these elements requires a protection scheme/strategy to solve the current challenges. As a strategy for protection, emphasis can be placed upon the utilization of FCLs, or the disconnection of DGs immediately after the fault detection, or also the improvement of traditional schemes based on distance and differential protection. Besides, the adaptive approach has been considered as a viable solution for protecting MGs, as well as DSs with DGs. Through the bibliometric analysis carried out in this paper, a growing amount of publications can be observed related to adaptive protection in recent years, especially associated with the MG context. This analysis indicated some of the most productive authors and countries, and through this analysis, researchers may try to improve their global collaboration level on the topic. Additionally, by means of a comprehensive survey, innovative schemes and strategies of adaptive protection based on computational intelligence, or not, were presented. Table 2 summarizes many of the studies discussed. In this table, these studies are categorized according to the following aspects:

- Approach – Is the study based on computational intelligence or not?
- Protection Type – Is the study based on overcurrent, distance or other function protection?
- Software – For the development and validation of this research, what software was used to carry out the simulations?
- Scenarios Analyzed – In simulations, does the research consider grid-connected, islanding and contingency scenarios?
- Other Factors – In the research, is the required communication/control infrastructure briefly discussed? Does the study consider synchronous based distributed generator (SBDG), IBDG or both types of DGs in the simulations? Does the research analyze LLL, LL, LLG, LG or all type faults?

Based on Table 2 derived from the discussed studies, some aspects may be observed. Most of the studies related to adaptive protection, consider the overcurrent protection philosophy. Some papers use overcurrent protection together with distance protection. Thus, the usage of other protection philosophies, or a hybrid approach, could be more explored. Many studies do not consider contingency situations and, based on the characteristics of the MGs, the reliable performance of protection in these situations is desirable. Most of the studies consider only three-phase (LLL) faults to evaluate the performance of the proposed methods. A tendency to consider MGs and DSs with both types of DGs can be observed, i.e., IBDG and SBDG. Finally, two specific aspects deserve attention in future studies: (i) communication failures and cyberattacks; and (ii) the increasing use of energy storage systems. These aspects are discussed next.

7.1. Communication failures and cyberattacks

Noteworthy here is that in many of the reviewed proposals, a communication structure for the MG protection is necessary. However, the risk of communication link failures and cybersecurity threats are concerned in implementing a fast, robust, and mainly, a reliable adaptive protection scheme [127]. Thus, this issue may be considered as a major drawback of most adaptive protection proposals. Considering this issue, Habib et al. [127] presented a review of communication failure impacts on adaptive MG protection schemes. These authors showed, for example, that when the communication fails, the relay settings are not adjusted, which implies unsuccessful rendering of any adaptive protection scheme. The authors also showed different types of cyberattacks that may impact adaptive protection schemes. For example, the attacker may transmit malicious code to an IED and write oversized data to cause a buffer overflow. In another example, the attacker can capture and keep the GOOSE messages and subsequently sends a message to trip a circuit breaker under normal operation, resulting in an undesirable action.

A real case of a cyberattack is given by Hansen et al. [128] when, in 2015, a Russian hacker group attacked the Ukrainian power grid. The hackers remotely opened substation breakers, which resulted in a blackout affecting more than 225,000 customers. Unfortunately, these attacks are possible as a result of vulnerabilities of IEDs and communication networks. In this regard, a publication of CIGRE [129] highlights that IEDs based on IEC 61850, for example, are subject to the same threats as any other industry distributed control system based on TCP/IP/Ethernet protocols. Some proposals to overcome the issues mentioned can be found in Refs. [127,130–132]. In spite of the effort of these authors, the matters mentioned above remain as a challenge in implementing a reliable adaptive protection scheme and should be addressed in future studies.

7.2. Energy storage systems

ESSs integrate the MGs, and the application of these systems at the

Table 2
Summary of studies addressing adaptive protection in the context of microgrids and distribution systems with DGs.

Reference	Approach		Protection Type			Software						Scenarios			Other Factors		
	CI	OT	OVC	DIS	OT	PS	RS	DIg	ET	Sim	OT	GC	IS	CG	COM	DG	Faults
Chattopadhyay et al. [45]	●		●								●	●		●	●	SBDG	LLL
Zayandehroodi et al. [46]	●		●					●				●			●	SBDG	ALL
Papaspiliotopoulos et al. [51]	●		●				●	●				●			●	SBDG	LLL
Atteya et al. [52]	●		●								●	●	●	●		SBDG	–
Shih et al. [53]	●		●								●	●		●	●	SBDG	LLL
Singh et al. [54]	●		●	●			●					●		●	●	ALL	–
Shih et al. [55]	●		●								●	●	●	●	●	ALL	–
Papaspiliotopoulos et al. [59]	●		●				●					●		●	●	SBDG	LLL
Naily et al. [61]	●		●						●			●	●		●	SBDG	LLL
Ojaghi and Mohammadi [71]	●		●								●	●		●	●	SBDG	–
Kumar and Srinivasan [64]	●		●							●		●	●	●		ALL	LLL, LLG, LG
Nascimento and Rolim [66]	●		●			●						●	●	●	●	ALL	LG
George and Ashok [67]	●				●				●			●			●	ALL	LLL
Liu et al. [32]	●		●								●	●	●		●	ALL	LLL
Faria et al. [68]	●		●				●					●				IBDG	LG
Daryani and Karkevandi [69]	●		●							●		●	●		●	IBDG	LG
Lin et al. [50]	●		●	●				●				●	●	●		ALL	LLL
Alam et al. [60]	●		●								●	●	●	●	●	ALL	LLL
Brahma and Girgis [43]		●	●								●	●			●	SBDG	ALL
Mahat et al. [30]		●	●					●				●	●	●	●	ALL	LLL
Liu et al. [72]		●	●					●				●	●	●	●	ALL	LLL
Ma et al. [73]		●			●	●						●		●	●	SBDG	LLL, LL
Hussain et al. [74]		●	●								●	●			●	IBDG	LLL
Laaksonen et al. [75]		●	●			●						●	●		●	SBDG	LLL, LG
Coffele et al. [76]		●	●				●					●	●	●	●	SBDG	LL, LG
Bhattarai et al. [33]		●	●				●					●	●		●	ALL	LLL
Ates et al. [77,78]		●	●							●		●	●		●	IBDG	LLL
Sitharthan et al. [79]		●	●			●						●	●		●	IBDG	LLG
Muda and Jena [81,82]		●	●				●					●	●		●	ALL	LLL, LG
Piesciorovsky and Schulz [84]		●	●								●	●	●			SBDG	–
Fani et al. [85]		●	●								●	●		●	●	IBDG	LLL, LLG
Zanjani et al. [86]		●	●					●				●		●	●	ALL	–
Ferreira et al. [88]		●	●							●		●	●		●	SBDG	LLL
Singh and Basak [90]		●	●							●		●	●		●	ALL	ALL

Legend – Approach: CI = Computational intelligence-based approaches; and OT = Other adaptive approaches.
Protection Type: OVC = Overcurrent; DIS = Distance; and OT = Other.
Software: PS = PSCAD; RS = RSCAD/RTDS; DIg = DIgSILENT; ET = ETAP; Sim = Simulink; and OT = Other.
Scenarios: GC = Grid-connected; IS = Islanded; and CG = Contingency.
Other Factors: COM = Communication; DG = Type of DG (i.e, IBDG, SBDG or both); and Faults = Faults analyzed (ALL includes LLL, LL, LLG and LG types).

distribution level can be useful for arbitrage [133,134], renewable energy integration emphasizing power smoothing and time-shifting [135–137], renewable energy capacity firming [138], power loss reduction [139,140], and voltage and frequency control [141,142]. ESS can be provided by some technologies, such as compressed air energy storage, pumped hydraulic storage, flywheel energy storage, supercapacitors, BESS, and MBESS. Every type of ESS has extensive advantages and disadvantages, and the selection of an ESS type, its size and placement depend on the expected performances, application types, network topology, and system size [143]. Regarding the BESS, for example, the global installation of this technology reached over 1.6 GW in October 2016. Considering this context, some papers can be found that propose strategies for protecting MGs, while utilizing BESS, as in Refs. [144–148]. However, none of the studies presented in this review paper, related to adaptive protection, consider the presence of these elements. Therefore, future studies can explore the presence of ESSs in order to propose and evaluate new adaptive protection schemes for MGs, keeping in mind the importance and increasing application of ESSs.

8. Conclusion

This paper presented the main challenges related to the protection of MGs and DSs with DGs, as well as the most recent schemes proposed by a number of different studies, focusing on a bibliometric analysis of adaptive protection schemes. Factors inherent to these systems were seen, mainly, from their possible operation in grid-connected and islanded modes, along with the presence of DGs, which can imply in a failure of traditional protection schemes. The emphasis given to adaptive protection schemes is due to the fact that some recent papers highlight it as a promising solution for MG protection. Noteworthy, however, is that schemes are proposed in a particular context, i.e., for a determined topology, a quantity of DGs, power output, fault situation, etc., thus linking the proposed schemes to boundary conditions. Therefore, more effort is still needed in terms of overcoming the limitations of proposed protection schemes for all situations and scenarios. On the other hand, many schemes notably depend on communication, where the need arises for more studies related to communication failures and cyberattacks in the context of MG protection. The presence of ESSs such as BESS/MBESS on MGs should also be considered in future studies. Considering this, further effort is still needed in order to obtain a complete and general solution concerning this kind of protection.

Acknowledgements

This work was supported by the São Paulo Research Foundation (FAPESP) [Grant Number 17/16742-7] and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES) [Finance Code 001]. The authors would also like to thank the São Carlos School of Engineering, University of São Paulo, São Carlos, Brazil for the facilities provided.

References

[1] Green M. Community power. Nature Energy 2016;1(3):16014. https://doi.org/10.1038/nenergy.2016.14.

[2] Hirsch A, Parag Y, Guerrero J. Microgrids: a review of technologies, key drivers, and outstanding issues. Renew Sustain Energy Rev 2018;90:402–11. https://doi.org/10.1016/j.rser.2018.03.040.

[3] Yang Y, Bremner S, Menictas C, Kay M. Battery energy storage system size determination in renewable energy systems: a review. Renew Sustain Energy Rev 2018;91:109–25. https://doi.org/10.1016/j.rser.2018.03.047.

[4] Hatziargyriou N, Asano H, Iravani R, Marnay C. Microgrids, IEEE Power and Energy Magazine 2007;5(4):78–94. https://doi.org/10.1109/mpae.2007.376583.

[5] Chowdhury PCSP. Microgrids and active distribution networks. The Insitution of Engineering and Technology; 2009.

[6] Palizban O, Kauhaniemi K, Guerrero JM. Microgrids in active network management—part i: hierarchical control, energy storage, virtual power plants, and market participation. Renew Sustain Energy Rev 2014;36:428–39. https://doi.org/10.1016/j.rser.2014.01.016.

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

[8] Mirsaeidi S, Said DM, Mustafa MW, Habibuddin MH, Ghaffari K. Progress and problems in micro-grid protection schemes. Renew Sustain Energy Rev 2014;37:834–9. https://doi.org/10.1016/j.rser.2014.05.044.

[9] Memon AA, Kauhaniemi K. A critical review of AC microgrid protection issues and available solutions. Electr Power Syst Res 2015;129:23–31. https://doi.org/10.1016/j.epsr.2015.07.006.

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

[11] Kamel RM, Alsaffar MA, Habib M. Novel and simple scheme for micro-grid protection by connecting its loads neutral points: a review on micro-grid protection techniques. Renew Sustain Energy Rev 2016;58:931–42. https://doi.org/10.1016/j.rser.2015.12.319.

[12] Mirsaeidi S, Dong X, Shi S, Tzelepis D. Challenges, advances and future directions in protection of hybrid AC/DC microgrids. IET Renew Power Gener 2017;11(12):1495–502. https://doi.org/10.1049/iet-rpg.2017.0079.

[13] Dadhich M, Prajapati OS. A brief review on factors affecting flow and pool boiling. Renew Sustain Energy Rev 2019;112:607–25. https://doi.org/10.1016/j.rser.2019.06.016.

[14] Navas-Anguita Z, García-Gusano D, Iribarren D. A review of techno-economic data for road transportation fuels. Renew Sustain Energy Rev 2019;112:11–26. https://doi.org/10.1016/j.rser.2019.05.041.

[15] Apostolou D, Enevoldsen P. The past, present and potential of hydrogen as a multifunctional storage application for wind power. Renew Sustain Energy Rev 2019;112:917–29. https://doi.org/10.1016/j.rser.2019.06.049.

[16] Falagas ME, Pitsouni EI, Malietzis GA, Pappas G. Comparison of PubMed, scopus, web of science, and google scholar: strengths and weaknesses. FASEB J 2008;22(2):338–42. https://doi.org/10.1096/fj.07-9492lsf.

[17] Zyoud SH, Fuchs-Hanusch D. A bibliometric-based survey on AHP and TOPSIS techniques. Expert Syst Appl 2017;78:158–81. https://doi.org/10.1016/j.eswa.2017.02.016.

[18] What content is included in scopus, acessed on: Aug. 20, 2019. URL https://www.elsevier.com/solutions/scopus/how-scopus-works/content.

[19] van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 2009;84(2):523–38. https://doi.org/10.1007/s11192-009-0146-3.

[20] Park JY, Nagy Z. Comprehensive analysis of the relationship between thermal comfort and building control research - a data-driven literature review. Renew Sustain Energy Rev 2018;82:2664–79. https://doi.org/10.1016/j.rser.2017.09.102.

[21] Sweileh WM, Al-Jabi SW, Zyoud SH, Sawalha AF, Abu-Taha AS. Global research output in antimicrobial resistance among uropathogens: a bibliometric analysis (2002–2016). J. Global Antimicrob Resist 2018;13:104–14. https://doi.org/10.1016/j.jgar.2017.11.017.

[22] van Nunen K, Li J, Reniers G, Ponnet K. Bibliometric analysis of safety culture research. Saf Sci 2018;108:248–58. https://doi.org/10.1016/j.ssci.2017.08.011.

[23] Wasilewski J. Optimisation of multicarrier microgrid layout using selected metaheuristics. Int J Electr Power Energy Syst 2018;99:246–60. https://doi.org/10.1016/j.ijepes.2018.01.022.

[24] Moreira CL, Resende FO, Lopes JAP. Using low voltage MicroGrids for service restoration. IEEE Trans Power Syst 2007;22(1):395–403. https://doi.org/10.1109/tpwrs.2006.888989.

[25] Fu Q, Nasiri A, Solanki A, Bani-Ahmed A, Weber L, Bhavaraju V. Microgrids: architectures, controls, protection, and demonstration. Electr Power Compon Syst 2015;43(12):1453–65. https://doi.org/10.1080/15325008.2015.1039098.

[26] Haddadian H, Noroozian R. Optimal operation of active distribution systems based on microgrid structure. Renew Energy 2017;104:197–210. https://doi.org/10.1016/j.renene.2016.12.018.

[27] Lopes JAP, Moreira CL, Madureira AG. Defining control strategies for microgrids islanded operation. IEEE Trans Power Syst 2006;21(2):916–24. https://doi.org/10.1109/TPWRS.2006.873018.

[28] Ustun TS, Ozansoy C, Zayegh A. Recent developments in microgrids and example cases around the world—a review. Renew Sustain Energy Rev 2011;15(8):4030–41. https://doi.org/10.1016/j.rser.2011.07.033.

[29] Che L, Khodayar ME, Shahidehpour M. Adaptive protection system for microgrids: protection practices of a functional microgrid system. IEEE Electrification Mag 2014;2(1):66–80. https://doi.org/10.1109/mele.2013.2297031.

[30] 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(3):428–37. https://doi.org/10.1109/tsg.2011.2149550.

[31] Barker P, Mello RD. Determining the impact of distributed generation on power systems. i. radial distribution systems. In: 2000 power engineering society summer meeting. IEEE; 2000. https://doi.org/10.1109/pess.2000.868775.

[32] Liu Z, Su C, Hoidalen HK, Chen Z. A multiagent system-based protection and control scheme for distribution system with distributed-generation integration. IEEE Trans Power Deliv 2017;32(1):536–45. https://doi.org/10.1109/tpwrd.2016.2585579.

[33] Bhattarai BP, Bak-Jensen B, Chaudhary S, Pillai JR. An adaptive overcurrent protection in smart distribution grid. In: 2015 IEEE eindhoven PowerTech. IEEE; 2015. https://doi.org/10.1109/ptc.2015.7232310.

[34] Kauhaniemi K. Impact of distributed generation on the protection of distribution networks. In: Eighth IEE international conference on developments in power system protection. IEE; 2004. https://doi.org/10.1049/cp:20040126.

[35] Kumpulainen L, Kauhaniemi K. Distributed generation and reclosing coordination. In: Nordic distribution and asset management conference, citeseer; 2004.

[36] Kumpulainen L, Kauhaniemi K. Analysis of the impact of distributed generation on automatic reclosing. In: IEEE PES power systems conference and exposition. IEEE; 2004. https://doi.org/10.1109/psce.2004.1397623.

[37] Njozela M, Chowdhury S, Chowdhury SP. Impacts of DG on the operation of auto-reclosing devices in a power network. In: 2011 IEEE power and energy society general meeting. IEEE; 2011. https://doi.org/10.1109/pes.2011.6039234.

[38] Phadke AG, Thorp JS. Computer relaying for power systems. second ed. John Wiley & Sons; 2009.

[39] Horowitz S, Phadke A, Thorp J. Adaptive transmission system relaying. IEEE Trans Power Deliv 1988;3(4):1436–45. https://doi.org/10.1109/61.193942.

[40] Phadke AG, Politis A, Thorp JS. Improved protection and control of power systems with digital computers. In: International conference on large high voltage electric systems; 1986.

[41] Scopus database:, acessed on: Aug. 20, 2019. URL https://www.scopus.com/.

[42] Naduvathuparambil B, Valenti M, Feliachi A. Communication delays in wide area measurement systems. In: Proceedings of the thirty-fourth southeastern symposium on system theory. IEEE; 2002. https://doi.org/10.1109/ssst.2002.1027017.

[43] Brahma S, Girgis A. Development of adaptive protection scheme for distribution systems with high penetration of distributed generation. IEEE Trans Power Deliv 2004;19(1):56–63. https://doi.org/10.1109/TPWRD.2003.820204.

[44] Brown RE. Impact of smart grid on distribution system design. In: 2008 IEEE power and energy society general meeting - conversion and delivery of electrical energy in the 21st century. IEEE; 2008. https://doi.org/10.1109/pes.2008.4596843.

[45] Chattopadhyay B, Sachdev M, Sidhu T. An on -line relay coordination algorithm for adaptive protection using linear programming technique. IEEE Trans Power Deliv 1996;11(1):165–71. https://doi.org/10.1109/61.484013.

[46] Zayandehroodi H, Mohamed A, Shareef H, Farhoodnea M. A novel neural network and backtracking based protection coordination scheme for distribution system with distributed generation. Int J Electr Power Energy Syst 2012;43(1):868–79. https://doi.org/10.1016/j.ijepes.2012.06.061.

[47] Rezaei N, Haghifam M-R. Protection scheme for a distribution system with distributed generation using neural networks. Int J Electr Power Energy Syst 2008;30(4):235–41. https://doi.org/10.1016/j.ijepes.2007.07.006.

[48] Javadian SAM, Haghifam M-R, Rezaei N. A fault location and protection scheme for distribution systems in presence of dg using MLP neural networks. In: 2009 IEEE power & energy society general meeting. IEEE; 2009. https://doi.org/10.1109/pes.2009.5275863.

[49] Tang W-J, Yang H-T. Self-adaptive protection strategies for distribution system with DGs and FCLs based on data mining and neural network. In: 2017 IEEE international conference on environment and electrical engineering and 2017 IEEE industrial and commercial power systems europe (EEEIC/I&CPS europe). IEEE; 2017. https://doi.org/10.1109/eeeic.2017.7977738.

[50] Lin H, Sun K, Tan Z-H, Liu C, Guerrero JM, Vasquez JC. Adaptive protection combined with machine learning for microgrids. IET Gener, Transm Distrib 2019;13(6):770–9. https://doi.org/10.1049/iet-gtd.2018.6230.

[51] Papaspiliotopoulos VA, Korres GN, Hatziargyriou ND. Protection coordination in modern distribution grids integrating optimization techniques with adaptive relay setting. In: 2015 IEEE eindhoven PowerTech. IEEE; 2015. https://doi.org/10.1109/ptc.2015.7232558.

[52] Atteya AI, Zonkoly AME, Ashour HA. Optimal relay coordination of an adaptive protection scheme using modified PSO algorithm. In: 2017 nineteenth international Middle East power systems conference (MEPCON). IEEE; 2017. https://doi.org/10.1109/mepcon.2017.8301256.

[53] Shih MY, Salazar CAC, Enríquez AC. Adaptive directional overcurrent relay coordination using ant colony optimisation. IET Gener, Transm Distrib 2015;9(14):2040–9. https://doi.org/10.1049/iet-gtd.2015.0394.

[54] Singh M, Vishnuvardhan T, Srivani S. Adaptive protection coordination scheme for power networks under penetration of distributed energy resources. IET Gener, Transm Distrib 2016;10(15):3919–29. https://doi.org/10.1049/iet-gtd.2016.0614.

[55] Shih MY, Conde A, Leonowicz Z, Martirano L. An adaptive overcurrent coordination scheme to improve relay sensitivity and overcome drawbacks due to distributed generation in smart grids. IEEE Trans Ind Appl 2017;53(6):5217–28. https://doi.org/10.1109/tia.2017.2717880.

[56] Das S, Suganthan PN. Differential evolution: a survey of the state-of-the-art. IEEE Trans Evol Comput 2011;15(1):4–31. https://doi.org/10.1109/tevc.2010.2059031.

[57] Das S, Mullick SS, Suganthan P. Recent advances in differential evolution – an updated survey. Swarm Intell Evol Comput 2016;27:1–30. https://doi.org/10.1016/j.swevo.2016.01.004.

[58] Alam MN, Das B, Pant V. A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination. Electr Power Syst Res 2015;128:39–52. https://doi.org/10.1016/j.epsr.2015.06.018.

[59] Papaspiliotopoulos VA, Korres GN, Kleftakis VA, Hatziargyriou 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(1):393–400. https://doi.org/10.1109/tpwrd.2015.2509784.

[60] Alam MN, Chakrabarti S, Sharma A, Srivastava SC. An adaptive protection scheme for AC microgrids using μPMU based topology processor. In: 2019 IEEE international conference on environment and electrical engineering and 2019 IEEE industrial and commercial power systems europe (EEEIC/I&CPS europe). IEEE; 2019. https://doi.org/10.1109/eeeic.2019.8783396.

[61] Naily NE, Saad SM, Hussein T, Mohamed FA. Minimizing the impact of distributed generation of a weak distribution network with an artificial intelligence technique. Appl Sol Energy 2017;53(2):109–22. https://doi.org/10.3103/s0003701x17020128.

[62] Naily NE, Saad SM, Wafi J, Elhaffar A, Husseinzadch N. Adaptive overcurrent protection to mitigate high penetration of distributed generation in weak distribution systems. In: 2017 9th IEEE-GCC conference and exhibition (GCCCE). IEEE; 2017. https://doi.org/10.1109/ieeegcc.2017.8448233.

[63] Naily NE, Saad SM, Hussein T, El-Arroudi K, Mohamed FA. On-line adaptive protection scheme to overcome operational variability of DG in smart grid via fuzzy logic and genetic algorithm. In: 2018 9th international renewable energy congress (IREC). IEEE; 2018. https://doi.org/10.1109/irec.2018.8362498.

[64] Kumar DS, Srinivasan D. A numerical protection strategy for medium-voltage distribution systems. In: 2018 IEEE innovative smart grid technologies - asia (ISGT asia). IEEE; 2018. https://doi.org/10.1109/isgt-asia.2018.8467835.

[65] Momesso AE, Bernardes WMS, Asada EN. Fuzzy adaptive setting for time-current-voltage based overcurrent relays in distribution systems. Int J Electr Power Energy Syst 2019;108:135–44. https://doi.org/10.1016/j.ijepes.2018.12.035.

[66] do Nascimento LL, Rolim JG. Multi-agent system for adaptive protection in microgrids. In: 2013 IEEE PES conference on innovative smart grid technologies (ISGT Latin America). IEEE; 2013. https://doi.org/10.1109/isgt-la.2013.6554435.

[67] George SP, Ashok S. Multiagent based adaptive relaying for distribution network with distributed generation. In: 2015 international conference on energy, power and environment: towards sustainable growth (ICEPE). IEEE; 2015. https://doi.org/10.1109/epetsg.2015.7510154.

[68] Faria IM, Furlan RH, Martins PET, Menezes TS, Oleskovicz M, Coury DV. The proposition of a multiagent system for adaptive protection of a distribution system. In: 2018 simposio brasileiro de Sistemas eletricos (SBSE). IEEE; 2018. https://doi.org/10.1109/sbse.2018.8395648.

[69] Daryani MJ, Karkevandi AE. Decentralized cooperative protection strategy for smart distribution grid using multi-agent system. In: 2018 6th international istanbul smart grids and cities congress and fair (ICSG). IEEE; 2018. https://doi.org/10.1109/sgcf.2018.8408958.

[70] Hosseini SA, Abyaneh HA, Sadeghi SHH, Eslami R. Improving adaptive protection to reduce sensitivity to uncertainties which affect protection coordination of microgrids. Iran J Sci Technol, Trans Electr Eng 2018;42(1):63–74. https://doi.org/10.1007/s40998-018-0049-5.

[71] Ojaghi M, Mohammadi V. Use of clustering to reduce the number of different setting groups for adaptive coordination of overcurrent relays. IEEE Trans Power Deliv 2018;33(3):1204–12. https://doi.org/10.1109/tpwrd.2017.2749321.

[72] Liu C, Chen Z, Liu Z. A communication-less overcurrent protection for distribution system with distributed generation integrated. In: 2012 3rd IEEE international symposium on power electronics for distributed generation systems (PEDG). IEEE; 2012. https://doi.org/10.1109/pedg.2012.6253992.

[73] Ma J, Ma W, Wang X, Wang Z. A new adaptive voltage protection scheme for distribution network with distributed generations. Can J Electr Comput Eng 2013;36(4):142–51. https://doi.org/10.1109/cjece.2014.2302858.

[74] Hussain B, Sharkh SM, Hussain S, Abusara MA. An adaptive relaying scheme for fuse saving in distribution networks with distributed generation. IEEE Trans Power Deliv 2013;28(2):669–77. https://doi.org/10.1109/tpwrd.2012.2224675.

[75] Laaksonen H, Ishchenko D, Oudalov A. Adaptive protection and microgrid control design for Hailuoto Island. IEEE Trans Smart Grid 2014;5(3):1486–93. https://doi.org/10.1109/tsg.2013.2287672.

[76] Coffele F, Booth C, Dysko A. An adaptive overcurrent protection scheme for distribution networks. IEEE Trans Power Deliv 2015;30(2):561–8. https://doi.org/10.1109/tpwrd.2013.2294879.

[77] Ates Y, Boynuegri A, Uzunoglu M, Nadar A, Yumurtacı R, Erdinc O, Paterakis N, Catalão J. Adaptive protection scheme for a distribution system considering grid-connected and islanded modes of operation. Energies 2016;9(5):378. https://doi.org/10.3390/en9050378.

[78] Ates Y, Uzunoglu M, Karakas A, Boynuegri AR, Nadar A, Dag B. Implementation of adaptive relay coordination in distribution systems including distributed generation. J Clean Prod 2016;112:2697–705. https://doi.org/10.1016/j.jclepro.2015.10.066.

[79] Sitharthan R, Geethanjali M, Pandy TKS. Adaptive protection scheme for smart microgrid with electronically coupled distributed generations. Alexandria Eng J 2016;55(3):2539–50. https://doi.org/10.1016/j.aej.2016.06.025.

[80] Swathika OVG, Hemamalini S. Prims-aided dijkstra algorithm for adaptive protection in microgrids. IEEE J Emerg Sel Top Power Electron 2016;4(4):1279–86. https://doi.org/10.1109/jestpe.2016.2581986.

[81] Muda H, Jena P. Sequence currents based adaptive protection approach for DNs with distributed energy resources. IET Gener, Transm Distrib 2017;11(1):154–65. https://doi.org/10.1049/iet-gtd.2016.0727.

[82] Muda H, Jena P. Superimposed adaptive sequence current based microgrid protection: a new technique. IEEE Trans Power Deliv 2017;32(2):757–67. https://doi.org/10.1109/tpwrd.2016.2601921.

[83] Shen S, Lin D, Wang H, Hu P, Jiang K, Lin D, He B. An adaptive protection scheme for distribution systems with DGs based on optimized thevenin equivalent parameters estimation. IEEE Trans Power Deliv 2017;32(1):411–9. https://doi.org/10.1109/tpwrd.2015.2506155.

[84] 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. https://doi.org/10.1016/j.epsr.2017.05.035.

[85] Fani B, Dadkhah M, Karami-Horestani A. Adaptive protection coordination scheme against the staircase fault current waveforms in PV-dominated distribution systems. IET Gener, Transm Distrib 2018;12(9):2065–71. https://doi.org/10.1049/iet-gtd.2017.0586.

[86] Zanjani MGM, Mazlumi K, Kamwa I. Application of μPMUs for adaptive protection of overcurrent relays in microgrids. IET Gener, Transm Distrib 2018;12(18):4061–8. https://doi.org/10.1049/iet-gtd.2018.5898.

[87] Ferreira RR, Grilo AP, Teixeira JC, Santos RC. Method for adaptive overcurrent protection of distribution systems with distributed synchronous generators. In: 2015 IEEE power & energy society general meeting. IEEE; 2015. https://doi.org/10.1109/pesgm.2015.7286515.

[88] Ferreira RR, Colorado PJ, Grilo AP, Teixeira JC, Santos RC. Method for identification of grid operating conditions for adaptive overcurrent protection during intentional islanding operation. Int J Electr Power Energy Syst 2019;105:632–41. https://doi.org/10.1016/j.ijepes.2018.09.004.

[89] Gu J-C, Liu C-H, Wang J-M, Yang M-T. Using IEC 61850 GOOSE messages in microgrid protection. Int Trans Electr Energy Syst jul 2019. https://doi.org/10.1002/2050-7038.12122.

[90] Singh M, Basak P. Adaptive protection methodology in microgrid for fault location and nature detection using q0 components of fault current. IET Gener, Transm Distrib 2019;13(6):760–9. https://doi.org/10.1049/iet-gtd.2018.6347.

[91] Purwar E, Choudhary MM. Novel adaptive algorithm for optimal relay setting with improved coordination. In: 2014 students conference on engineering and systems. IEEE; 2014. https://doi.org/10.1109/sces.2014.6880078.

[92] Nascimento JP, Brito NSD, de Souza BA. An adaptive protection algorithm for distribution systems with distributed generation. In: 2015 IEEE PES innovative smart grid technologies Latin America (ISGT LATAM). IEEE; 2015. https://doi.org/10.1109/isgt-la.2015.7381147.

[93] Nascimento JP, Brito NSD, de Souza BA. Proposition of an adaptive protection scheme for distribution systems with distributed generation. IEEE Lat Am Trans 2018;16(5):1439–44. https://doi.org/10.1109/tla.2018.8408439.

[94] Singh MK, Reddy PN. A fast adaptive protection scheme for distributed generation connected networks with necessary relay coordination. In: 2013 students conference on engineering and systems (SCES). IEEE; 2013. https://doi.org/10.1109/sces.2013.6547562.

[95] Ma J, Mi C, Wang T, Wu J, Wang Z. An adaptive protection scheme for distributed systems with distributed generation. In: 2011 IEEE power and energy society general meeting. IEEE; 2011. https://doi.org/10.1109/pes.2011.6039832.

[96] Buque C, Ipinnimo O, Chowdhury S, Chowdhury SP. Modeling and simulation of an adaptive relaying scheme for a microgrid. In: 2012 IEEE power and energy society general meeting. IEEE; 2012. https://doi.org/10.1109/pesgm.2012.6344569.

[97] Baran M, El-Markabi I. Adaptive over current protection for distribution feeders with distributed generators. In: IEEE PES power systems conference and exposition, 2004. IEEE; 2004. https://doi.org/10.1109/psce.2004.1397672.

[98] Cheung H, Hamlyn A, Yang C, Cheung R. Network-based adaptive protection strategy for feeders with distributed generations. In: 2007 IEEE Canada electrical power conference. IEEE; 2007. https://doi.org/10.1109/epc.2007.4520385.

[99] Conti S. Analysis of distribution network protection issues in presence of dispersed generation. Electr Power Syst Res 2009;79(1):49–56. https://doi.org/10.1016/j.epsr.2008.05.002.

[100] Chaitusaney S, Yokoyama A. Prevention of reliability degradation from recloser–fuse miscoordination due to distributed generation. IEEE Trans Power Deliv 2008;23(4):2545–54. https://doi.org/10.1109/tpwrd.2007.915899.

[101] Chen J, Fan R, Duan X, Cao J. Penetration level optimization for DG considering reliable action of relay protection device constrains. In: 2009 international conference on sustainable power generation and supply. IEEE; 2009. https://doi.org/10.1109/supergen.2009.5348221.

[102] Funmilayo HB, Butler-Purry KL. An approach to mitigate the impact of distributed generation on the overcurrent protection scheme for radial feeders. In: 2009 IEEE/PES power systems conference and exposition. IEEE; 2009. https://doi.org/10.1109/psce.2009.4840233.

[103] Viawan F, Karlsson D, Sannino A, Daalder J. Protection scheme for meshed distribution systems with high penetration of distributed generation. In: 2006 power systems conference: advanced metering, protection, control,

communication, and distributed resources. IEEE; 2006. https://doi.org/10.1109/psamp.2006.285378.

[104] Ebrahimi E, Sanjari MJ, Gharehpetian GB. Control of three-phase inverter-based DG system during fault condition without changing protection coordination. Int J Electr Power Energy Syst 2014;63:814–23. https://doi.org/10.1016/j.ijepes.2014.05.058.

[105] Yazdanpanahi H, Xu W, Li YW. A novel fault current control scheme to reduce synchronous DGs impact on protection coordination. IEEE Trans Power Deliv 2014;29(2):542–51. https://doi.org/10.1109/tpwrd.2013.2276948.

[106] El-Khattam W, Sidhu T. Restoration of directional overcurrent relay coordination in distributed generation systems utilizing fault current limiter. IEEE Trans Power Deliv 2008;23(2):576–85. https://doi.org/10.1109/tpwrd.2008.915778.

[107] El-khattam W, Sidhu T. Resolving the impact of distributed renewable generation on directional overcurrent relay coordination: a case study. IET Renew Power Gener 2009;3(4):415. https://doi.org/10.1049/iet-rpg.2008.0015.

[108] Khederzadeh M. Application of TCSC to restore directional overcurrent relay coordination in systems with distributed generation. In: IET conference publications. IET; 2009. https://doi.org/10.1049/cp.2009.0515.

[109] Huchel L, Zeineldin HH. Planning the coordination of directional overcurrent relays for distribution systems considering DG. IEEE Trans Smart Grid 2016;7(3):1642–9. https://doi.org/10.1109/tsg.2015.2420711.

[110] Chabanloo R, Abyaneh H, Agheli A, Rastegar H. Overcurrent relays coordination considering transient behaviour of fault current limiter and distributed generation in distribution power network. IET Gener, Transm Distrib 2011;5(9):903. https://doi.org/10.1049/iet-gtd.2010.0754.

[111] Shukla V, Mohapatra A, Singh S. On adaptive fault current limiterin distribution systems with distributed generations. In: 2017 IEEE region 10 symposium (TENSYMP). IEEE; 2017. https://doi.org/10.1109/tenconspring.2017.8070005.

[112] Manigilla PKR, Sharma NK, Samantaray SR. Application of superconducting fault current limiter to cloud the presence of distributed generation. In: 2017 IEEE PES asia-pacific power and energy engineering conference (APPEEC). IEEE; 2017. https://doi.org/10.1109/appeec.2017.8308949.

[113] Tsimtsios AM, Korres GN, Nikolaidis VC. A pilot-based distance protection scheme for meshed distribution systems with distributed generation. Int J Electr Power Energy Syst 2019;105:454–69. https://doi.org/10.1016/j.ijepes.2018.08.022.

[114] Chilvers I. The use of 11 kV distance protection to increase generation connected to the distribution network. In: Eighth IEE international conference on developments in power system protection. IEE; 2004. https://doi.org/10.1049/cp:20040183.

[115] Uthitsunthorn D, Kulworawanichpong T. Distance protection of a renewable energy plant in electric power distribution systems. In: 2010 international conference on power system technology. IEEE; 2010. https://doi.org/10.1109/powercon.2010.5666058.

[116] Ma J, Li J, Wang Z. An adaptive distance protection scheme for distribution system with distributed generation. In: 2010 5th international conference on critical infrastructure (CRIS). IEEE; 2010. https://doi.org/10.1109/cris.2010.5617480.

[117] Abdulhadi I, Coffele F, Dysko A, Booth C, Burt G. Adaptive protection architecture for the smart grid. In: 2011 2nd IEEE PES international conference and exhibition on innovative smart grid technologies. IEEE; 2011. https://doi.org/10.1109/isgteurope.2011.6162781.

[118] Lin H, Liu C, Guerrero JM, Vasquez JC. Distance protection for microgrids in distribution system. In: IECON 2015 - 41st annual conference of the IEEE industrial electronics society. IEEE; 2015. https://doi.org/10.1109/iecon.2015.7392186.

[119] Casagrande E, Woon WL, Zeineldin HH, Svetinovic D. A differential sequence component protection scheme for microgrids with inverter-based distributed generators. IEEE Trans Smart Grid 2014;5(1):29–37. https://doi.org/10.1109/tsg.2013.2251017.

[120] Kar S, Samantaray SR, Zadeh MD. Data-mining model based intelligent differential microgrid protection scheme. IEEE Syst J 2017;11(2):1161–9. https://doi.org/10.1109/jsyst.2014.2380432.

[121] Liu X, Shahidehpour M, Li Z, Liu X, Cao Y, Tian W. Protection scheme for loop-based microgrids. IEEE Trans Smart Grid 2017;8(3):1340–9. https://doi.org/10.1109/tsg.2016.2626791.

[122] Ustun TS, Khan RH. Multiterminal hybrid protection of microgrids over wireless communications network. IEEE Trans Smart Grid 2015;6(5):2493–500. https://doi.org/10.1109/tsg.2015.2406886.

[123] Soleimanisardoo A, Karegar HK, Zeineldin HH. Differential frequency protection scheme based on off-nominal frequency injections for inverter-based islanded microgrids. IEEE Trans Smart Grid 2018. https://doi.org/10.1109/tsg.2017.2788851. 1–1.

[124] Aghdam TS, Karegar HK, Zeineldin HH. Variable tripping time differential protection for microgrids considering DG stability. IEEE Trans Smart Grid 2018. https://doi.org/10.1109/tsg.2018.2797367. 1–1.

[125] Math B, Bollen HJ. Understanding power quality problems. John Wiley & Sons; 1999.

[126] Fitzer C, Barnes M, Green P. Voltage sag detection technique for a dynamic voltage restorer. IEEE Trans Ind Appl 2004;40(1):203–12. https://doi.org/10.1109/tia.2003.821801.

[127] 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 2018;54(2):1194–207. https://doi.org/10.1109/tia.2017.2776858.

[128] Hansen A, Staggs J, Shenoi S. Security analysis of an advanced metering infrastructure. Int J Crit Infrastruct Protect 2017;18:3–19. https://doi.org/10.1016/j.ijcip.2017.03.004.

[129] CIGRE Working Group B5.38. The impact of implementing cyber security requirements using IEC 61850, t. Aug. 2010.

[130] Habib HF, Mohamed A, Hariri ME, Mohammed OA. Utilizing supercapacitors for resiliency enhancements and adaptive microgrid protection against communication failures. Electr Power Syst Res 2017;145:223–33. https://doi.org/10.1016/j.epsr.2016.12.027.

[131] Habib HF, Hariri AO, ElSayed A, Mohammed OA. Deployment of electric vehicles in an adaptive protection technique for riding through cyber attack threats in microgrids. In: 2017 IEEE international conference on environment and electrical engineering and 2017 IEEE industrial and commercial power systems europe (EEEIC/I&CPS europe). IEEE; 2017. https://doi.org/10.1109/eeeic.2017.7977729.

[132] Habib HF, Hariri ME, Elsayed A, Mohammed OA. Utilization of supercapacitors in protection schemes for resiliency against communication outages: a case study on size and cost optimization. IEEE Trans Ind Appl 2018;54(4):3153–64. https://doi.org/10.1109/tia.2018.2819620.

[133] Zafirakis D, Chalvatzis KJ, Baiocchi G, Daskalakis G. The value of arbitrage for energy storage: evidence from european electricity markets. Appl Energy 2016;184:971–86. https://doi.org/10.1016/j.apenergy.2016.05.047.

[134] Kang BO, Lee M, Kim Y, Jung J. Economic analysis of a customer-installed energy storage system for both self-saving operation and demand response program participation in South Korea. Renew Sustain Energy Rev 2018;94:69–83. https://doi.org/10.1016/j.rser.2018.05.062.

[135] Lamsal D, Sreeram V, Mishra Y, Kumar D. Output power smoothing control approaches for wind and photovoltaic generation systems: a review. Renew Sustain Energy Rev 2019;113:109245. https://doi.org/10.1016/j.rser.2019.109245.

[136] Lamsal D, Sreeram V, Mishra Y, Kumar D. Smoothing control strategy of wind and photovoltaic output power fluctuation by considering the state of health of battery energy storage system. IET Renew Power Gener 2019;13(4):578–86. https://doi.org/10.1049/iet-rpg.2018.5111.

[137] Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN. Review of energy storage system for wind power integration support. Appl Energy 2015;137:545–53. https://doi.org/10.1016/j.apenergy.2014.04.103.

[138] Abdelrazek S, Kamalasadan S. A weather-based optimal storage management algorithm for PV capacity firming. IEEE Trans Ind Appl 2016;52(6):5175–84. https://doi.org/10.1109/tia.2016.2598139.

[139] Monteiro RV, Guimarães GC, Moura FA, Albertini MR, Silva FB. Long-term sizing of lead–acid batteries in order to reduce technical losses on distribution networks: a distributed generation approach. Electr Power Syst Res 2017;144:163–74. https://doi.org/10.1016/j.epsr.2016.12.004.

[140] Hemmati R, Ghiasi SMS, Entezariharsini A. Power fluctuation smoothing and loss reduction in grid integrated with thermal-wind-solar-storage units. Energy 2018;152:759–69. https://doi.org/10.1016/j.energy.2018.04.004.

[141] Zhao H, Hong M, Lin W, Loparo KA. Voltage and frequency regulation of microgrid with battery energy storage systems. IEEE Trans Smart Grid 2019;10(1):414–24. https://doi.org/10.1109/tsg.2017.2741668.

[142] Datta U, Kalam A, Shi J. Battery energy storage system to stabilize transient voltage and frequency and enhance power export capability. IEEE Trans Power Syst 2019;34(3):1845–57. https://doi.org/10.1109/tpwrs.2018.2879608.

[143] Das CK, Bass O, Kothapalli G, Mahmoud TS, Habibi D. Overview of energy storage systems in distribution networks: placement, sizing, operation, and power quality. Renew Sustain Energy Rev 2018;91:1205–30. https://doi.org/10.1016/j.rser.2018.03.068.

[144] Zamani MA, Yazdani A, Sidhu TS. A communication-assisted protection strategy for inverter-based medium-voltage microgrids. IEEE Trans Smart Grid 2012;3(4):2088–99. https://doi.org/10.1109/tsg.2012.2211045.

[145] Moon W-S, Won J-N, Huh J-S, Kim J-C. A study on the application of a superconducting fault current limiter for energy storage protection in a power distribution system. IEEE Trans Appl Supercond 2013;23(3). https://doi.org/10.1109/tasc.2013.2238594. 5603404–5603404.

[146] Zamani MA, Sidhu TS, Yazdani A. Investigations into the control and protection of an existing distribution network to operate as a microgrid: a case study. IEEE Trans Ind Electron 2014;61(4):1904–15. https://doi.org/10.1109/tie.2013.2267695.

[147] Padullaparti HV, Chirapongsananurak P, Hernandez ME, Santoso S. Analytical approach to estimate feeder accommodation limits based on protection criteria. IEEE Access 2016;4:4066–81. https://doi.org/10.1109/access.2016.2589545.

[148] Yuan C, Lai K, Illindala MS, Haj-ahmed MA, Khalsa AS. Multilayered protection strategy for developing community microgrids in village distribution systems. IEEE Trans Power Deliv 2017;32(1):495–503. https://doi.org/10.1109/tpwrd.2016.2544923.