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Status and power electronics-induced challenges

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Reliability aspects in microgrid design and planning: Status and power electronics-induced challenges

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ABSTRACT

Microgrids are highlighted as the technology which can help in providing sustainable and efficient electrical energy solutions. They employ distributed energy resources to efficiently supply local load and increase the reliability of the local network. Design and planning are of a pivotal importance in yielding all of the advantages this concept can provide. Reliability-oriented design is of a special interest for microgrids utilizing a large share of the renewable energy-based, power electronics-interfaced distributed energy resources. A state-of-the-art overview included in this paper has shown that the main reliability-oriented microgrid design improvements are done in the field of distributed energy resources sizing and scheduling combined with the relevant forecasting and optimization methods. It is, further on, concluded that the standard power system reliability assessment within the design often excludes the wear-out failure of power electronics. However, previous field experience has shown that the power electronics is prone to wear-out failure and can have adverse impact on the reliability of the power electronics-dominated system. Therefore, it is necessary to adjust the current reliability methods to enable accurate investigation of power electronics reliability and its impact on system design. To do so, the main characteristics of the wear-out modelling concepts together with the recent publications bridging the power electronics and power system reliability are discussed in detail. Finally, the main findings included in this overview paper can serve as basis for development of the new procedures for reliability-oriented design and planning of future, power electronics-dominated microgrids.

1. Introduction

To facilitate the grid modernization, fossil fuel reduction and the integration of the new technologies, the microgrid concept has gained much popularity in recent years. Microgrids are electrical structures with small decentralized generation sources placed in the vicinity of the local loads [1,2]. Commonly, they are connected to the larger distribution system, but they can also operate independently. An example of such structure with integrated renewable energy sources is shown in Fig. 1. Microgrids are more cost-effective and efficient electrical systems with higher flexibility and scalability than large conventional power systems. This is also reflected in the number of newly deployed microgrid projects, which increases on a yearly basis. According to recent statistics, 546 new microgrid projects were deployed in 2019 in United States solely. This is approximately 4 times higher number of the new projects compared to 2013 [3,4]. Furthermore, microgrids have already proven to be a reliable solution for power delivery when the main grid is unavailable, as in case of the Texas blackout in January 2021 [5]

To ensure that the number of installation sites continues to increase in the future, adequate microgrid design and planning procedures are necessary. This often includes design targeting the environmental protection, cost-effectiveness and increased reliability [6]. Depending on the microgrid application, the importance of one design target can prevail. For example, the reliability is the main design concern in rural areas, separated from the main electricity grids or the institutions carrying out the critical roles, such as hospitals [7]. Contrary, efficiency increase and cost reduction play the main role in the design process for microgrids connected to the distribution system [8].

Previous state-of-art reviews on microgrid design mainly focused on the microgrid architecture and control [9–11], optimization techniques [12–14] and energy management strategies [15–17]. For example, Strasser et al. in [9] discussed the state-of-art achievements in the field of microgrid architecture and their relations to smart devices and control concepts. It is concluded that further improvements in robustness, decentralization and intelligence of future microgrids lie in those design aspects. Similar concern is pointed out in [11], where

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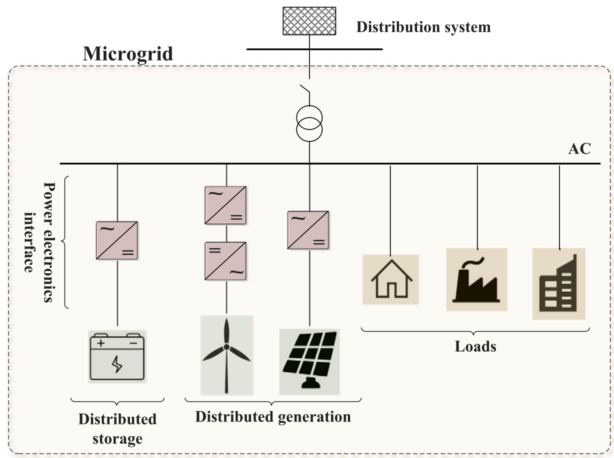

Fig. 1. Example of a microgrid structure with integrated renewable energy-based distributed generation and storage adapted from IEEE Std 2030.9 - Recommended Practice for the Planning and Design of the Microgrid [6].

the main challenges in control design are addressed together with a comprehensive review of the proposed solutions over different control levels. In [17], a critical analysis of more than 150 publications is provided on the topic of optimal use of the distributed energy resources (DER). The study summarizes the main contributions and limitations of the existing methods and the optimization techniques in energy management design. Fontenot and Dong in [12] discussed all of the aforementioned aspects (i.e., architecture, control, energy management) from an optimal definition of design objectives, constraints and methods point of view. They mentioned the importance of such study to further reduce the uncertainty and inaccuracy in microgrid design. The reviews covering broader design aspects are given in [18,19], however, they are limited to specific microgrid applications. In [18], recent design approaches combining cooling, heating and power microgrid are reviewed, while [19,20] provide insights on the main issues and challenges related to the energy storage applications. A more comprehensive literature reviews on different aspects of the microgrid design and planning are provided in [21,22], with [21] including an overview of the demonstration microgrid projects and their applications.

However, regardless the design objectives and targeted applications, certain technical requirements need to be fulfilled during the design and planning. According to [6], one of those requirements includes assuring sufficient generation capacity of a microgrid system over time. Such is investigated during the reliability (i.e., adequacy) assessment, which is increasingly challenging in the microgrids incorporating the renewable energy-based units, e.g., photovoltaic and wind power systems. Firstly, due to the intermittent and stochastic nature of renewable energy sources as well as the limited storage capability of energy storage systems, secondly, due to its failure-prone power electronics interface. The impact of the former has been the subject of research to a greater extent, while the latter has only been included to limiting extent. Aforementioned comprehensive literature reviews [21,22] only provide limited information on the microgrid reliability study and its impact on overall design, while a more detailed survey can be found in [13,23]. Authors in [23] provided an overview of the main trends in reliability analysis. However, no clear distinction between the design and operation-related reliability analysis is provided. More details on that topic are given in [13], where the main focus is put on the review of different stochastic-based methodologies that can be used within the reliability assessment. Nonetheless, even though comprehensive, the review in [23] and the review in [13] were published in 2014 and 2015, respectively and require update with the recent research achievements.

It is expected that the future microgrid systems will be heavily dominated by the renewable-based, power electronics-interfaced units.

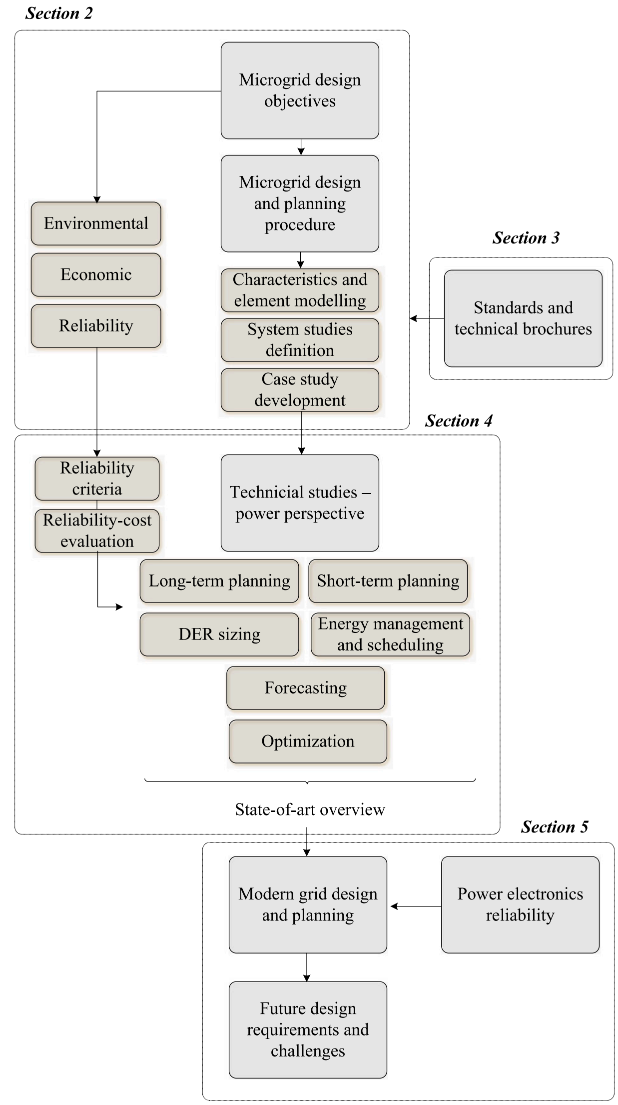

Fig. 2. Microgrid design and planning aspects included in the overview in this paper.

In such case, power electronics reliability will have significant impact on microgrid design and planning. Therefore, it is expected that current reliability process within design procedure will undergo an inevitable change. To indicate the main challenges and necessary changes in the design procedure, an overview of the current practices in reliability-oriented microgrid design and planning is provided. The rest of the paper is organized as follows and it is graphically represented in Fig. 2. In Section 2, an overview of the common microgrid framework is provided. This is followed by an overview of the relevant microgrid design standards in Section 3. A state-of-the-art review of the reliability aspects in the microgrid design is given in Section 4. Section 5 outlines the necessary change in the reliability related design procedures for the future power electronics-dominated microgrid systems. In Section 6, concluding remarks are provided.

2. Overview of microgrid design framework

Microgrid design procedure is divided into a research and development stage and an implementation and validation stage. In [24–27] microgrid design considerations and planning concepts are discussed. A procedure outlined in [24] can be used for variety of applications and it is summarized in the remaining part of the Section. Research

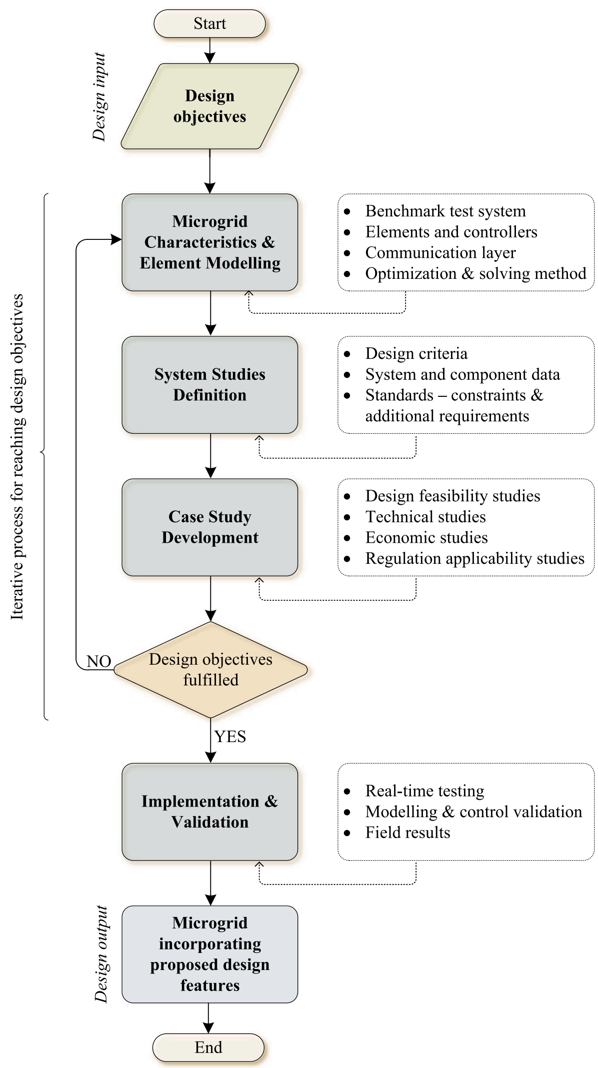

Fig. 3. Microgrid design and planning procedure.
Source: Adapted from [24].

and development stage of the design procedure can be further divided into three sub-stages. Those are microgrid characteristics and element modelling, system studies definition, and case study development. An overview of the stages is shown in Fig. 3.

2.1. Microgrid characteristics and element modelling

The main aim of this sub-stage is to decide on the adequate microgrid benchmark, model the components, control, and communication elements. This serves as a preparation of the system that can be used for testing of the proposed design features.

In the first step, the choice of the adequate test system benchmark is taking place. The decision is based on the benchmark's characteristics and level of suitability to test the proposed design. For example, for reliability design objective, the benchmark needs to provide adequate reliability data. Similarly, to design the microgrid with the aim of reducing fossil fuel usage, benchmark incorporating renewable energy-based units is a favourable option. A comprehensive overview of the different test systems in [28] can serve as a guide in this step. It provides information on the test systems characteristics, data availability and suitability for different types of study. As a part of the next step, the models of the microgrid elements are defined. Here, the factors such as model complexity, time-scale, necessary variables and associated control systems are important aspects in the decision-making process. As a part of this step, a modelling matrix can be a helpful tool. For each type of the microgrid model, information on a type of study, type of simulation, time-scale, relevant units and complexity of the controllers should be placed in the modelling matrix. Afterwards, the matrix is evaluated and compared with the requirements of the proposed design. In the third step, information and communication system modelling is performed. This is an important step which assures seamless data exchange within the microgrid and with the main grid [24]. A flowchart of the aforementioned processes is shown in Fig. 4.

If followed, the outlined procedure will result in a microgrid designed as a multi-dimensional layered structure. In such way, the physical elements of the microgrid and their intended operation are connected with the implemented functionalities and the communication infrastructure. The design structure is in accordance with the recommended reference architecture presented in [29].

2.2. System studies definition

The second sub-stage is used to define the system study. This includes definition of design criteria and data necessary to carry out the study. Moreover, different standards applicable to microgrid design are investigated and relevant information are applied to the study definition. At the end of this sub-stage, the system is completely defined and can be used for testing the proposed design features.

The central task of this sub-stage is adequate definition of the design criteria. They are used to evaluate whether the proposed design features fulfil the design objectives. Therefore, it is important to define them in a right manner assuring they cover all aspects of the design objective. In general, the design criteria can be categorized as environmental, reliability and economic. In Table 1, the examples of the studies covering design and planning of microgrid or some of its aspects are provided with respect to the main design objective. Furthermore, the collection of relevant, complete and up-to-date system data is the second task of this sub-stage. The data needs to cover all the microgrid aspects—benchmark system, parameters of the defined models and their parts, data necessary for carrying out the simulations indicated in the modelling matrix, etc. Finally, different standards, application guides and recommended practices need to be advised. They can, in certain cases, provide additional guidelines or impose constraints that also need to be included in the defined study. A detailed overview of the relevant standards is provided in Section 3.

2.3. Case study development

As a part of this stage, the case studies are defined and executed. They are used to investigate whether the proposed design features fulfil the design criteria, as well as to analyse different microgrid aspects. The case studies can be divided into four groups. Those are design feasibility, technical, economic, and standards and regulation applicability studies. The design feasibility studies are defined according to the design features and previously defined design criteria. Therefore, they do not necessarily need to be a separate category, but can be included into one of the remaining categories. Technical studies include communication- and power-related studies. An overview of the relevant communication studies is provided in [24], while the remaining is focused on power-related studies.

In power system planning, the studies are divided into long-term system development planning and short-term operational planning [28]. Those case studies differ from the ones related to the real-time operation. The same principle can be applied to microgrid design studies. In long-term design and planning, the target is optimal and economical microgrid development. This analysis is performed on a time-scale of years and includes the forecast of the change in the load demand and planning under uncertainty [31,48]. Accordingly, it requires the planning of the optimal time for the addition of the generation capacity

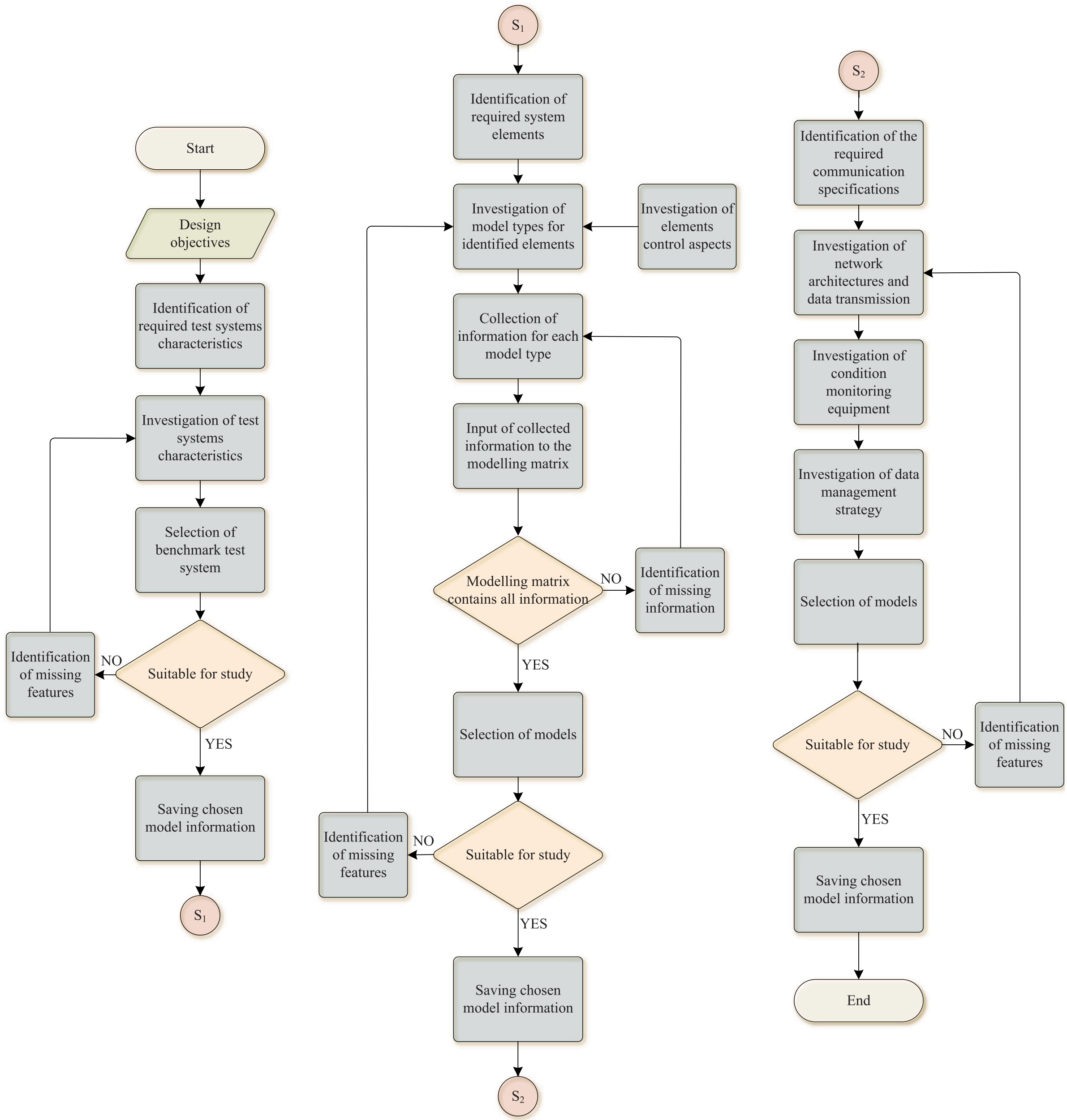

Fig. 4. Procedure for determination of microgrid characteristics and element modelling as a part of the first sub-stage of design and planning procedure defined in Fig. 3.

Table 1
Overview of microgrid design research considering three design criteria categories.

	Common design objectives	Reference No.
Environmental	Energy cost minimization Carbon neutral system deployment Fossil fuel-based units minimization	[8,30,31], [32–34], [35–37]
Reliability	Supply reliability increase to rural areas Resilience increase for system with critical loads Distribution network reliability increase	[8,34,37], [38–40], [41,42]
Economic	Expected net present cost minimization Investment cost decrease Operation cost decrease	[8,30,31], [34,36,39], [40,43,44], [45–47],

to supply the changing load demand [44]. This also includes the analysis of the optimal size and type of the units to be added, as well as it evaluates the need for the system reinforcement over time [31, 32]. Depending of the design criteria, the case studies that are often included in the long-term microgrid design are DER sizing, long-term

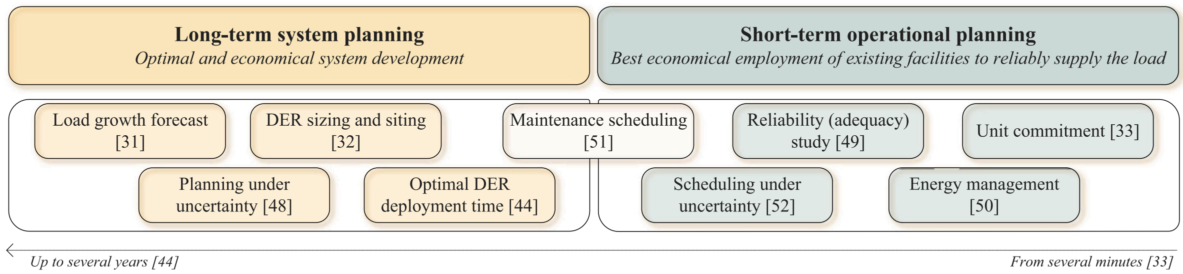

Fig. 5. Microgrid long-term and short-term planning: overview of the main planning targets and other relevant studies.

planning under usage uncertainty, service availability, etc. In short-term design and planning, the target is to achieve the best economical employment of the existing facilities to reliably supply the load in real-time operation [28]. This analysis can be performed from several minutes up to several years of time-scale. It commonly includes microgrid adequacy study [49], unit and generation commitment [33,50], reliable and maintenance scheduling [51] as well as scheduling under uncertainty [52]. An overview of the long-term and short term targets and studies is provided in Fig. 5. Complementary to the technical studies, to assure economical system development and operation, the cost-benefit and cost-reliability analysis are also often included. The last category includes policy, standards and regulatory studies, which need to be performed to assure that the proposed microgrid complies with both, global policies as well as standards and local regulations.

2.4. Implementation and validation

Once the proposed design fulfils the design criteria, microgrid implementation and validation stage is performed. Often, to reach this stage, several iterations of the previous stages are necessary until the optimum design is reached. During this stage the proposed microgrid design is tested in real-time, where hardware-in-the-loop platforms or physical systems can be employed.

3. Overview of microgrid design standards

The standards and technical brochures aim to act as norms providing requirements and guidelines on the best practices for different aspects of the microgrid design and planning. The two most relevant committees in this domain are the Institute for Electrical and Electronics Engineering (IEEE) and the International Council on Large Electric Systems (Cigre).

3.1. Standards and technical brochures applicability to microgrid design

The IEEE Standards Coordinating Committee 21 sponsors two series of the relevant standards. Those are IEEE Std 1547-2018, namely IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces and IEEE Std 2030-2011, namely IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power Systems, End-Use Applications, and Loads. The IEEE Std 1547-2018 provides guidelines and criteria for the integration and operation of DER in the power system with the aim of keeping a high level of reliability and system safety [53]. Similar can be found in the Cigre C6 Study Committee technical brochures. Additionally, C6.22 working group released a comprehensive Microgrid evolution roadmap as a part of the technical brochure 635 [54]. The IEEE Std 2030-2011 deals with the main characteristics, performance and functionalities of a smart grid, as well as provides relevant evaluation criteria. The importance of this standard lies in dealing with the topics of bidirectional power flow, communication and control aspects of smart grid. Each of the aforementioned IEEE standards and Cigre technical brochures consists of complementary documents, which in part are relevant to various aspects and stages of microgrid design. Those are summarized in Tables 2 and 3 and they are listed below.

Design- and planning-relevant standards:

1. IEEE Std 1547.3-2007 - IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems [53]
2. IEEE Std 2030.3-2016 - IEEE Standard Test Procedures for Electric Energy Storage Equipment and Systems for Electric Power Systems Applications [55]
3. IEEE Std 2030.5-2013 - IEEE Standard for Smart Energy Profile Application Protocol [56]
4. IEEE Std 2030.6-2016 - IEEE Guide for the Benefit Evaluation of Electric Power Grid Customer Demand Response [57]
5. IEEE Std 2030.7-2017 - IEEE Standard for the Specification of Microgrid Controllers [58]
6. Technical brochure 311 - Operating Dispersed Generation with ICT, Cigre WG C6.03 [59]
7. Technical brochure 450 - Grid Integration of Wind Generation, Cigre WG C6.08 [60]
8. Technical brochure 457 - Development and Operation of Active Distribution Networks, Cigre WG C6.11 [61]
9. Technical brochure 458 - Electric Energy Storage Systems, Cigre WG C6.15 [62]
10. Technical brochure 475 - Demand Side Integration, Cigre WG C6.09 [63]
11. Technical brochure 575 - Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources, Cigre WG C6.04.02 [64]
12. Technical brochure 591 - Planning and Optimization Methods for Active Distribution Systems, Cigre WG C6.19 [65]

Implementation- and Validation-relevant standards:

13. IEEE Std 2030.8-2018 - IEEE Standard for the Testing of Microgrid Controllers [66]

Following the stages of the design procedure presented in Section 2, an overview of the standards applicability to each design stage is shown in Fig. 6. Aside from the standards targeting the specific microgrid design aspects and components, the IEEE Std 2030.9-2019 provides general recommendations intended for microgrid application [6]. In the remaining part, the most important aspects of the IEEE Std 2030.9-2019 are outlined. Furthermore, its compliance with the standard design procedure presented in Section 2 is discussed.

3.2. IEEE Std 2030.9-2019

The recommended practices within the IEEE Std 2030.9-2019 [6] provide technical requirements and specifications for the microgrid design process. Their key target is to further standardize the microgrid design procedure, which has been lacking in the past. The standard defines the microgrid design and planning procedure consisting of six

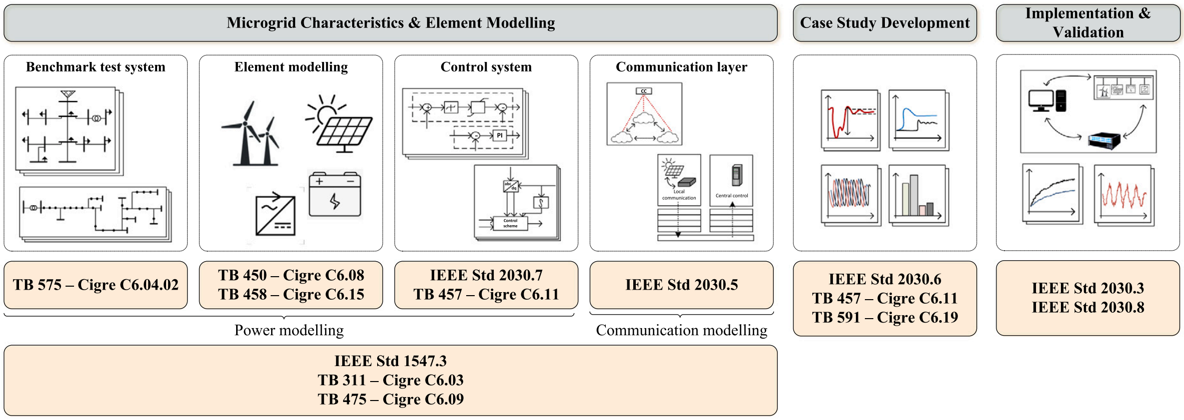

Fig. 6. Overview of IEEE Standards (Std) and Cigre technical brochures (TB) applicability to different parts of the microgrid design and planning procedure.

Table 2
Technical aspects and main scope of standards and technical brochures relevant to microgrid design and planning process.

No.	Technical aspects	Main scope
IEEE Std 1547.3	Control ICT	DER monitoring, information exchange and control. It includes information modelling and development of information exchange interface as well as selection of system protocol and main security guidelines.
IEEE Std 2030.3	Testing validation	Test procedures for energy storage system performance evaluation for meeting system requirements (e.g., reliability and safety). It includes type, production, commissioning and period tests.
IEEE Std 2030.5	ICT, power & communication	Application layer of communication system. It includes energy management functions for e.g., demand response and distributed generation coordination. It defines application messages exchanging mechanism and security features.
IEEE Std 2030.6	System studies, control power & communication	Demand response evaluation framework. It includes monitoring the performance, effects, cost, and benefits of different demand response strategies.
IEEE Std 2030.7	Control, power & communication	Testing procedures for microgrid energy management strategy. It includes functional requirements for controllers and their modularity and interoperability as well as metrics for microgrid dispatch function.
Cigre TB 311	ICT, power & communication	Monitoring and control of distributed generation by means of information and communication technology. It includes functionalities for coordination of distributed generation.
Cigre TB 450	Element modelling	Power flow and congestion management (including the influence of sizing) in the system with high integration of wind power generation.
Cigre TB 457	Control	Recommendations for design of active distribution networks. It includes the list of regulatory barriers for integration of DER as well as the recommendations for system planning with DER.
Cigre TB 458	Element modelling	Sizing methodology for energy storage supporting transition to carbon-neutral systems. It indicates the specific parameters and technical, economic, and reliability requirements.
Cigre TB 475	Power & communication	Demand side integration overview. It includes overview of the existing barriers and standards as well as the role of ICT and impact of demand side integration on planning procedure.
Cigre TB 575	Benchmark ICT	Test system for analysis and validation purposes. Benchmark includes DER integration and enables examining their integration issues.
Cigre TB 591	System studies	Methodology for long-term and short-term planning of active distribution networks. It includes the methods for reliability assessment and demand side integration.
IEEE Std 2030.8	Element modelling	Function test for microgrid controllers. It aims to help in verification and performance assessment of microgrid components as well as testing functional requirements.

main stages. This includes the recommended practices for the system configuration, electrical design, safety, power quality monitoring and control, electric energy measurement and scheme evaluation, as shown in Fig. 7.

In the first stage, the microgrid planning objectives need to be defined. Those need to reflect the benefits and the application-oriented solutions the microgrid aims to provide. The standard categorizes the planning objective into 3 main groups, namely economic, reliability and environmental. Further on, it recommends the design evaluation index for each category and provides typical application scenarios. In the second stage, the system configuration is defined. In the third stage, the electrical system design is taking place. This, among others, includes definition of the system voltage, selection of point of common coupling for grid-connected microgrids, design of the grid structure and safety assessment. In the fourth stage, the automation system is designed. This includes the protection and communication design, control and energy management, where the requirements and detailed guidelines for each process are provided. In the fifth and sixth stages, different microgrid schemes are proposed, compared and evaluated with respect to the design objective. Detailed technical and economical evaluation parameters are provided. From the technical perspective, power supply reliability, grid loss and power quality evaluation indices are recommended. From the economic perspective, those are the life-cycle cost, payback time and net present value. The environmental indices include energy emission reduction, gaseous pollutants emissions, fossil fuel consumption and renewable energy generation proportion. The scheme with the highest score of the indicators obtained through the evaluation procedure is then selected as the best design solution.

The recommended practices outlined in the IEEE Std 2030.9-2019 comply with the standard design procedure presented in Section 2 and based on [24]. The standard design procedure provides a more complete guideline on the microgrid design and it can be seen as

Table 3
Characteristics of standards and technical brochures relevant to microgrid design and planning.

Standard no.	Target elements	Application	Impact level
IEEE Std 1547.3	DER technologies, e.g., photovoltaics, wind turbines, and energy storage	Electric power system with application to microgrid	Guidelines
IEEE Std 2030.3	Energy storage	Electric power system with application to microgrid	Standard
IEEE Std 2030.5	Communication layer	Electric power system with application to microgrid	Standard
IEEE Std 2030.6	System	Electric power system with application to microgrid	Guidelines
IEEE Std 2030.7	System	Microgrid	Standard
Cigre TB 311	Communication layer	Distribution system with application to microgrid	Technical brochure
Cigre TB 450	Wind power generation unit	Electric power system with application to microgrid	Technical brochure
Cigre TB 457	System	Distribution system with application to microgrid	Technical brochure
Cigre TB 458	Storage technologies including e.g., batteries and compressed air storage systems	Electric power system with application to microgrid	Technical brochure
Cigre TB 475	System	Electric power system with application to microgrid	Technical brochure
Cigre TB 575	DER units	Electric power system with application to microgrid	Technical brochure
Cigre TB 591	System	Distribution system with application to microgrid	Technical brochure
IEEE Std 2030.8	System	Microgrid	Standard

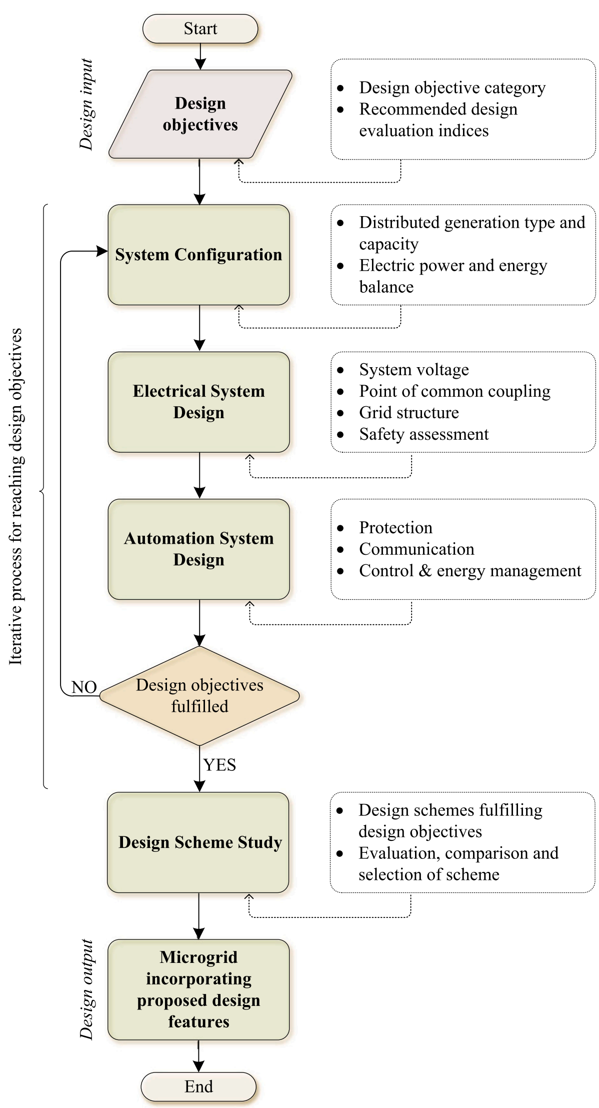

Fig. 7. Microgrid design and planning procedure, as outlined in the IEEE Std 2030.9-2019 - IEEE Recommended Practice for the Planning and Design of the Microgrid [6].

complementary to the recommended practices in [6]. The standard acts as a microgrid design foundation providing the pivotal requirements in the design including the main objectives and their appropriate evaluation indices. It is, therefore, recommended to follow the design guidelines outlined in the IEEE Std 2030.9-2019 as a base to which complementary design procedures can be added.

4. Reliability aspects in microgrid design

4.1. Reliability evaluation procedure

During the design and planning stage, it is necessary to fulfil the main design objectives while assuring the adequate level of reliability and economic profitability, as elaborated in Section 2. To evaluate the reliability of the proposed design, reliability concepts for power system application can serve as a basis to which the microgrid-specific aspects can be added. To estimate the significance and the severity of the events leading to the system interruptions, a quantitative reliability analysis is necessary. For a reparable system, such as microgrid, the frequency and the duration of the interruptions need to be assessed. According to IEEE Std 2030.9-2019, a part of the distribution system reliability indices elaborated in [67] can be used. These indices are divided into load-point and system indices. Both are the indicators of service continuity level, where load-point indices refer to an individual load and system indices to the groups of loads. Therefore, load-point indices can be seen as fundamental indices, where their weighted average represents the system indices [67].

The load-point indices are the average failure rate λ_s, average annual outage time (unavailability) U_s and average outage time per failure r_s. The average failure rate λ_s represents the estimate of the interruption rates and is usually given as the number of interruptions per year. The average annual outage time U_s represents the estimate of the overall downtime (in hours) during one year. Average outage time per failure r_s represents the average duration of the interruption and it is usually measured in hours per each interruption. The mathematical expressions for the three load-point indices are as follows [67]:

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \tag{1}$$

$$U_s = \sum_{i=1}^{n} \lambda_i \cdot r_i \tag{2}$$

$$r_s = \frac{U_s}{\lambda_s} = \frac{\sum_{i=1}^{n} \lambda_i \cdot r_i}{\sum_{i=1}^{n} \lambda_i} \tag{3}$$

where λ_i, r_i and U_i are the average failure rate, annual outage time (unavailability) and average outage time per failure of the components connected to the ith load point, respectively and n is the number of load points in the microgrid.

To reflect the severity and significance of the distribution system outage, system indices are used. The first one is the System Average Interruption Frequency Index $SAIFI$, and it is defined as a ratio of the total number of customers interrupted and total number of customers served [67]:

$$SAIFI = \frac{\sum \lambda_i \cdot N_i}{N_T} \tag{4}$$

where N_i is the number of interrupted customers for ith interruption, n is the number of interruptions and N_T is the number of all customers served.

The second index is the Average Service Availability Index $ASAI$, and it is defined as the ratio of the actual served hours and total demanded service hours during one year [67]:

$$ASAI = \frac{N - \sum P \cdot (C_i \cdot L_i)}{N} \tag{5}$$

where C_i and L_i represent the available generation capacity and maximum load of the ith day respectively and N represents the number of days.

The third index is System Average Interruption Duration Index $SAIDI$, and it is defined as the ratio of the sum of customer interruption durations and total number of customers served [67]:

$$SAIDI = \frac{\sum r_i \cdot N_i}{N_T} \tag{6}$$

where r_i is the restoration time for ith interruption.

The additional microgrid-related index is defined as follows [6]:

$$MAIDI = \frac{\sum U_i \cdot N_i}{\sum N_i} \tag{7}$$

where U_i and N_i are the equivalent of average interruption time and the number of customers at ith load point.

The main difference between $SAIDI$ and $MAIDI$ indices is that the former represents the average duration of the all interruptions while latter represents the duration of a single average interruption. Finally, the last reliability index covered in [6] is Loss of Load Probability $LOLP$. This index differs from others by being related to the generation capacity instead of customer. It is used to evaluate the probability that the generation capacity is exceeded by the load demand:

$$LOLP = \frac{\sum P \cdot (C_i \cdot L_i)}{N} \tag{8}$$

Complementary to the $LOLP$ index, the loss of load expectation $LOLE$ is a more common generation capacity-related index. It represents the expected accumulated time in a year for which the generation capacity shortage occurs [67].

To assess the system reliability by means of the aforementioned reliability indices, analytical and simulation methods are available. Both can be used to evaluate the mean values and probability distribution of the reliability indices. The analytical methods include the definition of the system through the series of the mathematical expressions and models, such as Markov model [68–70]. The simulation methods simulate the actual processes and random behaviour of the system. Commonly, this includes the statistical distribution and methods like Monte Carlo simulations [52,71–75].

4.2. State-of-the-art review of microgrid design and planning aspects

Reliability as a design objective is investigated with regards to the long-term and short-term planning goals. A state-of-art overview is presented as shown in Fig. 8.

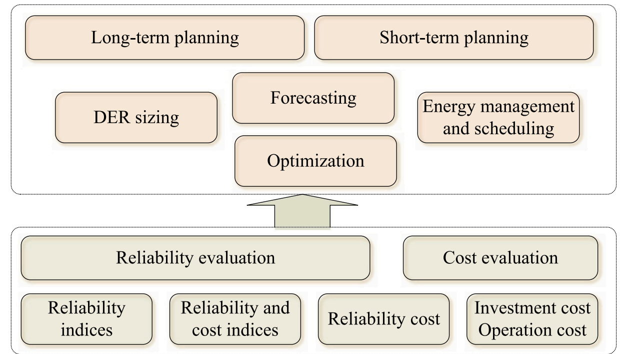

Fig. 8. Topics covered within the state-of-art overview for microgrid design and planning.

4.2.1. Distributed energy resources sizing

In the long-term planning, a dominant topic is the DER sizing as a method to assure adequate level of reliability [32,34,69,76–79]. This is particularly important for low-inertia microgrids, where a probability of system outage due to the lack of generation capacity is high. The main goal of DER sizing is to find the optimal technology type, size, location and deployment time of the DER. This is done to assure enough generation capacity from the flexible, small-scale units to reliably cover the growing electricity demand over years. One of the characteristics of this approach is that disadvantages of one technology type can be covered by the advantages of other. For example, energy storage system can be used to increase the reliability of the system with a large penetration of intermittent renewable energy-based generation [76].

The DER sizing problem is often set as a multi-objective optimization problem, where, aside from reliability, cost, environmental impact, optimal siting for increased efficiency, and reduced losses are complementary objectives. The procedure is performed on a time-scale of years. One approach to DER sizing considers a typical year with hourly resolution that includes characteristic changes in the environmental conditions and the load demand patterns. Often, such simulation setting is a trade off between the accuracy and the computational burden. In case of more complex control and optimization techniques, such as [79], typical days are used. However, both approaches have a downside of not including the effect of uncertainty and dynamic changes in the performance of the components over multi-year time scale. Those are addressed in [44], where the DER sizing methodology including a larger time span (e.g., several years with hourly resolution), is proposed. However, the computational requirements of such analysis is still one of the main obstacles in its larger deployment.

Therefore, DER sizing can promote increased integration of renewable energy-based units, optimal economical deployment, and reduced reliability-related costs. However, certain challenges related to this method exist. Optimal DER sizing extensively relies on the forecasting of load demand, where the forecast uncertainty is often not addressed. This is discussed in [34,78], where the need to include the prediction of load growth, the changes of environmental conditions (e.g., solar irradiance and wind speed) and component lifetime prediction are discussed. The importance of the later is the topic of [79], where performance degradation of DER over time is included in the DER sizing. From the previous research [80], it was shown that neglecting the performance-degradation can have a significant negative impact on overall system performance and economic feasibility. Furthermore, prediction of technology development in the future, projection of technology costs, changes in regulatory and governmental policies, and societal impact on the load demand growth are other often not included aspects in DER sizing principles.

Table 4
Overview of long-term and short-term microgrid design research aspects.

Study type	Time horizon	Method	Ref. No.
DER sizing	Typical days One year Several years	Linear programming Convex optimization Genetic algorithms Particle swarm optimization	[32,34,69], [76–78], [79]
Forecasting	Application dependent Hours and days for short-term planning Years for long-term planning	Neural Networks Auto-regressive Moving average models	[31,50]
Energy management & scheduling	Ranging from minutes, hours, days and week	Linear programming Stochastic programming Genetic algorithms Differential evolution algorithms Particle swarm optimization	[30,31,33], [34,40,43], [50] [52,78], [79,81]

4.2.2. Energy management & scheduling

Energy management and scheduling are dominantly researched topics within short-term planning [30,31,33,40,43,50,52,81]. One of the main advantages of this approach is the presence of different DER units. Relying on multiple sources (with different technology characteristics and response time) can be more advantageous than relying on several large-scale single type units (as more common in conventional systems). However, such diverse and complex DER structure can lead to certain operation challenges. Additionally, loads in small systems are often less predictable than in conventional systems [30]. Therefore, it is important to develop the adequate energy management and scheduling schemes to reliably supply the load.

The main goal is to define methods for power allocation from multiple DERs in a manner, which will assure a high level of reliability under grid-connected and islanded mode of operation. To do so, the problem is usually set as an optimization problem with operational constraints of DER units and their electricity and heat balance requirements. Additionally, minimized cost and environmental impact reduction can be added [30,33]. The time-scale includes days with resolution ranging from 15 min up to an hour. Similarly to DER sizing, uncertainty in load demand and environmental conditions can have an impact on the results accuracy. Hence, it is necessary to include it in the scheduling problem. In [31], the concept of corrective scheduling is proposed, where the scheduling is adjusted at times when new information about load demand or environmental conditions are available. The proposed solution can help in reducing the error introduced by uncertainty. Another factor that impacts the energy management and scheduling is the DER size. If the DER units are not sized in a right way, assuring adequate generation capacity for both modes of operation, optimal reliable scheduling cannot be achieved. Hence, the two tasks (DER sizing and scheduling) are in certain cases studied together [34,78,79] (see Table 4).

4.2.3. Forecasting

As discussed, uncertainty of forecast data, i.e., load demand and environmental conditions, is one of the main factors influencing the accuracy of DER sizing and optimal scheduling. If forecast data deviates significantly from the actual conditions, the results of the applied methods can pertain from the optimal ones. Such is even more important in microgrids with a large integration rate of renewable energy-based units. Therefore, forecasting is an important aspect in reliability-oriented planning of microgrid systems.

The forecasting models consist of three main steps; data processing, model training and forecasting. The models can further be divided into three categories including physical models, machine learning and deep learning models. Each model type has characteristics, which make them more suitable for long-term or short-term forecasting. A comprehensive overview including advantages and disadvantages of different models and their applicability for microgrid design is provided in [82].

One of the main challenges of forecasting models is related to acquisition of data. The representative data is not always available publicly or sufficiently large. Furthermore, certain models assuring higher level of accuracy can require extensive resources and impose large computational burden. Certain machine learning methods require previous expertise and skills in model development. Finally, majority of models with higher accuracy cannot be used for both long-term and short-term planning. This is mainly due to different requirements as well as size and characteristics of historical data necessary for long-term and short-term planning [82]. In such case, it is necessary to develop two separate forecasting models.

4.2.4. Optimization techniques

Different optimization techniques are employed for efficient and accurate microgrid planning. They are chosen depending on the type and the complexity of the problem. Similarly to the forecasting methods, complexity and accuracy influence the selection of method. An overview of the optimization methods is provided in Table Table 4 based on the type of the study and the time horizon characteristics.

In [92], a unified framework for optimal microgrid design including the reliability and contingency assessment is presented. The framework incorporates the mixed integer linear programming and particle swarm optimization techniques. In [93], the optimal design of a microgrid topology based on graph partitioning is presented. Mixed integer linear model is incorporated in [94,95] for long-term microgrid development planning and short-term operational planning, respectively. Mixed-integer quadratically constrained quadratic programming model is developed in [96] for microgrid capacity planning purpose. The author in [97] presented the planning procedure for provisional microgrids with the emphasis on the robust optimization method accounting for physical and economic characteristics. The optimization procedure is employed to minimize the total planning cost subjected to the operational constraints.

4.2.5. Reliability & cost evaluation indices

To assess the reliability of the proposed design features, the reliability indices presented in Section 4.1 are commonly used [49,74,75,83–85]. Regardless of the proposed method or type of the study, the indices are used to assess and compare the proposed design features. As indicated in Fig. 8, the reliability evaluation can be done purely by means of reliability indices presented in Section 4.1, a combination of reliability and economic indices, or by incorporating reliability into the cost analysis, e.g., cost of reliability.

Examples of studies which only used reliability indices for assessment are [49,83–85]. To assure a desired level of reliability at lowest cost, economic indices are complementary used in [7,48,76,86–91,98]. When the reliability analysis is done within the cost assessment, the reliability indices are not determined separately. In such case, the reliability is defined through the relevant reliability cost index. Those are included in [86], where the main target is the optimal DER size

Table 5
Overview of microgrid design research aspects considering reliability and cost-related analysis.

Ref.	Research output	Reliability indices	Cost indices
[2]	Reliability and economic indices considering microgrid characteristics	Islanded mode operation-related, distributed generation-related, etc.	Purchase and selling probability, unit cost reliability benefit, etc.
[7]	Design of a microgrid system with a large share of renewable energy for a reliable supply of the rural areas	–	Net present cost, net annual cost, levelized cost of energy
[48]	Model for the microgrid planning with uncertainty of the load forecast, market prices and variable renewable generation	–	Investment cost, operation cost, cost of unserved energy
[49]	A multi-state probability model for adequacy assessment of an autonomous microgrid, used for assessing the uncertainty of the renewable energy resources	U_s defined in (2), $LOLE$ complementary to $LOLP$ defined in (8)	–
[76]	Reliability-oriented optimal sizing of energy storage in microgrid	$LOLE$ complementary to $LOLP$ defined in (8)	Investment cost, microgrid expected operation cost
[83]	An evaluation method for microgrid reliability considering energy storage and real-time price	$SAIFI$, $SAIDI$ defined in (4) and (6) respectively	–
[84]	Reliability assessment with included demand response strategy. Model defines satisfaction index considering the degree to which the demand is covered with renewable energy	$SAIFI$, $SAIDI$, $ASAI$ defined in (4)-(6)	–
[85]	Reliability-oriented systematic design approach for microgrid cluster considering	$SAIFI$, $SAIDI$, $MAIDI$ defined in (4), (6) and (7)	–
[86]	A microgrid planning model for determination of the microgrid type and the optimal size of DER	–	Investment cost, operation cost, cost of the purchase energy, reliability cost
[87]	System planning under uncertainty using unascertained number method	Probability of overload	Investment cost, cost-benefit index
[88]	Method for reliable design of a hybrid wind–solar generation microgrid with hydrogen energy storage considering reliability and cost-effectivity	$LOLE$ complementary to $LOLP$ defined in (8), expected energy not served, loss of power supply probability	Cost of loss of load, investment cost, replacement cost, operation and maintenance cost
[89]	Microgrid planning method for determination of the optimal interconnection of micro-sources and the load	Loss of load, expected power not served, energy index of reliability	Cost of node interconnection
[90]	Method for microgrid planning with dynamic boundaries—reconfiguration strategy for cost reduction	–	Microgrid expansion investment cost, cost of grid-connected operation, energy loss cost
[91]	Microgrid-based co-optimization consisting of planning problem and annual reliability sub-problem aiming to minimize the system planning cost	Expected energy not served.	Investment cost, operation cost, cost of unserved energy (reliability-related), total planning cost

for design of cost-effective microgrid system. Similar approach is taken in [48], where microgrid planning procedure under uncertainty is proposed. In both cases, the cost of reliability is defined as the cost of the unserved energy representing the compensation cost of the unserved customers.

An overview of the aforementioned microgrid design research is provided in Table 5, where the main reliability and cost-related indices are given. In certain cases, a broader planning approach is carried out, as in e.g., [2,99–102]. There, aside from the reliability and cost indices, other factors such as sustainability goals and the utility and customer involvement are included in the design procedure.

5. Reliability-related design requirements for future power electronics-based microgrids

5.1. Power electronics reliability in power system analysis

During the quantitative power system reliability analysis presented in Section 4, power electronics reliability is included through the failure rate λ of the installed converter units. During operation, failure rate of each unit can be divided into two main categories, i.e., useful life and wear-out phase. During useful life, the unit experiences random chance failures with a constant failure rate. In the subsequent stage, the failure rate is no longer constant and it raises significantly due to the unit wear-out [103] as shown in Fig. 9. Thus, the mathematical expression for a failure rate of a single converter is defined as:

$$\lambda_{PE} = \lambda_c + \lambda_w \tag{9}$$

where λ_c is the constant failure rate during the useful life and λ_w is the wear-out failure rate due to component ageing.

To accurately estimate converter reliability, both failure rates should be considered and accurately estimated for the designed system and expected operating conditions [104]. This is especially important, as the unit wear-out can occur faster due to uncertainties. However, in the majority of the research related to the power system reliability analysis, the impact of non-constant failure rate due to power electronics ageing is neglected [105–107]. Further more, a constant failure rate is usually estimated based on availability and accuracy of the present information. The least accurate source is expert judgement about failure of the newly designed unit, which needs to be used when no other relevant sources are available. The least available, but more accurate way includes data from previous field experience (user-provide data), while in certain cases, it can be provided from a supplier [108]. However, the most common approach includes the estimation of failure rate based on the reliability handbooks. Those provide failure rate information based on relevant statistics and field data. A summary of commonly used handbooks is provided in Table 6, while a more detailed review can be found in [109,110]. The main disadvantage of such approach is that the failure rate of the system under study/design is decided based on the historical data. Those data can often be outdated or available for obsolete technology. Moreover, the handbooks provide empirical models with the limited explanation of the failure mechanisms and narrow the operating conditions under which the failures occur.

The methodology presented in [115], namely FIDES, is a more accurate approach for failure rate prediction tackling some of the aforementioned drawbacks. The main principle of the methodology is to predict reliability of a component based on its sensitivity to physical

Table 6
Overview of relevant reliability prediction handbooks for power electronics components.

Handbook	Characteristics	Availability
MIL-HDBK-217	Base failure rates based on field experience. Modification factors available to account for conditions such as environmental, operating, manufacturing etc.	Available as a handbook [111], and as a part of the commercial softwares
PRISM	Similar approach to reliability prediction as in MIL-HDBK-217 with addition of more comprehensive field and test data.	Available as open-source software [112]
HRD5	Simple models with minimized data requirement. Includes technology development over time in reliability prediction.	Available as a part of the commercial softwares
IEC-62380-TR	Complex stress models classifying different stress phases translated to reliability predictions. Requires larger set of input information.	Available [113]
IEC-61709	Guidance for using failure rate in reliability prediction and construction of failure database for components.	Available [114]
Siemens SN29500	Provides failure rates based on the specified conditions for different applications and testing.	Restricted
Telecordia SR-322	Instructions for suppliers on how to define the reliability of their products.	Available as a part of the commercial softwares

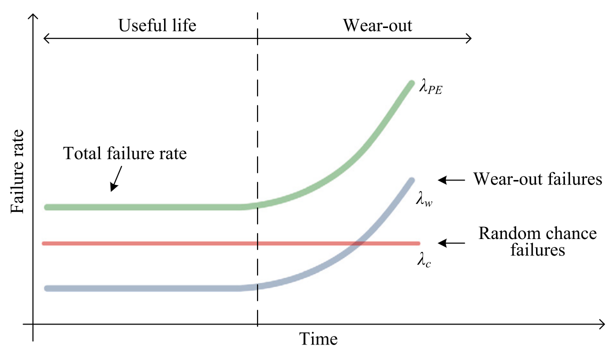

Fig. 9. Typical failure rate curve of power electronics units λ_{PE}. It considers useful life with dominated constant failure rate λ_c and wear-out phase with non-constant failure rate λ_w.

stress. This is done by disintegrating the input mission profiles into different phases, as shown in Fig. 10(a). Each phase has characteristic values of relevant stress parameters. The failure rate is obtained by mapping different phases into the physical failure rates, while factoring in the physical constraints during the expected operation. The output of the process is a constant failure rate of the converter for the input mission profile. The obtained failure rate is used to evaluate the power system reliability indices, e.g., (1)–(8) defined in Section 4.

The FIDES approach is sufficient for planning of systems with a low installation rate of power electronics. There, the inaccuracy introduced by excluding the wear-out failure rate is not significant enough to impact the overall system-level reliability. However, it is expected that it will have a more adverse impact for future microgrid systems, where the installation rate of the power electronics-interfaced units will be significant. This is supported by field experience data, reporting power electronics failure due to wear-out as one of the main causes of a system downtime [116]. For example, field data from more than 1000 wind turbine systems in United Kingdom indicate that power electronics failure was one of the top five common causes of failures during 2016 [117]. Similar experience is reported in [118], where the analysis of data from the Chinese wind power industry is carried out. In case of photovoltaic power systems, power electronics failure accounts for approximately 60% of the total system failures, with wear-out being one of the dominant reasons [119]. This is aligned with the investigation carried out in [120] including the industrial maintenance reports from 2016–2018.

Therefore, the question of applicability of the current reliability procedures for design of the future systems is raised. Such is addressed in Cigre working group C1.27 technical report [121], as well as in some recent publications [122,123]. A more accurate approach would be to include wear-out failure rate of power converters in the reliability analysis. A given failure rate should be estimated based on the actual causes of failure and it should include the impact of different materials and also the environment [104]. Such can be done by shifting from empirical, handbook-based analysis to the Physics-of-Failure (PoF)-based deterministic modelling. PoF approach is based on the investigation of the failure mechanisms and their root-causes. It can be used to address and improve the main design weaknesses [124]. Its application is found in the design for reliability within power electronics engineering [125–127].

5.2. Wear-out modelling approach in power electronics design for reliability

A procedure for wear-out modelling including PoF-based reliability prediction approach and stress–strength analysis is outlined in Fig. 10(b). The main aim of the physics-of-failure approach in design for reliability of power converters is to evaluate the damage caused by the stress and predict when the dominant degradation mechanisms will be triggered, i.e., when the failure of the devices will occur. Therefore, the first step includes determination of the critical components and their dominant failure mechanisms. For converters, power semiconductors and electrolytic capacitors are identified as the reliability-critical components [126]. In [125], the analysis of the different stress categories and their impact on the reliability-critical components is presented. It concludes that the electro-thermal stress is the main life-limiting factor for both. The applied stress is causing the degradation of materials and parameter drift within the components. Consequently, this will lead to triggering the dominant temperature-related degradation mechanisms. For semiconductors, the most common failure mechanisms are cracking of chip solder joint and baseplate solder joints as well as bond wire lift-off. For electrolytic capacitors, those include electrolyte vaporization and electro-chemical reaction [128].

A mission profile (representing operating conditions) needs to be translated into the stress profile of the critical components in the second step. Such is done by means of electro-thermal modelling. A detailed procedure in the case of photovoltaic and wind power applications can be found in [129–135], respectively. The output of the electro-thermal modelling is a thermal stress profile. To evaluate the impact of each stress level within the thermal profile, it is necessary to decompose it. This is often done by employing the cycle counting algorithms, such as Rainflow [136]. The decomposed stress profile is used in the next step, i.e., lifetime consumption estimation. There, the stress of the component needs to be compared with its strength. To model the strength of each component, degradation/lifetime models are used [108]. For semiconductors and capacitors, a number of lifetime models differing in level of accuracy and design specification requirements are available. The overview of the relevant models is provided in [137,138]. The output of this step is information about the amount of semiconductor and capacitor lifetime consumed for input mission profile. To include uncertainties related to e.g., manufacturing, mission profile, lifetime

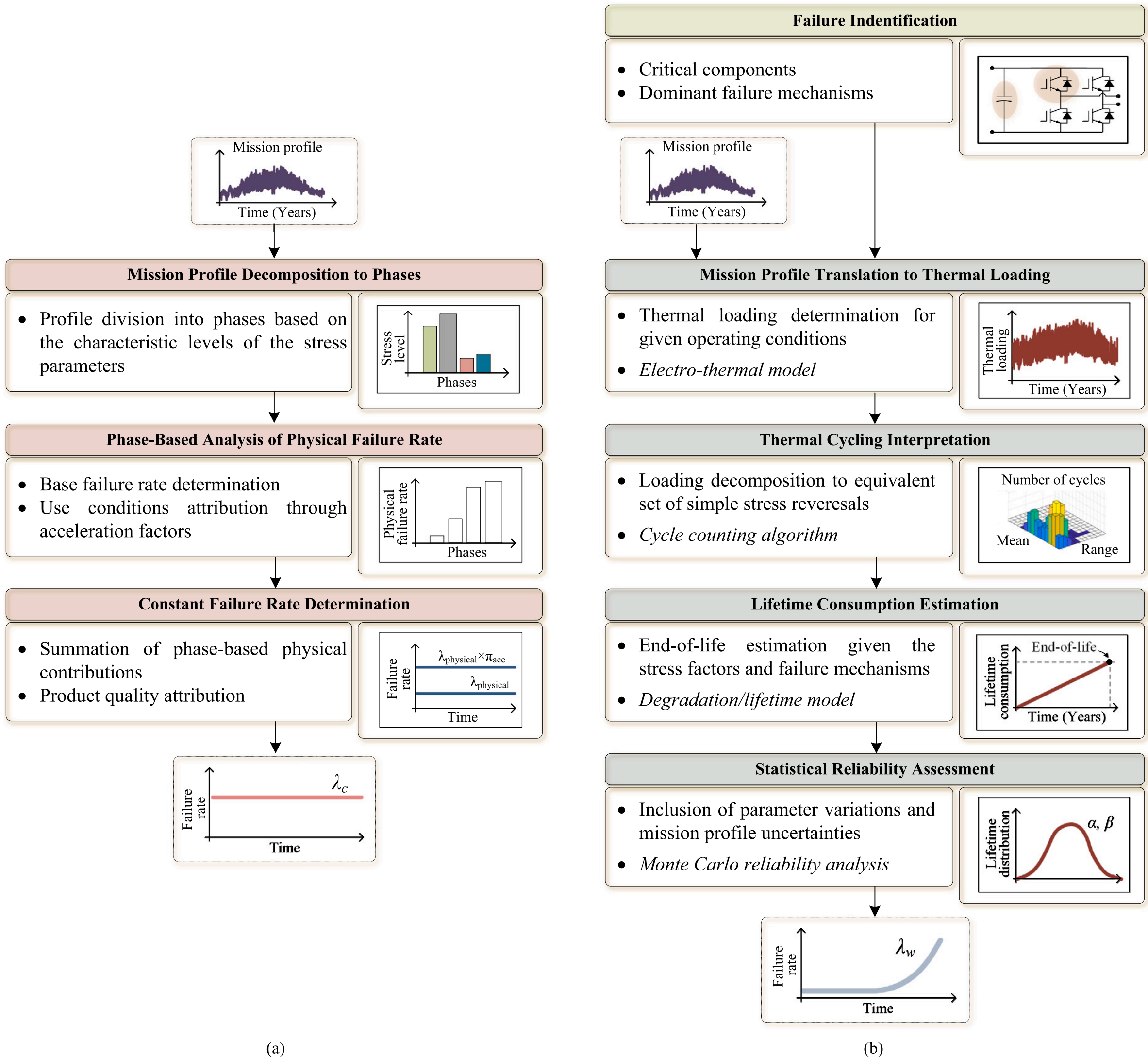

Fig. 10. Failure rate estimation for power electronics based on: (a) FIDES approach employed in power system reliability analysis, and (b) Wear-out modelling based on stress–strength analysis employed in design for reliability in power electronics application.

model parameters, a probabilistic assessment including Monte Carlo simulation is employed [139]. As a result of the PoF, a wear-out failure rate of the critical components is obtained for given design specifications and operating conditions.

5.3. Bridging power electronics and power system design for reliability

Design accuracy can be diminished for microgrids with larger share of power electronics if traditional power system reliability-oriented design methods are applied. In such case, the failure of power electronics is not predicted in long-term planning, resulting in insufficient generation capacity and unpredictable outages in the microgrid. This will result in unplanned power electronics replacement and higher microgrid cost in practice than previously assumed during the design. In short-term planning, excluding power electronics reliability considerations when deciding on the optimal scheduling can lead to extensive stress on the power electronics. This will result in accelerated damage accumulation, which will over time shorten the component lifetime. Such can further diminish the reliability and cost improvements achieved within other aspects in the design.

Therefore, a need for incorporating the power electronics reliability concepts based on PoF approach into power system reliability assessment is expressed. Such can be the basis for further development of the design guidelines suitable for reliability-oriented design of future, power-electronics dominated microgrid systems. However, the research on joint power electronics and power system reliability concepts is limited. This topic has been recently introduced in [122,147]. There, a comprehensive reliability evaluation procedure is presented for a modern power system with its application to microgrid planning. The procedure is outlined in Fig. 11, and it consists of a three-layered structure investigating the reliability from the device level up to the microgrid system level. The first layer evaluates the reliability of the failure-prone power converter components (e.g., semiconductors and electrolytic capacitors). PoF approach employed in design for reliability (see Fig. 10(b)) is preferred assessment method in this layer. It can assure that the reliability prediction of the component is based on actual expected operating and environmental conditions of the microgrid under design. The second layer, namely subsystem layer, is used to define the reliability of the converters based on the available information about the failure rate of the individual components (determined in the first layer). The output of this layer is availability of the each individual converter in the system. To determine the availability, the information about the converter failure rate due random chance failures and wear-out is used. This information is then used in the last layer, i.e., power system layer. There, a standard reliability procedure, as elaborated in Section 4, is employed.

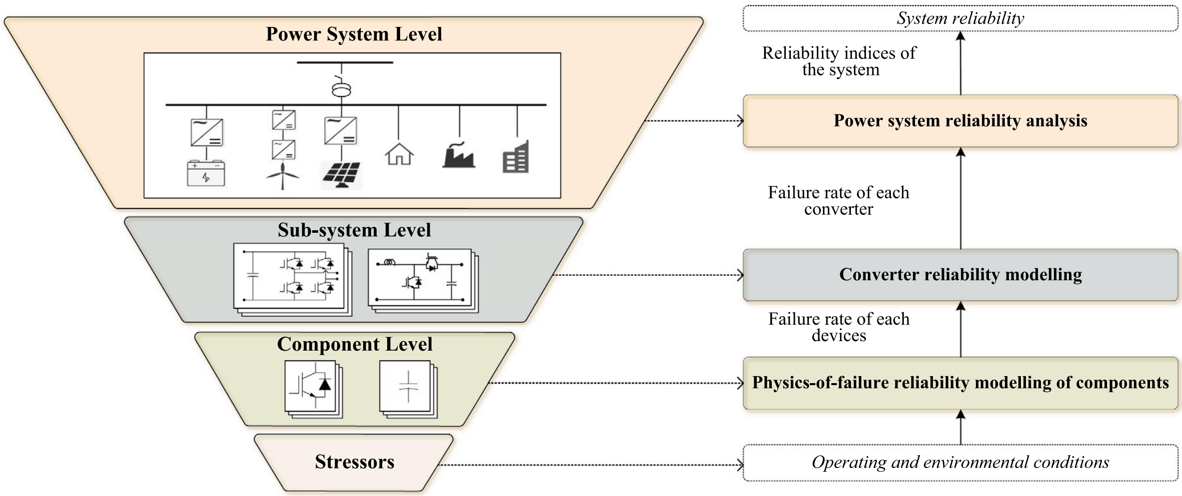

Fig. 11. Framework for reliability assessment of power-electronics dominated system.
Source: Adapted from [122].

Table 7
Overview of research aspects incorporating power electronics and power system reliability concepts.

Ref. No.	Research output	Application	Investigated impact	Power electronics reliability	Power system reliability
[123,140]	Procedure for reliability assessment of power electronics-dominated system	Power electronics-based power system with application to microgrid	Topology, control and switching of converters on power electronics and power system reliability, Maintenance scheduling on power system reliability	✓	✓
[141]	Control strategy for improving performance, power density and reliability of converters	Microgrids	Switching strategy of converters on power electronics reliability	✓	X
[142]	Control strategy for DC converters aiming in reduction of thermal stress and increasing overall system reliability	DC power system with application to microgrids	Converter control on power electronics reliability	✓	X
[143]	Active and reactive power sharing control strategy aiming to increase the overall system reliability	Microgrids	Converter control on power electronics reliability	✓	X
[144]	Energy management strategies impact on system reliability	Microgrids	Energy management strategies of the system to power electronics reliability	✓	X
[145]	Converter non-exponential failure rate impact on availability and power system reliability	Microgrids	Converter wear-out failure on power system reliability	X	✓
[146]	Reliability procedure for multi-converter system	DC microgrids with the extension to any power electronics-based system	Environmental and operating conditions, system architecture, switching schemes on power electronics reliability	✓	X
[147]	Model-based maintenance planning	Power electronics-based power system with application to microgrids	Maintenance scheduling and power electronics reliability on power system reliability	✓	✓
[148]	Framework for reliability assessment accounting for converter uncertainties	Power electronics-based power system with application to microgrids	Environmental and operating conditions and uncertainties of power converters on power system reliability	✓	✓

In [122], the proposed reliability procedure is used to illustrate the impact of the converter non-constant failure rate (due to wear-out) on the power system reliability. Two cases are analysed, the first one with a low power electronics installation rate, and the second one where the system is fully power electronics-based. The results have shown that in the first case the power system reliability due to the converter ageing is negligibly impacted. However, as the installation rate of power electronics prevails (the second case), the wear-out failure due to ageing effect on the system reliability becomes significant. The proposed reliability procedure can be employed to characterize the power electronics impact on the optimal design with respect to the long-term and short-term planning goals. Moreover, relevant research, as outlined in Table 7, can serve as the supplementary guidelines during design. In [141–144,146], different aspects of power electronics reliability are investigated. They include the evaluation of the first two layers of the comprehensive reliability procedure. For the power electronics-based systems, the wear-out of the reliability critical components is evaluated considering the system configuration, environmental, operating condition, control strategies, etc. A more detailed analysis, using the comprehensive reliability procedure is presented in [123,140,147,148].

Those include investigation of the topology, control and switching of power converters as well as different uncertainties on their reliability as well as the whole power system reliability.

5.4. Future design requirements

The outcomes of the given analyses can, therefore, be used in the development of the new guidelines for microgrid design. To do so, it is necessary to extend the aforementioned analysis to provide complete and extensive information on the power electronics interactions and reliability impacts on the microgrid system. This includes investigation of different stressors on power converter reliability, as well as the analysis of the interactions among the converters in the microgrid system. Furthermore, it is necessary to broaden the investigation of the mission profile, architecture, converter control and energy management strategies on the system-level reliability. Such needs to be done over a broad timescale including seconds and minutes (short-term planning) as well as years (long-term planning). The results of alike studies can further be used to investigate the impact of power converter reliability on common procedures within the long-term and short-term planning (as discussed in Section 4).

In case of long-term planning tasks, it is necessary to develop new methods for reliability-oriented DER sizing. Those should include power electronics reliability procedure based on wear-out modelling and its connection with other parts of the sizing procedure. Similar is required in the case of short-term planning, where the methods for reliable DER scheduling need to be revised. Their interaction with the power electronics loading and stress levels need to be included in the analysis. In addition, applicability of standard forecast and optimization methods needs to be re-evaluated. The new guidelines should include procedures and timescales enabling the investigation of the main power electronics reliability characteristics. Finally, extensive analysis and the proposed methods need to be properly incorporated into the standard microgrid design and planning procedure (as outlined in Sections 2 and 3). In such way, new reliability-oriented design guidelines for future microgrid systems can be defined. They will assure the multi-converter microgrid design and planning for reliable and safe operation. Such research is important to enable further development of the system, harvest the full reliability potential of microgrids and meet the climate requirements as well as minimize cost.

6. Discussion & conclusion

In this paper, an overview of the microgrid design and planning procedure is provided. Furthermore, the main standards and recommended practices relevant to the design of a microgrid or its parts are listed. An overview of the state-of-art research related to the reliability-oriented microgrid design is further included. This is followed by the discussion on the impact of power electronics reliability on current design practice. The conclusions that can be drawn based on the presented work are as follows:

- Microgrid design procedure is still undergoing a standardization process. Hence, there is no a single compulsory design process being followed. However, certain standards and technical brochures (such as IEEE and Cigre) can be employed to different aspects of the design process, e.g., benchmark, element modelling, control and communication systems design and validation instructions.
- According to IEEE standards, the microgrid design objectives are categorized as environmental, economic and reliability-related, each provided with a certain set of design criteria. In case of reliability-oriented design, standard distribution system reliability indices are proposed as adequate design criteria. State-of-art research on reliability-oriented microgrid design extensively complies with the recommended criteria.
- The state-of-art overview reveals that common design for reliability improvements can be categorized with respect to long-term and short-term planning objectives. They often include novel methods for DER sizing, energy management and scheduling, forecasting and optimization.
- During the reliability evaluation of the proposed microgrid design, the power electronics reliability is included in the limited manner. Often, it is considered through constant failure rate based on handbooks. The main downsides of such approach include usage of outdated handbook information as well as the negligence of wear-out failure rate due to component ageing, both resulting in inaccurate reliability prediction.
- Recent research has shown that the power electronics impact on the system reliability becomes significant for microgrids with a large installation rate of power electronics-interfaced DERs. Therefore, it is necessary to include their wear-out failure rate in the standard power system reliability procedure to avoid deteriorated design reliability.
- The physics-of-failure approach is a more accurate method for power electronics reliability estimation than using outdated handbooks. It can be used to predict ageing failures for certain set of operating and environmental conditions based on the actual failure mechanisms. Physics-of-failure is a standard practice in design for reliability as well as advanced monitoring of power electronics systems. However, its application in power system reliability analysis is limited.
- To accurately assess reliability of power electronics-based microgrid, a procedure covering different layers of the system, i.e., component level, converter level, system level and their interactions needs to be used during design. In the further research, it is necessary to define new design guidelines for reliability-oriented design incorporating aforementioned procedure.

Finally, the main reliability-oriented challenges of the future, power electronics-dominated microgrid discussed in this work, together with the state-of-art review, can serve as a basis for design reinforcement in the future to achieve cost-efficient and reliable microgrids.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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