A Systematic Review of Reliability Studies of Grid-Connected Renewable EnergyMicrogrids

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***Abstract*—this paper has carried out a comprehensive review of the reliability analysis of microgrid. Survey papers on grid-connected microgrids have reported. In addition, the most applicable indices used in the reliability analyses of microgrids have been investigated. Different techniques used for coupling microgrids have been reported. In the same vein, a survey of different models used for comprehensive reliability analysis of microgrids is also reported. In a similar passion, the most frequent indices used in the reliability evaluations of microgrid have been defined. Different microgrids existing globally have also been presented in the paper. Finally, some future research topics in the area of this research have been identified.**

Keywords—Microgrids, reliability, Hybrid microgrids, Grid-connected microgrids

INTRODUCTION

In this section, the definition of reliability and also recent trends in the area of microgrids were proposed. Generally, there are many definitions of reliability. In this paper, reliability can be defined as the probability of a product or system to operate properly over a specified period of operating condition(s) without failure. Therefore, reliability is already defined as the most important factor to be considered by system planners/designers. In any engineering projects or design; the success could be attributed to the ability of the system to operate for a long period without failure. Reliabilibility can be define as the possibility that a system, prodeuct operates for a specific period of time under defined operating condition(s) without failure(s).

Microgrids could be defined as a single electrical power system consisting of small number of distributed energy resources. The combinations of these energy resources could be in grid-connected mode or standalone. In terms of application, individual source of energy in the form of a microgrid can cause many problems in the power network. Some of the problems include voltage rise, possibility of exceeding the thermal limits of lines and transformers island and huge capital cost. Fortunately, microgrids can address all these problems. On the other hand, microgrids can have some attributes such as it can be considered and operates as a single load. From the demand side, it has the ability to meet local requirements in terms of heat and power, voltage support, better reliability, better power quality, decrease in system losses, and decrease environmental emissions due to the nature of the technology been used. Also, it is important to note that for the microgrid to be realistic, more factors need to be considered, these include energy scenarios, the policy of the place to install the system, and environmental factors. Therefore basically, microgrids can be illustrated in Fig. 1 that is,

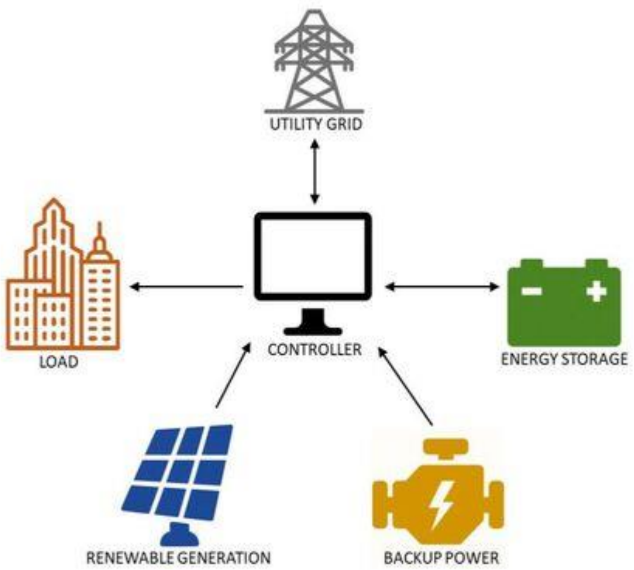

FIG 1: TYPICAL MICROGRID STRUCTURE [1]

Looking at the Fig 1, it is very clear that microgrid has a very complex structure; therefore, it is penetration is increasing by the day. In a similar manner, it has many applications that are inexcusable. Some of the applications can be seen in Table 1.

TABLE 1: DIFFERENT TYPES OF MICROGRID BASED ON APPLICATION [2]

S/No.	Application	Purpose
1	Campus/ Institutional	It includes a fuel cell, solar PV, diesel generators, and a lithium-ion battery. The purpose was to provide peak load reduction. The system also is suitable for establishing tradeoffs during grid mode when optimization is needed between facility and grid needs.
2	Military microgrids	Normally it can be used in order to support the existing and new energy sources to support the entire base station. An example is a three-phase program in the USA called Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) Joint Capability Technology Demonstration (JCTD)
3	Residential	This mode has the ability to combine business potentials of a grid-connected

		rooftop, electric vehicle, slow and medium chargers, and storage
4	Remote and rural microgrids	This system is used to supply about rural 1 billion people electricity in developing and under-developing countries and isolated systems in developing countries. The aim is to allow children to study at night, medical systems such as telemedicine, and enable entrepreneurs to improve their strategies. Example of this microgrids can be seen in Huatacondo Island in Chile, Xingxingxia in Xinjiang, China and Lencois island in Brazil

I. TYPES OF MICROGRIDS

Practically and theoretically, it has been established that the choice of microgrids depends on many factors and criteria. These include stability, capacity, available energy sources, and connectivity. More details on these issues are discussed here, that is

A. Connectivity

Connectivity plays a major role in the inertia of the grid that a microgrid is to be connected. It also depends on the sources available. Unfortunately, due to existing of AC network all over, most of the microgrids are AC. However, the preferred choice for remote locations is low voltage drect current (LVDC) Maintaining the Integrity of the Specifications

B. Availability

Available sources, such as to control deviation from the main grid is very critical in the design of microgrids. Sources such as wind and PV are not controllable. Therefore, they fall in the category of non-synchronous and therefore become threats to microgrid stability. In addition, while some sources generate AC, DC, and at different levels. Due to these factors and others looking at the available AC, eventually, it is preferable to install sources that will supply AC power for utilization. However, the new installed microgrids are constructed to supply DC and can be made to perfectly operate with DC networks.

C. Stability

This factor can be termed as the major player in this area of microgrids power delivery via due to non-synchronous nature of the renewable energy sources. Strategic control is critically needed in order to counter this problem. Therefore, researchers have established some facts on the improvement of system stability; some of them include the use of storage systems and exchange through tie lines to mentioned just a few. In the meantime, more strategies are needed to achieve the desired objective of microgrids.

D. Total Capacity

In the design of a low capacity grid load to generation ratio is very critical. On the other hand, this situation is different when the system is designed for higher capacity due to the balance between capacity load and swing due to change in the loading effects of the power generated.

II. MICROGRIDS CLASSIFICATIONS

Due to all the above requirements, microgrid can be classified as AC, DC, and hybrid microgrids. More details about these classifications can be found in the next section of this paper

A. AC Connected-Microgrid

These types of microgrids are usually developed in which all the sources of power are connected to AC bus. In the case of power sources that generate DC power, the conversion is achieved with the help of power electronics inverter. On the other hand, the AC sources of power are connected directly to the AC bus without any power electronic converter. In a similar passion, the storage units are connected via bidirectional converters. Due to the nature of this type of configuration, kit is easy to expand. In this case, the reliability analysis of this type of configuration is easily determined. Fig. 2 shows the schematic diagram of this type of configuration.

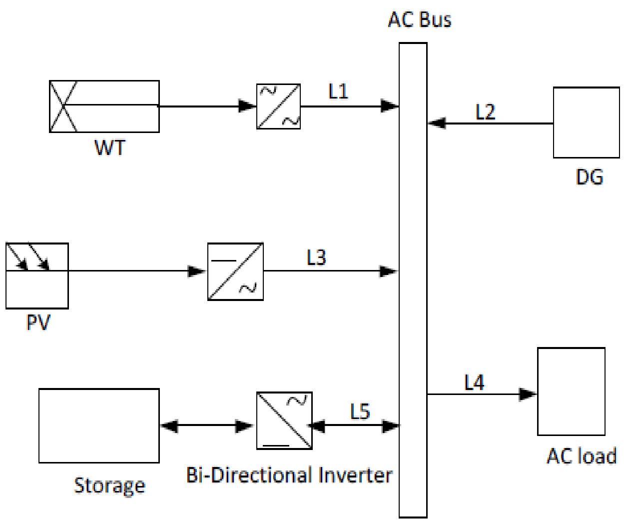

FIG 2: AC MICROGRID MODEL [3]

B. DC connected Microgrid

This type of configuration of microgrids is opposite to that DC-coupled microgrids system. Since the network used only a single DC bus, therefore the DC power sources are connected directly to DC sources with the help of charge controllers. On the other hand, the AC power sources are connected to the microgrids through the power electronic devices. This configuration suffers a setback of a decrease in the efficiency of a similar model. Fig. 3 shows the schematic diagram of this type of configuration.

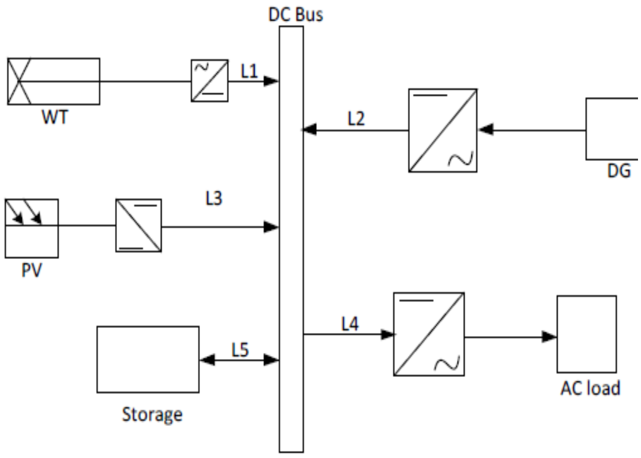

FIG3: DC MICROGRID MODEL [3]

C. *Hybrid AC-DC Microgrid*

The hybrid model combined the use of AC and DC microgrids as shown in Fig. 4. In this model, it can be observed that; all AC power sources are connected to AC bus. In the same manner, the corresponding DC power sources are connected to DC bus. The connection between the two buses is achieved with the help of a bidirectional converter. Also, battery storage can be connected directly to the corresponding bus.

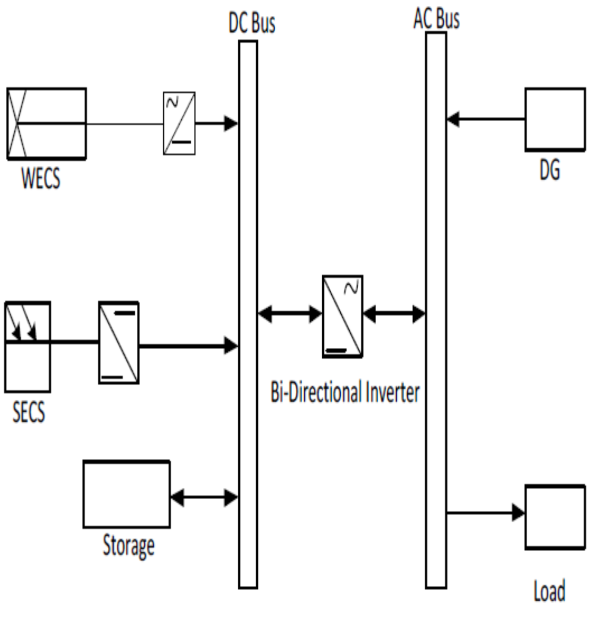

FIG 4: HYBRID MICROGRID NETWORK [4]

III. A SYSTEMATIC REVIEW OF RELIABILITY STUDIES OF GRID-CONNECTED MICROGRID

Some of the existing literatures in this area can be found in [5]. In this paper, the reliability analysis of the microgrids was based on operating conditions of the microgrids. In [6], the microgrid's reliability has been investigated using Monte Carlo simulation. The microgrid used in the study consist of conventional and renewable energy sources with specific consideration in the difference between load and generations. Advanced techniques based on the minimum path method has been developed in [7] for reliability analysis of microgrid considering different types of loads. In the same way, the effects of repair rates on the reliability of microgrids have been considered in [8]. Others considered the effects of customers on microgrid [9], while distributed generation`s effects on microgrids in [10] and customers interruptions cost effects on microgrids in [11].

In another development, wind energy microgrid analysis has been considered in [12], the authors considered the effects of site and size factors on the reliability study of the network. Battery storage effects on the reliability of similar microgrids were investigated in [13]. A technique that used discrete wind speed frame analysis for the reliability of microgrid has been studied in [14]. Authors in [15] carried out a comprehensive study on the effects of capacity limitations and transmission force outage rate on the reliability of microgrids.

However, there is some recent reliability development in solar energy microgrids. One of the studies is the reliability study of standalone microgrids [16]. In this paper, the authors developed a multi-stage model for the reliability analysis of solar energy microgrids. Improvement of the model in [16] was proposed by other authors in [17]. Hybrid microgrids have been analyzed in [18]. Others, in this regard, developed a multi-state technique for the analysis of similar microgrids in [19]. Other authors considered the reliability of microgrids considering load and supply in [20]. A similar study was carryout in Davutpasa University microgrid. Loss of load expectation and loss of load factor were used as reliability indices in [6]. A similar network has been analyzed in [21]. Another paper combined deterministic and probabilistic methods to analyze the reliability of hybrid microgrid in [22]. Recently, the effects of the priority load of renewable energy microgrids have investigated in [23], the authors developed a hybrid analytical-simulation method based on Monte-Carlo simulation. In addition, the effects of microgrids islanding failure have been analyzed.

Furthermore, mixed integer programming was used in [24] to maximize the reliability of microgrids by determining the number of critical loads. Eventually, the paper has shown that the system average frequency interruption index of microgrids improved with the addition of battery storage. Different strategies were proposed in [25] to improve the reliability of microgrid with high penetration of renewable energy. The strategies proposed include load shielding, energy storage distributed generation, and the creation of smaller microgrids with a microgrid structure.
In another paper [26] used fault tree analysis to evaluate the reliability of a distribution system consisting of the microgrid. The results from the analysis have shown how microgrids enhanced the reliability of the distribution system by decreasing the failure rate of the local load point.

A paper proposed new reliability indices for reliability and economic analyses of microgrid connected to distribution networks. The developed method was base on the two-step Monte Carlo simulation model. The developed model extensively evaluates the reliability and economic parameters of microgrids. The work could be used for comparative technical analysis of different designs of microgrids.

The effects of demand response on the reliability of microgrid have been investigated in this paper [27]. The paper was able to establish how demand response strategies determined the degree to which microgrids can satisfy the load demand connected to it, which eventually improved the reliability of the overall network. The analysis was for different illumination stages.

It has been shown that clustering smaller microgrids could enhance the reliability of the whole/or bigger microgrid network. The authors have tried to design microgrids considering reliability and power supply related issues in the model. Also, the developed model proved that with careful considerations of these factors, the reliability of microgrids would be improved, and the future grid networks will be cost-efficient [28].

Authors in [29], the reliability of a microgrid consisting of wind and solar renewable energy sources have been evaluated. A method was proposed that takes the stochastic nature of renewable energy sources into consideration. This stochastic nature was considered in the model with the help of state sampling simulation. However, the analytical method was used to determine the overall reliability of the system. Also, the model was able to study the effects of priority loads on the reliability of the system. The results have shown that priority loads greatly affects the reliability of microgrids models.

In the same year, a researcher investigated the effects of random failure of components that make up a microgrid. The study developed a reliability model taking the state variable into considerations

A recent work [30] was on microgrids show that network structure influenced the reliability of the system. In the same paper, it was observed that the reliability of microgrids is very sensitive to many factors; such factors include system demand, network structure, and with the proposed method of coupling.

Authors in this paper [31]; have has shown energy storage smoothen the output power of solar energy microgrids, thereby increasing the reliability of microgrid provided the energy storage does not exceed certain limits. In the same paper, the loads-sharing strategy could also influence the reliability of microgrids. The visualization technique was proposed for the reliability analysis of grid-connected microgrid. The method developed allowed malticriterion analysis by using different indices. The developed method takes into account the mode of distribution operations [32]

Other possible techniques for reliability analyses of the microgrid is reliability block diagram. Some authors in [33] have demonstrated the possibility of using reliability block diagram, and the model was implemented using Monte Carlo simulations. It has been established that it is possible to determine the impact of stochasticity of wind speed on the reliability of microgrids. It was confirmed that battery storage system has a serious impact on the reliability of microgrid. The storage system reliability analyses were carried out considering the presence and absence of the storage system. It was observed that the storage system enhanced the reliability of microgrid [34].

Authors in [35] evaluated the reliability of microgrids by developing a model that hybridized the reliability model of wind turbine and system reliability concept. Monte Carlo simulation was used to implement the developed model. It was observed that the maximization of wind power generation and storage systems could increase the reliability of the proposed microgrids considering different operating conditions.

In a recent development, hybrid microgrids penetration in on the increase. In view of that, the literature review has shown that, for realistic development in this area, it can be seen that most of the papers concentrated on load and supply mismatched. Also, grid-connected microgrids were not given adequate attention in recent times. However, reliability analysis of microgrid could be realistic considering other factors such as type of faults, non-electronic components, network structure. In this paper, it is assumed that the reliability of microgrids is beyond mismatch between loads and supply. This makes it possible to investigate microgrids considering some of these factors in many future studies. Also, other possible factors include network structure such as AC, DC, and hybrid microgrids that can be investigated for better system reliability.

IV. Terminologies used for Reliability studies of microgrids

In this section, indices and terminologies used in the reliability of microgrids are explained. These indices range from power and energy-related to failure rate dependency variables. Some of these could be defined as in Table 2. Also, the corresponding domain of each variable is identified.

TABLE II: INDICES USED FOR RELIABILITY ANALYSIS OF MICROGRIDS

S/No.	Reliability variable	Remark/definition
1	System average interruption frequency index (SAIFI)	this index is defined as the average number of times that customers connected to microgrid experienced interruption for a period of one year.
2	Customer average interruption frequency (CAIFI):	Usually, some customers will be experiencing sustained interruption for a period of one year. This index defined the mean frequency for such interruptions on the network.
3	Average system interruption frequency index (ASIFI)	in some areas it is possible to have large concentrations of loads, this index is used to measure the performance of such area.
4	SAIDI	this defines as the average duration a customer connected to microgrids experience outage for a period of one year. It is usually measured in customer minutes of average customer hours of power interruption.
5	Customer average interruption duration index (CAIDI):	This is the average time to restore electricity, and it is mathematically defined as the ratio of SAIDI to SAIFI

6	Average system interruption duration index (ASIDI):	this index is equivalent of SAIDI from the load point of view, and the mathematical equivalent is defined by many researchers
7	Average service availability index (ASUI):	the probability that all loads connected to the microgrids will be supplied is called ASUI
8	Average service availability index (ASAI):	the fraction of time that a particular customer is connected to the grid is defined to be ASAI. Therefore, the arithmetic addition of ASUI and ASAI will always be equal to one.

V. CONCLUSION

This work has shown that due to the complexity of future energy grids, there is an urgent need to shift from the traditional reliability methods to new techniques. It was observed that most of the existing works evaluate the reliability of microgrids considering mismatch between system demand and generation. Therefore, for realistic implementation and in order to achieve global ambitions on microgrids, there are urgent needs to developed new techniques that could and indices that accommodate those requirements. In addition, there are many factors that must be considered in order to exhaustively determine the reliability of microgrids structure globally. Some of the factors include the type of fault, weather, and network structure. In addition, this paper will assist researchers and system designers in identifying microgrids' requirements and directing them in the area of reliability study related to grid-connected microgrids.

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