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A Review of the Protection of Microgrids with Converter-Based Resources

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SUMMARY

With the increasing electricity demand along with the environmental concerns, the installation of renewable distributed energy resources (DERs) has been proliferated. These DERs, together with the nearby loads, result in the formations of microgrids, which can operate in either grid-connected or isolated mode [1]. The uncertainty and variability of generation and consumption, introduced by renewable DERs and new loads, pose significant protection challenges to the microgrids. Besides, the so-called converter-based resources (CBRs), which are DERs connected to the system through converters, also raise additional protection challenges associated with the converter characteristics. Although many studies have identified the challenges associated with the protection of microgrids with CBRs and have proposed various algorithms to address the challenges, only a few of them comprehensively discuss all the protection challenges within one system. Most studies use multiple small test systems to describe various protection challenges and the corresponding protection solutions. In this paper, a single test system is proposed and used to illustrate all the protection challenges and the developed innovative solutions to resolve the failure of the conventional protection systems in microgrids with CBRs. This paper uses the proposed test system to discuss the protection challenges of microgrids with CBRs, due to the various operation modes of microgrids, changes in microgrid configurations, bidirectional current flow, various fault current levels seen by relays, and also challenges associated with converter fault current characteristics. This paper also uses the proposed system to provide a review of the existing protection schemes, which have been proposed in the literature to tackle the protection challenges associated with microgrids with CBRs.

KEYWORDS

Converter-based resources (CBR), Microgrids, Renewable resources, Power system protection.

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1. Introduction

Over the past decades, microgrids with DERs have received large attention due to the increasing electricity demand and severe environment concerns. With the formation of microgrids, in the U.S., a 20% reduction in emission and a 20% improvement in system energy efficiency is anticipated by the year 2020 [2]. Although the existing microgrid market is still dominated by combined heat and power (CHP) generators and other conventional power generators such as diesel, studies have shown that there has been a significant increase in the installed capacity of renewable energy resources such as solar photovoltaic (PV) systems and wind turbine generators (WTGs), especially in community microgrids, utility microgrids, and remote microgrids [3].

Many of the renewable energy resources, such as solar PV and WTGs, are connected to the grid via converters. To interface with the alternating current (AC) grid, the solar PV systems, which generate direct current (DC) power, require AC/DC converters. The types III and IV WTGs, are also connected to the grid via back-to-back AC/DC converters to provide independent control of the active and reactive power injection to the grid [4]. Despite the various advantages of the microgrids with CBRs, such as uninterruptible provision of power supply, and peak shaving capability, the protection of microgrids with CBRs has numerous challenges that must be addressed. These protection challenges are due to the various operation modes of microgrids, changes in microgrid configurations, bidirectional current from and to the microgrids, and various fault current levels seen by relays. Furthermore, the fault current characteristics of converters add more challenges to the protection of microgrids with CBRs. Various studies have identified these challenges [5]–[16] and a number of them have proposed protection schemes to overcome the challenges [17]–[24]. Among these studies, only a few provide a comprehensive review of all the issues altogether. For example, [15] includes 6 different test systems to study the fault identification challenge associated with fault current characteristics and the possible solutions. Also, [9], [12], and [16] include more than three test systems to discuss the challenges of microgrids with CBRs from different aspects. Besides, the proposed protection schemes which address one or more protection challenges of the microgrids with CBRs, such as [17]–[20], discuss and simulate their schemes based on different test systems as well.

The lack of a comprehensive test system makes it difficult to extensively understand the various protection challenges of microgrids with CBRs. Thus, in section 2, this paper proposes a single comprehensive test system, which is utilized, in section 3, to illustrate all the protection challenges due to the various operation modes of microgrids, changes in microgrid configurations, bidirectional current flow, various fault current levels seen by relays, and converter characteristics. In section 4, the proposed test system is used to discuss the existing schemes, such as overcurrent-based schemes, and directional schemes, which have been developed to overcome the microgrid protection challenges.

2. Proposed Test System

Figure 1 shows the proposed test system, which is based on the conventional IEEE 13-bus system [25]. In this proposed system, buses 675, 692, and 652 are modified with the addition of loads and DERs. Switch SW1 is added between buses 646 and 611 so that a looped system is formed once the switch is closed. Once there is a power outage between buses 611 and 671, the connection between buses 646 and 611 can provide an alternate path to restore the power supply to buses 684 and 652. Circuit breakers (CBs), which are controlled by their corresponding relays and are connected to the DER-buses are also shown in this figure. Two islanded microgrids can be formed once CB2 and CB4 are open, and the rest of the system is considered as the main grid. Six short circuit fault scenarios F1-F6 are considered throughout this paper.

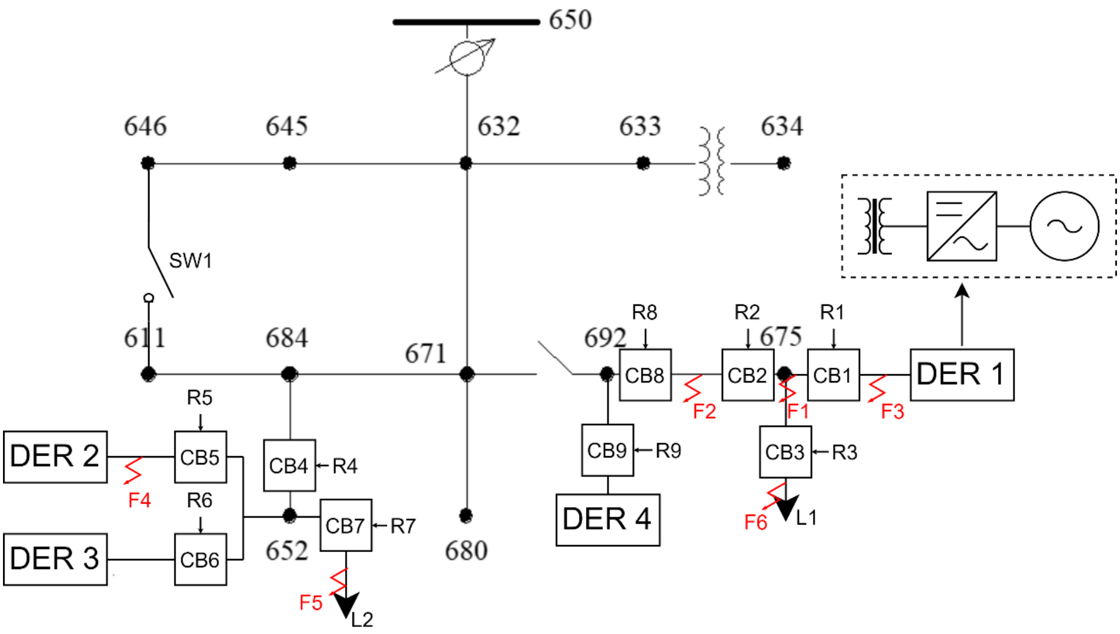

Figure 1 Proposed comprehensive system

3. Protection Challenges of Microgrids with CBRs [5]–[16]

This section will provide a comprehensive discussion about the protection challenges of microgrids with CBRs using the proposed test system. The discussion will focus on the protection challenges of buses 675 and 652, which are connected to one or multiple DERs. As shown in Figure 1, bus 675 is connected to a converter-based DER (DER 1) and bus 652 is connected to two general-type DERs (DER2 and DER3). In this section, DER 4 is assumed to be disconnected from the system. The challenges of various operation modes of microgrids, changes in microgrid configurations, bidirectional current from and to the microgrids, various fault current levels seen by the relays, will be discussed in sections 3.1-3.4, Then, section 3.5 will discuss the converter fault current characteristics that further complicate the protection of microgrids with CBRs.

3.1 Various Operation Modes of Microgrids [5][9]

There are two main operation modes of microgrids, namely grid-connected and islanded. For example, in Figure 1, the microgrid consisting of DER2, DER3 and L2 operates in the grid-connected mode when CB4 is closed; however, when CB4 is open, this microgrid is disconnected from the grid and operates in the islanded mode. The microgrid protection schemes should operate properly during both operation modes and the transition between them. Under the grid-connected mode, the protection system of the microgrid should be properly coordinated with that of the main grid. Considering the large current fed from the grid, the overcurrent settings of the relays in the grid-connected mode are different from those under the islanded mode where the fault current is much smaller. Besides, without proper protection schemes, the transition from the grid-connected mode to the islanded mode, so-called islanding, may result in off-nominal frequency and inaccurate voltage measurements, and may further prevent the re-connection and re-synchronization of the microgrid.

3.2 Microgrid Configuration [6]

In the conventional IEEE 13-bus system, switch SW1 is open and the test system is radial. In this radial system, the protection relays are coordinated by considering the upstream relay as the backup relay for the downstream relays. For example, with SW1 open, buses 611 and 652 are supplied through bus 684, and therefore the overcurrent relay at bus 684 should operate slower than the overcurrent relays at buses 611 and 652. However, once there is a power outage between buses 684 and 671, SW1 should close, so that buses 684 and 652 are supplied through bus 611, and thus the original coordination between relays at buses 611 and 684 will be lost. In this configuration, the overcurrent relay at bus 684 should operate faster than the overcurrent relay at bus 611, and the relay at bus 652 should operate faster than the relay at bus 684. To overcome the protection challenges due to the microgrid configuration, the relay settings are required to change adaptively with the changes in the system configurations and power flow directions [6].

3.3 Bidirectional Current Flow [9]

Another major protection challenge in the microgrids with DERs is due to the bidirectional current flow. In the test system shown in Figure 1, during the grid-connected mode of operation, three power flow scenarios are possible: (a) The DER is turned off, and the load is fully supplied from the main grid, and thus the power flows from the grid to the load; (b) The DER is turned on, and the load is supplied by both the main grid and the DER; (c) The DER generates more power than the load, and the DER feeds the grid (assuming back-feeding is enabled). Under the islanded mode of operation, the DER fully supplies the load. The four aforementioned possible power flow scenarios are illustrated in Figure 2. Three possible power flow scenarios under faults F1-F3 are shown in Figure 3. It can be observed that the power flow directions under some faults may resemble those under the normal condition, and in such scenarios, the relays might malfunction. For example, under F2, as shown in Figure 3(b), when there is a fault on the grid, DER 1 feeds both the load and the grid, and this scenario resembles scenario (c) of Figure 2 where there is no fault in the system. As a result, during the normal condition when DER1 generates a considerable amount of power, R2 may see a large current, comparable to the fault current and may detect a fault. Similarly, fault F1 shown in Figure 3(a) may resemble scenario (b) of Figure 2, and relays R1-R3 may malfunction under normal or fault conditions if they are not properly tuned.

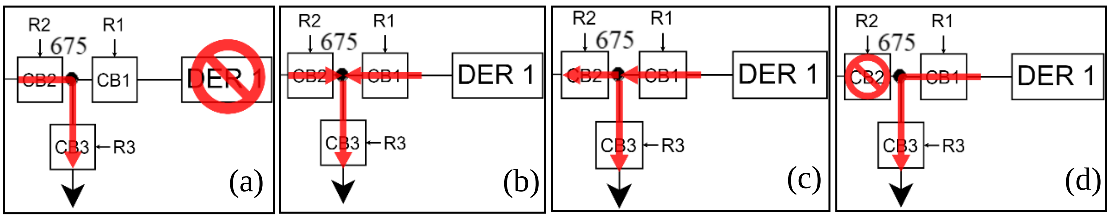

Figure 2 Possible power flow directions under the normal condition

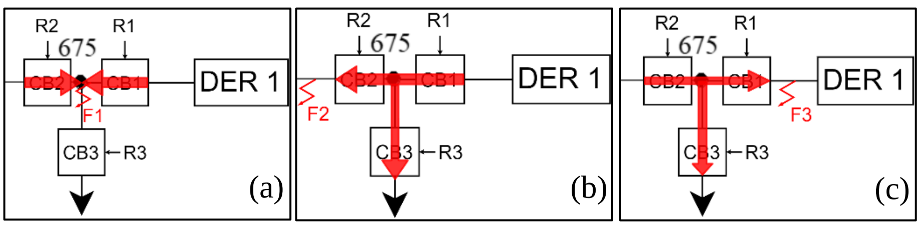

Figure 3 Possible power flow directions under faults F1, F2, and F3

Furthermore, fault detection becomes even more complicated once there are multiple DERs connected to the same bus. Taking bus 652 as an example, a bus fault at bus 652 has to be isolated from all sources including DER2, DER3, and the main grid. Assuming that the two DERs are initially turned off and are not supplying any current to the system, R5 and R6 will not send a trip signal to CB5 and CB6 during a fault at bus 652. However, once any of the DERs are turned on before the fault is removed, bus 652 will be energized. Thus, in the event of a bus fault, it is desired to lock out the connected DERs to avoid unexpected energization [9].

Another fault scenario is shown in Figure 4, where the overcurrent relay R5, without a directional element, may malfunction [9]. Assuming bus 652 is isolated from the grid, ideally, CB5 should trip for F4, but not for F5. Under F4, R5 sees a fault current I fed by DER3. Under F5, R5 sees a fault current I' fed by DER2. Assuming DER2 and DER3 are identical, |I| will be equal to |I'| but will be in the opposite direction. Since R5 is an overcurrent relay that does not include any directional element, it cannot distinguish F4 from F5. Therefore, R5 may send the wrong trip signal to CB5 for a fault F5. The same may happen to R6. Thus, a directional element is suggested to be added to the overcurrent relays to overcome this protection challenge. However, this is not the ultimate solution as the performance of directional relays can be affected by converters, which will be discussed in section 3.5.

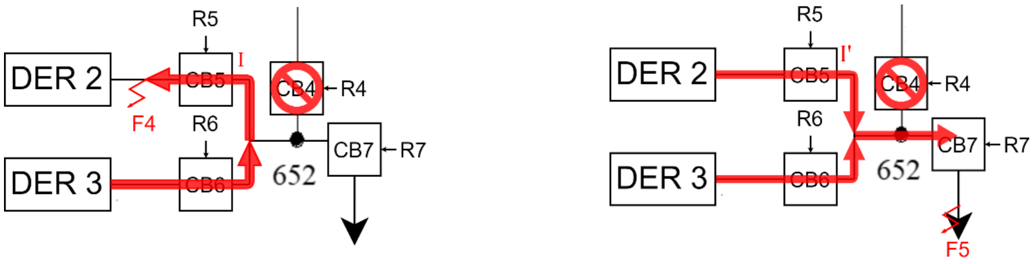

Figure 4 Bus 652 with multiple DERs

3.4 Various Fault Current Levels [10][11]

In a microgrid, the current magnitude may also increase or decrease with the addition of DERs to the grid [10]. Under different microgrid operation modes and different operation status of the DERs, the fault current level may vary at a certain location. Since the existing protection systems for distribution grids are mostly designed based on the assumption that power only flows from the grid towards the load and are based on overcurrent relays set at fixed current levels, they may malfunction with the addition of new DERs to the microgrid, and the coordination between relays may be lost [11]. For example, at bus 652, the fault current seen by R7 under F5 may have 5 different levels based on the microgrid operation modes and the connection status of the DERs, when (a) both DERs operate in the grid-connected mode; (b) only one of the DERs operate in the grid-connected mode; (c) the microgrid operates in the grid-connected mode and both DERs are turned off; (d) both DERs operate in the islanded mode; (e) one of the DERs operates in the islanded mode. As a result, R7 should be properly set up so that it can selectively identify fault events under all these scenarios, and back up relays R4-R6 should be coordinated accordingly with R7.

3.5 Converter Characteristics [9][12][13][16]

A large number of DERs are connected to the grid via converters. An example of such CBRs is DER1, which is represented with a source behind a converter (and a transformer upon necessity), as shown in Figure 1.
Due to the non-linear characteristics of converters, various challenges are introduced to the protection system by CBRs due to their complex short-circuit behavior, limited converter current, inaccurate sequence impedance model, and low inertia [12][13].

- The short-circuit behavior of CBRs depends on the converter control scheme such as droop control and PQ control [13], and the operation mode of the CBRs such as the sub-synchronous or super-synchronous operation of type III and IV WTGs [16]. Depending on the control scheme and the operation mode, when there is a sudden change in the voltage and current under fault events, transients with off-nominal frequencies are introduced to the system along with phase shifts. As the voltage and current frequencies deviate from the rated frequency, the measurement errors will cause relays to malfunction. When the current frequency is significantly different from the voltage frequency, the phasor forms of voltage and current and any related calculations will be erroneous [16].

- The internal protection system of converters limits the current within a certain level, even under faults. Thus, overcurrent-based schemes may malfunction as the limited fault current may not reach the trip setting of the relays. Besides, most converters are designed without the ability to provide a negative-sequence current component. Thus, negative-sequence relays, which are used for detecting unbalanced faults, can no longer function properly in microgrids with CBRs.
- Converters with fault ride-through (FRT) capability are controlled such that they remain connected to the grid during faults and provide reactive power support to the grid. Therefore, they should be modeled as current sources rather than voltage sources during fault studies [9]. The current sources are equivalent to either a constant voltage source along with a variable impedance or a variable voltage source with a constant impedance. However, in conventional analysis of CBRs during faults using symmetrical components, the voltage source magnitude and impedance representing CBRs are assumed to be constant. Hence, the corresponding calculations are inaccurate.
- Microgrids with CBRs have much lower inertia compared to those with synchronous generators, resulting in a higher rate of change of frequency (ROCOF) [9][12]. Due to the high ROCOF, the addition or loss of a large load or CBR due to faults will quickly cause a significant change in the frequency and might destabilize the microgrid. Thus, the protection system of microgrids should operate fast enough to detect and isolate faults to arrest the frequency changes to avoid cascading generation loss and ensure stable recovery of microgrids. Also, the relay settings need to be adjusted so that CBRs can tolerate higher ROCOF without being unnecessarily tripped offline. Besides, the conventional overcurrent relays may not be able to track large frequency decays, and may maloperate or lose coordination with other relays.

4. Existing Protection Schemes

This section addresses various types of recently proposed relays to solve the aforementioned challenges. The schemes based on overcurrent-relays can solve the challenges of various fault current levels and various operation modes of the microgrid [17]–[19]. The schemes based on directional-relays can solve the challenge associated with bidirectional current flow [20]–[22]. Other protection methods such as differential relays [15], setting-less schemes [23], and communication based-schemes such as pilot schemes and intelligent schemes [24] are also proposed to solve the challenges, respectively.

4.1 Overcurrent-Based Schemes

Due to the fault current characteristics of microgrids with CBRs, as discussed in section 3, the conventional overcurrent protection devices such as overcurrent relays may malfunction and lose coordination with downstream relays. Two of the most widely-proposed solutions to overcome the malfunctioning of overcurrent devices are fault current limiters (FCLs) and adaptive protection schemes.

To resolve the challenge of various fault current levels, FCLs are inserted between the DERs and buses to limit the fault current level. With the insertion of FCLs into the microgrid, the fault current can be limited to a level comparable to that of the original grid where there are no DERs [17]. By limiting the fault current levels, the coordination between the overcurrent devices can be restored. As an example, in Figure 1, assume R8 and R3 are coordinated before DER1 and DER4 are installed: When DER4 is added to the system, it will increase the fault current level at buses 675 under F6, and R8, as an upstream back-up relay, may trip faster than R3, and thus the coordination between R8 and R3 will be lost. The addition of an FCL between bus 692 and DER4 limits and restores the fault current level and trip time approximately to the scenario where DER4 is disconnected from the grid, thus restoring the coordination between R3 and R8. While the major advantage of FCLs is to restore the coordination of overcurrent protection devices by reducing the level of fault current, FCLs may lead to the maloperation of other overcurrent relays. In the previous example, due to the

FCL between DER4 and bus 692, the fault current detected by R9 is reduced and therefore, the performance of R9 is negatively affected.

Some alternate solutions, namely adaptive schemes, are proposed to solve the challenges of various operation modes and various fault current levels of microgrids. [18] proposes an adaptive scheme that identifies the operation mode of the microgrid, based on the measurement data from relays located at the main grid and the DERs, and calculates the time dial settings for the overcurrent relays at every sampling instant. One major requirement to achieve reliable performance in this method is a high communication capacity among relays at different locations. [19] proposes another adaptive scheme that identifies the operation mode of the microgrid based on the zero-sequence impedance angle, and uses a specific fault detection schemes under each operation modes. Under the islanded mode, since the overcurrent devices are more adversely affected due to the significantly smaller fault current level, voltage dip is used for fault detection, but the conventional overcurrent relays are still used under the grid-connected mode. While this scheme overcomes the challenge associated with various operation modes, it fails to resolve the various fault current levels challenge. For example, in Figure 1, assuming the system is properly grounded, the equivalent zero sequence impedance angles seen by R7 are different under grid-connected and islanded operation modes of the microgrid. The real-time zero-sequence impedance angle detected by R7 is compared with these expected angles to identify the real-time operation mode of the microgrid, and to choose the fault detection scheme accordingly. However, according to section 3.4, the fault current still varies under the grid-connected operation mode and the conventional overcurrent relays may malfunction.

4.2 Directional Schemes

Directional relays can detect the direction of current and power flow based on the torque caused by the angle difference between the measured current and voltage. The directional relays can be respectively categorized into positive-sequence relays for symmetrical fault detection, negative-sequence relays for asymmetrical fault detection, and ground relays for ground fault detection. For all three types, the torque depends on the magnitude and the phase angle of the measured voltage, measured current, and the sequence/phase impedance of DERs. Although directional relays can address some of the aforementioned challenges such as bidirectional current flow in microgrids [9], they may maloperate due to incorrect calculations of torque in microgrids with CBRs.

One of the issues is caused by the inaccurate modeling of the symmetrical components of CBRs [14] [20]. This problem can be solved by accurate modeling of the sequence impedance of the CBRs [20]. The idea of superimposed impedance is proposed to correctly evaluate the equivalent impedance of CBRs, using the memorized values of current and voltage measurements from the most recent cycle [20]. While the superimposed impedance significantly improves the accuracy of conventional directional relays, it can still be affected by the control scheme of the CBRs, fault condition, and load current. When the frequency is not high enough, the influence of the inductive and capacitive components in the circuit and the control system with high-bandwidth current loops on the superimposed impedance can not be neglected [7]. As a result, it is proposed that the high-frequency impedance of DERs should be used in combination with the superimposed impedance for fault detection in microgrids with CBRs [21]. The high frequency refers to the increase in the transient frequency when there is a sudden voltage drop during the fault. However, to calculate the high-frequency impedance, a high sampling rate is required for the relay, leading to an increased cost.

The maloperation of directional relays may be also caused by the phase and frequency deviation between the fault voltage and current measurements [16]. A modified load encroachment function is proposed in [22] to supervise the directional relays to prevent relay maloperation by ensuring all normal load conditions are excluded from the relay trip zone. The load encroachment zone is set up to block the relay from operating during large loads. To accommodate for the phase and frequency deviation, the modified load encroachment zone is phase-shifted, according to the phase shift of the fault current and voltage so that it can correctly block the maloperation of the directional relays.

4.3 Other Schemes

In addition to the aforementioned relays, other protection devices and schemes have been proposed for the protection of microgrids with CBRs [12][15][23][24]. Differential relays provide reliable protection in microgrids as they are based on Kirchhoff's current law (KCL) in the protection zone. However, the bidirectional current in microgrids may complicate the settings of such relays [15]. This issue can be avoided using setting-less protection schemes [23]. In a setting-less scheme, a fault is detected if any of the physical and electrical laws such as KCL, Kirchhoff's voltage law (KVL), Ohm's law, or heat transfer laws, are violated while system states are dynamically estimated from measured data. Relays based on traveling waves are also proposed for microgrid protection [12]. While the traveling-wave-based scheme is theoretically immune to the aforementioned challenges, it has not yet been tested in the real-world microgrids and requires further evaluation.

In addition to the aforementioned schemes, with the development of smart grid technologies, fast communication systems and phasor measurement units (PMUs), distance relays [5] and communication-based schemes such as pilot protection schemes, fault location isolation and restoration (FLISR) schemes [12], and schemes based on data mining [24] are proposed as alternate options to protect the microgrids. Although distance relays are not widely adopted due to the small impedances of microgrids, they can help protect high-cost transformers in industrial microgrids [12], and supervise pilot protection schemes which are favored for their fast operation. FLISR schemes are useful for microgrids with complex distribution and heavily depend on communication due to the ability to share information among protective devices [12]. The data-mining-based scheme uses the random forest tree technique as the classifier and a learning-from-data approach to classify the features of the acquired dataset from the relays and determine if any fault has occurred [24]. While the communication-based schemes are able to address almost all the aforementioned challenges with significant accuracy and reliable performance, communication bandwidth and cyber-security are non-negligible concerns that require attention as well.

5. Conclusions and Recommendations

This paper developed a single comprehensive test system based on the IEEE 13-bus system [25] with renewable DERs, which can be used to study all the protection challenges associated with microgrids with CBRs. Although various studies have identified these challenges [5]–[16] and a number of them have proposed protection schemes to overcome the challenges [17]–[24], only a few provide a comprehensive review of all the issues altogether. The lack of a comprehensive test system makes it difficult to extensively understand the various protection challenges of microgrids with CBRs. This paper comprehensively reviewed the protection challenges of CBR-connected microgrids and the existing protection schemes that are already proposed to address the challenges, using the proposed test system. The addressed protection challenges are associated with the various operation modes of microgrids, changes in microgrid configurations, bidirectional current flow, various fault current levels seen by relays, and the converters' fault current characteristics. The reviewed protection schemes include overcurrent-based, directional, differential, setting-less, traveling-wave-based, distance-based, communication-based, and data mining. So far, the communication-less schemes are not able to solve all the protection challenges of microgrids with CBRs, while the communication-based schemes require high communication bandwidth and have to deal with cyber-security concerns. It can be concluded that there are trade-offs among the performance, the complexity, and the cost of the proposed protection schemes, and a comprehensive protection scheme that solves all the challenges is of great demand.

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