A Brief Review on Microgrid Protection (DC)

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Abstract

In recent years, the Direct Current Microgrid (DCMG) has gained popularity and preference due to advancements in converters and DC loads. However, the protection challenges and standardization issues associated with microgrids have hindered the widespread adoption of DCMGs. This article provides a summary of recent research conducted in the field of microgrid protection. The discussion starts with an overview of voltage levels, topologies, and grounding methods in DC microgrids. Subsequently, the article briefly addresses the challenges specific to DC microgrids. Additionally, the study examines the latest developments in fault detection, location, and isolation techniques for protecting DC microgrids. Furthermore, it delves into the use of protective devices for DC microgrids. The hope is that this work will aid researchers in finding relevant references for further exploration of DC microgrid protection.

***Terms*—Protection Challenges, Grounding, Protection Coordination, Protective Devices, Fuses**,

INTRODUCTION

In recent years, the adoption of DC microgrids has surged significantly owing to their numerous advantages, including high efficiency, high power density, flexibility, and simplified control [1]. DC microgrids also facilitate the direct integration of various resources such as photovoltaic (PV) systems, fuel cells, and battery storage without the need for AC conversion [2]. Furthermore, advancements in DC technology have given rise to more efficient DC loads as compared to AC loads [3].

The DC system exhibits unique characteristics during steady-state, where the effects of inductance, capacitance, and skin effect are absent [4]. This absence of inductive effect results in excellent voltage regulation in DC systems. Additionally, the DC system experiences negligible power loss due to the charging and discharging of capacitors.

Since the skin effect is frequency-dependent, it is non-existent in DC systems, allowing the entire conductor cross-section area to be fully utilized. Consequently, the resistance in DC systems is considerably lower compared to AC systems. This advantage leads to a reduction in cable conductor size and weight, as the skin effect does not need to be accounted for [5].

The advantages of DC microgrids extend beyond the absence of inductive, capacitive, and skin effects. Some of the other notable advantages include

Enhanced Efficiency: DC microgrids offer higher efficiency due to reduced losses associated with AC power conversion.

Improved Power Quality: DC systems experience less harmonic distortion and offer better power quality.

Seamless Integration of Renewable Resources: DC microgrids allow straightforward integration of renewable energy sources, such as solar and wind, without the need for frequent conversions between DC and AC.

Scalability: DC microgrids are highly scalable, making them suitable for various applications, from small installations to large-scale power systems.

Enhanced Control: The simplified control and management of DC systems contribute to better grid stability and control.

Reduced Overall Costs: Due to lower power losses and reduced conductor size, DC microgrids can lead to cost savings in certain applications.

Reduced Environmental Impact: DC systems may contribute to a lower carbon footprint by optimizing energy conversion and utilization

As a result of these advantages, DC microgrids have found successful applications in areas like traction systems, data centers, vehicular power systems, and beyond [6].

The implementation of a DC microgrid offers various advantages over AC microgrids:

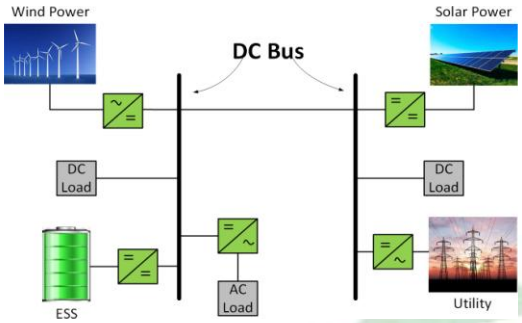
Reduced Current Leads: DC microgrids require only two current leads, while AC microgrids typically need four, resulting in reduced losses and improved overall efficiency.

Lower Cable Losses: DC cables do not experience the skin effect found in AC cables, leading to a reduction in cable losses of around 15% to 20%.

High Power Transmission Capacity: DC microgrids possess a high power transmission capacity, making them suitable for transmitting large amounts of power efficiently.

Minimized Converter Stages: With both loads and resources operating in DC, there are fewer redundant stages of converters, leading to lower losses and reduced heat generation.

Compatibility with DC Storage Devices: Storage devices such as batteries and fuel cells inherently operate in DC, making them seamlessly compatible with DC microgrids.



Elimination of Synchronization Issues: Unlike AC systems, DC microgrids do not encounter synchronization issues, simplifying grid integration and control.

Overall, the utilization of a DC microgrid provides improved efficiency, reduced losses, and greater compatibility with various DC-based resources and devices. This makes DC microgrids an attractive solution for various applications, offering potential advantages in terms of both energy efficiency and grid stability.

DC microgrids can be categorized into two voltage levels: medium voltage DC (MVDC) and low voltage direct current (LVDC).

Fig. 1 DC Microgrid

The MVDC microgrid has garnered significant attention in applications such as vehicle power systems and ship power systems. The rated voltage of MVDC systems typically ranges from 1500 V to 35 kV [7]. Various applications of MVDC systems are presented in references [8] and [9], highlighting the versatility of this technology.

On the other hand, the LVDC microgrid finds use in a wide range of applications, including railway traction systems, telecommunication power systems, and protection systems. LVDC systems operate at voltages below 1500 V. With the advancements in DC loads, particularly in electric vehicles (EVs), LVDC microgrids have become a viable option for commercial and residential applications.

The dual voltage levels of DC microgrids, MVDC, and LVDC, offer flexibility and suitability for diverse applications, contributing to the growing adoption of DC technology in various industries and sectors.

A basic schematic of two bus DC Microgrid is shown in Fig.1.

Topologies of DC Microgrid

The topology of a DC microgrid is a crucial factor in its design, as it directly influences the protection system's performance and the overall system reliability. DC microgrid topologies are broadly classified into four types:

Single Bus Structure [10]: In this topology, all the elements of the microgrid are connected to a single bus. It is a simple configuration where all components share the same bus for power transfer and control.

Multi Bus Structure: In this topology, multiple buses are used to connect different elements of the microgrid. It offers increased flexibility in the system design and allows for better load distribution and management.

Ring-Type Structure [11]: In the ring-type structure, a ring is formed by interconnecting multiple sources and loads. It resembles the ring main system of conventional power systems but with the presence of multiple sources in the ring. This configuration provides redundancy and alternate paths for power flow.

Meshed-Type Structure [6]: The meshed-type structure involves complex interconnections between various sources and loads, forming a mesh-like network. It provides multiple parallel paths for power transfer and ensures high system reliability.

The choice of topology significantly impacts the current direction and magnitude within the microgrid, which, in turn, affects the coordination of protective devices (PD). For instance, in a ring-type structure, fault currents may divide into two paths, while in a meshed-type structure, they may or may not divide into multiple parts.

Methods of Grounding in DC Microgrid

Selecting the most suitable topology depends on the specific requirements and objectives of the microgrid application. Factors such as power flow control, fault management, redundancy, and overall system stability must be carefully considered during the design phase to ensure effective protection coordination and reliable operation.

The grounding system in a DC microgrid serves three main purposes:

Fault Detection: Grounding systems help detect faults by providing a reference point for current flow. When a fault occurs, the grounding system provides a path for fault currents to flow, enabling the detection of the fault.

Minimization of DC Stray Currents: Proper grounding helps reduce the occurrence of DC stray currents, which can cause corrosion and damage to equipment and structures in the microgrid.

Safety Improvement: Grounding systems enhance equipment and personnel safety by reducing common mode voltage (CMV), which refers to the potential difference between exposed conductive parts and the ground.

DC grounding systems in accordance with IEC standard 60364-1 are classified into five types: TT, TN, and IT, based on how the source and conductive bodies of devices are connected to the earth.

TT Grounding System: Both the converter midpoint and appliance body are separately grounded in this system. One drawback is the potential for high circulating currents [14].

TN Grounding System: TN is further classified into three types: a. TN-S: In TN-S, a separate Protective Earth (PE) and Neutral (N) are used, providing a dedicated grounding path for protective purposes. b. TN-C: TN-C combines both the Protective Earth (PE) and Neutral (N) at the appliance side to form a PEN conductor, resulting in a cost-effective grounding system. c. TN-C-S: TN-C-S is a combination of both the TN-S and TN-C grounding systems, offering the advantages of both.

IT Grounding System: In the IT grounding system, the converter's neutral point is not grounded, and the appliance body is grounded separately.

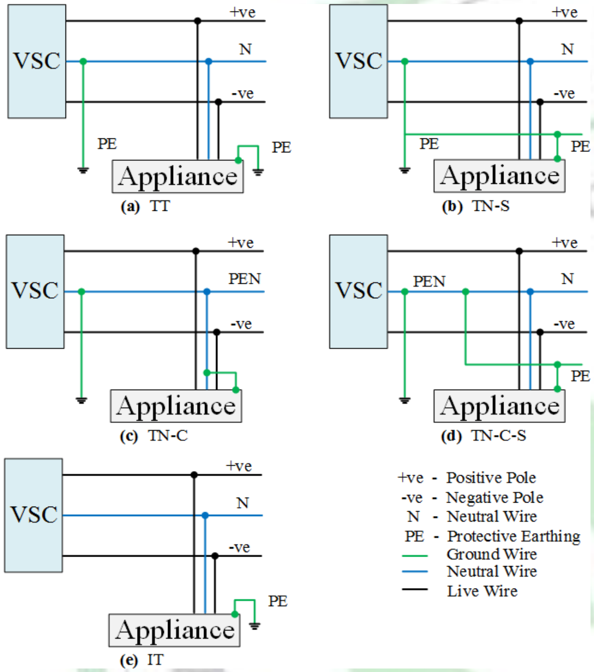


Fig. 2: Methods of Grounding

The choice of grounding system depends on factors such as safety requirements, cost considerations, and the specific needs of the DC microgrid application. Each grounding system has its advantages and limitations, and the selection should be made based on the overall objectives and safety considerations of the microgrid.

3. Challenges in DC Microgrid Protection

The main goal of proposing microgrids is to enhance reliability, but achieving this objective necessitates the implementation of proper protection systems. However, designing an appropriate protection method for microgrids presents challenges in two ways:

Dynamic Network: Microgrids are dynamic networks where Distributed Generation (DG) sources or loads can connect or disconnect at any time, leading to changing operating conditions that require flexible protection schemes.

Islanded and Grid-Connected Modes: Microgrids can operate in both islanded and grid-connected modes, resulting in variations in short-circuit levels. A comprehensive protection method is needed to ensure adequate protection in both modes.

Protecting DC microgrids using conventional methods can be challenging due to various factors, including the dynamic nature of Renewable Energy Sources (RES), fast converter response to fault transients, bidirectional power flow, and the presence of multiple and diverse resources.

4. Key challenges for DC microgrids include:

Bidirectional Power Flow: Unlike conventional radial power systems with unidirectional power flow, DC microgrids have multiple dynamic sources that change power flow and current direction, impacting Protective Devices (PDs) coordination.

Fault Current Limitation: Converter-interfaced DGs limit the maximum fault current to twice the rated output current, affecting fault detection schemes.

Change in Fault Current Level: Dual-mode operation in microgrids results in different short-circuit current levels between grid-connected and islanded modes.

Response of VSC (Voltage Source Converters): The low cable inductance in DC systems leads to rapid fault current rise, requiring a fast protection system to safeguard the system and converters.

High Impedance Fault: Detecting high impedance faults in DC systems is challenging as they resemble normal load changes, making it difficult to discriminate between the two.

Grounding: Proper grounding is crucial for accurate fault current detection during ground faults, as most fault detection methods rely on current magnitude.

Impact of CPL (Constant Power Load): In DC closed-loop, demanding constant power. During a fault, voltage drop leads to increased current consumption, exacerbating the fault current.

II PROTECTION OF DC MICROGRID

Despite extensive research to address these protection issues in DC microgrids, the lack of standards and experience in DCMG protection poses obstacles to its further development.

Continued research and collaboration are essential to develop effective protection schemes for DC microgrids, which will ultimately promote their widespread adoption and enhance the overall reliability of microgrid systems.

In this section, we will provide a comprehensive overview of protection coordination schemes and different fault detection protection schemes suitable for DC microgrids. Additionally, we will discuss various protection devices (PD) and their integration in the protection system.

Protection Coordination Schemes:

Protection coordination is crucial to ensure that the protective devices in the microgrid work together efficiently to detect and isolate faults while minimizing disruptions to the system.

Various protection coordination schemes, such as time coordination, current coordination, and directional coordination, can be employed to achieve selective fault isolation and maintain system stability.

Fault Detection Protection Schemes:

Different fault detection methods can be used to identify and locate faults in the DC microgrid promptly.

Some commonly used fault detection schemes include voltage-based methods, current-based methods, and impedance-based methods.

Advanced techniques like wavelet transforms, artificial intelligence, and pattern recognition can be applied to improve fault detection accuracy and reduce false alarms.

Protection Devices for DC Microgrid:

To protect the DC microgrid against faults and overcurrent conditions, various protection devices are used.

Circuit breakers, fuses, relays, and surge arresters are essential components integrated into the protection system.

Smart protective devices with communication capabilities allow for faster fault detection and coordination.

Integration of Protection Devices:

The integration of protection devices involves the proper arrangement and setting coordination to ensure the efficient functioning of the protection system.

Coordination between protective devices, such as upstream and downstream devices, is crucial to isolate faults without causing unnecessary tripping or disruption.

Suitability for DC Microgrid:

The protection coordination and fault detection schemes must be carefully selected and adapted to the unique characteristics of DC microgrids.

Consideration should be given to bidirectional power flow, dynamic changes in the network, converter response times, and the presence of various types of renewable energy sources and loads.

Challenges and Considerations:

Challenges in DC microgrid protection include bidirectional power flow coordination, fault current limitation in converter-interfaced DGs, change in short-circuit levels during grid-connected and islanded modes, and the rapid fault current rise due to low cable inductance.

High impedance fault detection and proper grounding are also critical aspects to address in the protection design.

The impact of Constant Power Loads (CPL) during fault conditions must be considered to prevent further escalation of fault currents.

Coordination DC Protection

To achieve reliable protection in DC microgrids, a comprehensive approach that considers the specific characteristics of the microgrid and the integration of appropriate protection devices and coordination schemes is essential. Continued research and development in this area will contribute to overcoming challenges and improving the overall protection of DC microgrid systems.

The protection process used to safeguard a DC microgrid involves several steps, as shown in the diagram:

Fault Detection: The protection system continuously monitors the microgrid for any abnormal conditions or faults. When a fault occurs, it must be swiftly detected and distinguished from transient events.

Fault Localization: Once a fault is detected, the protection system localizes the fault by identifying the unhealthy section(s) of the microgrid. This helps in isolating the faulty section(s) from the healthy ones to prevent the spread of the fault.

Fault Isolation: To protect the equipment and maintain system stability, fault isolation is crucial. The protection system utilizes fault limiting devices, such as fuses, power electronic switches, and circuit breakers, to promptly isolate the faulty section(s) from the rest of the microgrid.

Swift Response: The fault limiting devices act quickly to disconnect the faulted components from the rest of the system. This rapid response helps minimize the impact of the fault and reduces the chances of damage to equipment.

Backup Protection: To enhance the reliability of the system, backup protection can be implemented. Backup protection provides an additional layer of protection in case the primary protection fails to detect or isolate the fault. It serves as a redundancy to ensure a robust and reliable protection system.

Existing Protection Schemes in DCMG

The protection system's primary goal is to ensure the safe and stable operation of the DC microgrid by detecting and isolating faults promptly and accurately. The combination of fault detection, localization, isolation, and backup protection measures plays a crucial role in achieving this objective.

Fault Detection: The fault detection section in DC microgrid protection can be categorized into two major groups: direct measurement-based methods and signal processing-based methods [6]. When a short-circuit fault occurs in the system, it leads to an increase in current and a decrease in voltage. The magnitude and flow of fault current vary depending on the fault location.

a) Direct Measurement-Based Methods: These methods directly utilize the amplitude of parameters such as current (i), voltage (v), di/dt (rate of change of current), and d2i/dt2 (second derivative of current) to detect the fault. Since these methods directly use the parameters, they offer very high fault detection speed [3] [19]. Depending on the specific requirements, these methods may or may not utilize communication for their operation.

b) Signal Processing-Based Methods: This category includes techniques such as traveling wave analysis and wavelet analysis. Signal processing techniques are applied to process the captured data, and commands for fault detection are derived based on the processed signals. While these methods offer high accuracy, they may have drawbacks like high computational time and complexity in implementation [6].

The choice of fault detection method depends on factors such as detection speed, accuracy, complexity, and computational requirements. Direct measurement-based methods are faster due to their direct use of parameters, while signal processing-based methods offer higher accuracy but may require more computational resources. Proper consideration of these factors is essential to design an efficient and reliable fault detection system for the DC microgrid.

Fault Localization: After detecting a fault in the system, proper fault localization is crucial to minimize its impact and prevent healthy parts of the system from being affected. This section can be further divided into two parts: fault localization with communication-based methods and fault localization without communication-based methods.

a) Communication-Based Localization:

Communication-based fault localization methods involve data transfer between several relays or devices to achieve high accuracy in fault localization [20]. These methods rely on exchanging information and data from various points in the microgrid to pinpoint the fault location. While this approach can provide accurate results, it may suffer from time delays due to the communication process.

b) Without Communication-Based Localization: In without communication-based methods, fault localization is achieved without the need for extensive data exchange or communication. Instead, pre-selected threshold values of signals, such as fault voltage, current, and impedance, are used to trigger the trip command [21]. Different protection zones are defined with distinct operating times based on the amplitudes of fault parameters. When the fault values exceed the pre-defined thresholds, the corresponding protection zone is activated, and the faulted section is isolated.

The choice between communication-based and without communication-based localization methods depends on factors such as accuracy, time sensitivity, complexity, and availability of communication infrastructure. Communication-based methods can offer high accuracy but may be subject to time delays due to data exchange. On the other hand, without communication-based methods may be simpler to implement and may offer faster response times but could be less accurate in certain scenarios.

Efficient fault localization is crucial to ensure that faults are isolated promptly and only the affected sections are disconnected, thereby maintaining the reliability and stability of the DC microgrid.

Top of Form

In recent years, various protection methods have been developed and reported for safeguarding DC microgrids. These methods focus on fault detection and location, utilizing different parameters such as current, voltage, impedance, di/dt (rate of change of current), and wavelet transform. Here, we discuss some of the existing fault detection and location methods:

Current-Based Methods: Current-based fault detection methods involve monitoring the fault current magnitude and comparing it to predefined thresholds. When the fault current exceeds the set limit, it indicates the presence of a fault in the system.

Voltage-Based Methods: Voltage-based fault detection methods analyze the fault voltage magnitude to detect any abnormal conditions. Deviations from normal voltage levels signal the occurrence of a fault.

Impedance-Based Methods: Impedance-based fault detection methods utilize impedance measurements to identify fault locations and characteristics. Variations in impedance can indicate the presence and location of a fault.

di/dt-Based Methods: The rate of change of current (di/dt) is a useful parameter for detecting transient faults. Rapid changes in current levels indicate a fault condition.

Wavelet Transform Analysis: Wavelet transform is a powerful signal processing technique used for fault detection and location. It can effectively analyze the transient behavior of currents and voltages during faults.

Pattern Recognition Techniques: Pattern recognition methods use machine learning algorithms to analyze patterns in the data collected during fault conditions. These techniques can provide accurate fault detection and location results.

Hybrid Methods: Some protection schemes combine multiple parameters and techniques to create hybrid fault detection and location methods. These hybrid methods leverage the strengths of individual techniques to improve overall accuracy and reliability.

The choice of fault detection and location method depends on various factors, including system complexity, fault characteristics, computational resources, and accuracy requirements. Researchers continue to explore and improve these methods to enhance the protection capabilities of DC microgrids and ensure their reliable and safe operation.

Top of Form

The fault detection methods in DC microgrids can be categorized into direct measurement-based approaches. Several existing fault detection methods are discussed below:

Communication-Based Fault Detection: a. A communication-based approach is proposed in [25], utilizing the magnitude and direction of fault current and DC voltage. A sudden decrease in DC voltage during a fault is used as an indicator, and fault current direction aids in identifying the fault location. b. A hybrid passive overcurrent relay is proposed in [26], using an inductor and capacitor to generate a specific frequency under fault conditions. c. A communication-based fault detection method with a centralized protection coordinator is presented in [27], employing the principle of overcurrent relay with backup protection in case of communication failure. It also possesses a centralized self-healing property. d. In [28], a rate of change of current (di/dt) based scheme is proposed, optimizing di/dt computation during the fault by designing a Finite Impulse Response (FIR) filter and optimizing sampling frequency for faster fault detection. e. A current derivative approach is used in [3] to analyze the DC current profile under transients, helping to determine the direction of the fault location by considering the fault circuit up to the fault point. f. A non-unit protection scheme for DCMG is proposed in [19], using the first and second derivatives of fault current to identify and locate faults without communication.

Differential Protection-Based Methods: a. In [20], a current differential-based approach is given, and a trip decision is taken based on the measured current difference. b. A protection scheme based on differential protection strategy is presented in [29], and the amount of error in the proposed method is analyzed for different fault resistances. c. A communication-based differential protection scheme for remote area mine sites with DC circuit breakers is proposed in [30], utilizing line current differential protection as primary protection and overcurrent protection as backup.

Voltage Prediction-Based Protection: a. In [34], a voltage prediction-based protection technique is used, predicting voltage during a fault using a quadratic time function for fast fault detection. b. For high impedance fault detection, a communication-based approach is proposed in [35], using voltage and current transient measurements.

Event Classification Approach: a. A protection scheme based on event classification is proposed in [36], where local protection units classify current and voltage data and distribute the class of fault instead of transmitting actual data.

Impedance-Based Methods: a. In [33], impedance-based fault detection is presented, where impedance is calculated from voltage and current values, and a trip signal is generated based on the impedance value. b. In [38], an additional inductor is connected in series with the cable, and voltage across the inductor is observed for low resistance fault detection, while ground current measurement is used for high resistance fault detection.

Fault Location Based Approach: a. In [39], a fault location-based approach is proposed for cable fault analysis in VSC-based DC networks. An additional voltage sensor is used at each line segment, and voltage division is used to locate the fault.

These methods utilize various parameters and approaches to detect and locate faults in DC microgrids, catering to different fault types and scenarios. Continued research and development in fault detection techniques are essential to enhance the protection capabilities of DC microgrids.

Signal Processing-Based Methods: a. In [40], a protection scheme is proposed for detecting and locating faults in MVDC microgrids without the need for communication. This scheme utilizes the first and at least two subsequent Travelling Wave (TW) reflections for fault identification. The fault detection time for this scheme is only 128µs, and it offers accurate fault location independent of grid configuration. It is also sensitive to fault resistance up to 200Ω. b. An ultra-fast fault detection scheme for ±2.5KV TN-S grounded MVDC (Medium Voltage DC) is presented in [41]. This scheme focuses on polarity and waveshape properties of the first traveling wave (TW) rather than its arrival time, making it faster than earlier methods based on TW. Similar to the previous scheme, this method also doesn't require communication.

These signal processing-based methods leverage the properties of traveling waves to detect and locate faults in MVDC microgrids. They offer fast fault detection times and accurate fault location capabilities, making them suitable for medium voltage DC systems without the need for extensive communication infrastructure. The use of signal processing techniques enhances the fault detection performance and ensures a more reliable protection system for MVDC microgrids.

C. Protective Devices (PD) in DC Microgrid:

Fuses: Fuses are protective devices used in DC microgrids to protect the system from overcurrent and faults. They consist of a silver or copper wire connected in series with the power line. During a fault, the current increases, causing the fuse to heat up and melt, thus interrupting the circuit and protecting the system. There are two types of fuses: fast-acting fuses and time-delay fuses. In DC systems, the fusing time needs to be much faster, typically around 0.5 ms, due to the nature of DC faults. Properly selecting the fuse rating is crucial to avoid damage to the system. Researchers have provided guidelines for selecting the appropriate fuse rating for protecting DC to DC converters [47].

DC Circuit Breakers (DCCB): DC circuit breakers are used to isolate the system from faults and overcurrents. Mechanical circuit breakers have been suggested for DC systems but have relatively slower fault clearing times, ranging from 30 to 100 ms [50]. Solid State Circuit Breakers (SSCB) are a suitable solution for LVDC and MVDC systems. Vacuum circuit breakers and molded case circuit breakers (MCCB) have also been explored as options to limit and reduce DC fault currents [51]. A hybrid DCCB has been proposed in [52], consisting of a mechanical contactor, reactor (to limit the current), and converter, offering zero steady-state loss.

Switches: Switches such as MOSFET and IGBT are used in DC microgrids to rapidly isolate faults, typically within a few microseconds. MOSFETs are preferred for systems below 1200V, but they have higher voltage drops compared to other high-power devices [22]. IGBT switches are more suitable for high-power applications and are cost-effective [53][54]. However, IGBTs have the drawback of unidirectional current blocking, limiting their suitability for systems with bidirectional power flow. An alternative device, the IGCT (Integrated Gate Commutated Thyristor), has been proposed to overcome the drawbacks of IGBTs and is considered more suitable for MVDC systems [56]. Several protection schemes based on IGCT have been proposed and found to be successful in fault clearing [57][58].

The selection of appropriate protective devices depends on the specific requirements and characteristics of the DC microgrid, and a combination of these devices can ensure effective and reliable protection for the system. Continued research and development in protective devices are essential to enhance the safety and reliability of DC microgrids.

Conclusion

Indeed, the article provides valuable insights into the advantages of DC microgrid systems over AC systems, highlighting their increasing popularity and benefits in terms of efficiency, power density, and integration of renewable energy sources. The summary of the current state of the art in DC microgrid technology, including voltage levels, topologies, and grounding methods, helps readers grasp the current landscape of DC microgrids.

The discussion of key challenges in DC microgrid protection sheds light on the complexities involved in designing an effective protection scheme, considering dynamic network configurations and bidirectional power flow. Moreover, the review of various fault detection and localization schemes, along with protective devices such as fuses, circuit breakers, and switches, provides researchers with a comprehensive understanding of the available approaches.

However, as mentioned in the article, the lack of standardized protection methods and limited practical experience in DC microgrid protection pose obstacles to its widespread adoption. This creates an ample opportunity for researchers to work in this area, developing innovative solutions and standardized protection strategies for DC microgrids.

Overall, the article serves as a valuable reference for researchers and practitioners, highlighting the potential of DC microgrid systems, their protection challenges, and the scope for further advancements in this promising field. As technology evolves and research progresses, it is likely that DC microgrids will continue to gain prominence, contributing to a more efficient, reliable, and sustainable energy future.

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