A COMPREHENSIVE REVIEW OF DC MICROGRID PROTECTION TECHNIQUES

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Abstract - *Due to the possible usage of photovoltaic (PV), wind, and battery-based energy sources, microgrids have become popular in industry and research. Both academic institutions and private businesses have paid a considerable amount of attention to DC microgrids during the last decade. In terms of dependability, control simplicity, integration of renewable energy sources,efficiency and connectivity of dc loads, DC microgrids have shown themselves to be superior than AC microgrids. In spite of these many benefits, developing and deploying a suitable protection system for DC microgrids continues to be a considerable issue. Even though there aren't any usual zero crossings, the issue is brought on by the sudden spike in dc fault current that needs to be put out. If this isn't done, prolonged arcs might result. In this article, the difficulties associated with DC microgrid protection are studied from a variety of perspectives. These viewpoints cover the features of dc fault currents, ground systems, fault detection methods, protective device approaches, and fault localization methods. An in-depth analysis has been performed on each individual section of this report. In conclusion, a short discussion is provided on emerging tendencies in the field of DC microgrid protection.*

KEYWORDS : DC Microgrid Protection , Renewable energy sources , DC converter , DC Faults , Grounding.

I. INTRODUCTION:

There is a growing body of evidence indicating that direct current (DC) systems are superior than rival alternating current (AC) systems in terms of efficiency, complexity, power transfer ratio, and overall cost [1, 2]. The majority of loads, including electric vehicles (EVs) and light-emitting diode (LED) lights, are made to operate on DC power, and many Distributed Energy Resource (DER) systems, including photovoltaic (PV), fuel cells, and battery energy storage, also operate on DC power. As a result, DC systems make the most sense at the point of use. DC systems also make economic sense.

The power quality implications that DC systems have on public utility networks is another another benefit of using DC systems. Because such systems, Will only connect through a single point of interface, if there is any AC interface at all [1,] the management of reactive power flow and frequency control may be accomplished at a lower cost and with a reduced risk.The use of multiterminal High Voltage DC (HVDC) distribution systems to incorporate renewable energy sources into electrical utility grids in Europe and China [3], [4], the application of mobile transportation systems with integrated power and energy management to ships, aircraft, and vehicles [5], [6], and the electrification of remote areas through local DC microgrids that incorporate solar energy and battery energy storage into community and home electrification. [3] [4] Distributed energy resources (DERs) and local loads can be easily incorporated into mobile transportation systems with integrated power and DC microgrids that have at least one point of interface to the AC electrical grid using a bidirectional AC - to - DC converter. A smart grid is another name for this kind of microgrid.All of the instances shown above might be classified either as a DC microgrid in the traditional sense (one that is connected to the grid) or as an islanded DC microgrid (i.e., for transportation systems).The design of an adequate protection system for DC microgrids has been and continues to be a considerable issue over the last 10 years, despite the various benefits that come with doing so. The difficulty is caused by dc fault current's features, which include the absence of a zero crossing point that naturally arises and the ability to abruptly surge to more than a hundred times the nominal current during sudden fault initiation [9], [10]. (which is the main mechanism that AC electromechanical circuit breakers rely on to put an end to arcs and finally isolate faults.) An suitable grounding design, a fault detection strategy that is quick and effective, a fault current limiting mechanism, and an appropriate DC circuit breaker are required to get around the challenges that come with DC microgrid protection. Grid reliability, leakage current reduction, ground fault detection, and the safety of workers and equipment during fault conditions are all impacted by grounding in DC microgrids.. A safe, fault ride-through, and easy-to-detect grounding system must be presented [11]. To avoid equipment damage, the fault must be diagnosed and found quickly and accurately due to DC fault current characteristics. The rapid shift of unexpected dc fault current initiation makes protective relay coordination problematic [10], [12].There are five fault detection techniques that have been presented: directed overcurrent, overcurrent, current derivative,distance-based and differential. DC microgrids have lower line resistance and reactance than AC systems, making fault location techniques, including passive and active approaches, significantly more difficult. A defect detection/location technique must balance cost, computing load, simplicity, and performance. A suitable DC circuit breaker (DCCB) isolates the problem and returns the DC microgrid to safe functioning. The issue is completely air-gapped or galvanically isolated from the system. For dc fault current characteristics, DCCBs must have a quick response time,high reliability, galvanic isolation, low cost, low conduction loss and extended lifespan [9],[13]. DCCBs must be built to meet expectations or selected from devices that are already on the market.

This paper defines fault as a short-circuit from, across two lines, any line to ground, or as two lines to ground anyplace in the system. Any practical fault protection strategy must handle the sudden-inception short-circuit problem to reduce equipment damage. Section 2 analyses DC fault current to emphasise the need of quick fault identification, localization, and isolation. Section 3 compares dc microgrid grounding solutions for stray current, fault detection , common mode voltage, and ride through. Section 4 reviews overcurrent, directed overcurrent, current derivative, differential, and distance fault detection techniques. Discussing each protection method's pros and cons. Section 5 compares fuses, mechanical DCCB, solid-state DCCB, hybrid DCCB, and Zsource DCCB for cost, reaction time, and losses. Finally, Section 6 discusses local measurement, Traveling Wave (TW), injection-based fault finding techniques and differential.

II. DC FAULT ANALYSIS:

Numerous topological topologies, including zonal , multi-terminal and DC looping, are used to group DC microgrids.The application, degree of dependability, and voltage level are the three primary considerations that should guide one's selection about the architecture of a DC microgrid [14]. For instance, the United States Navy places a strong emphasis on the development of zonal DC microgrids in order to establish a shipboard system with high power density, high survivability, and low implementation cost [15]. Two different types of DC bus architectures exist, regardless of the various topological configurations that can be found in DC microgrids (Fig.1). These are the unipolar DC bus topology, which makes use of two-level Voltage Source Converters (VSCs), and the bipolar bus topology, which makes use of three-level neutral-pointclamped VSCs. The unipolar DC bus topology has several benefits, but the bipolar DC bus topology offers some advantages that are more advantageous than the unipolar DC bus architecture. These advantages include better reliability, larger power capacity, and flexibility in the connections between loads and DGs [16].

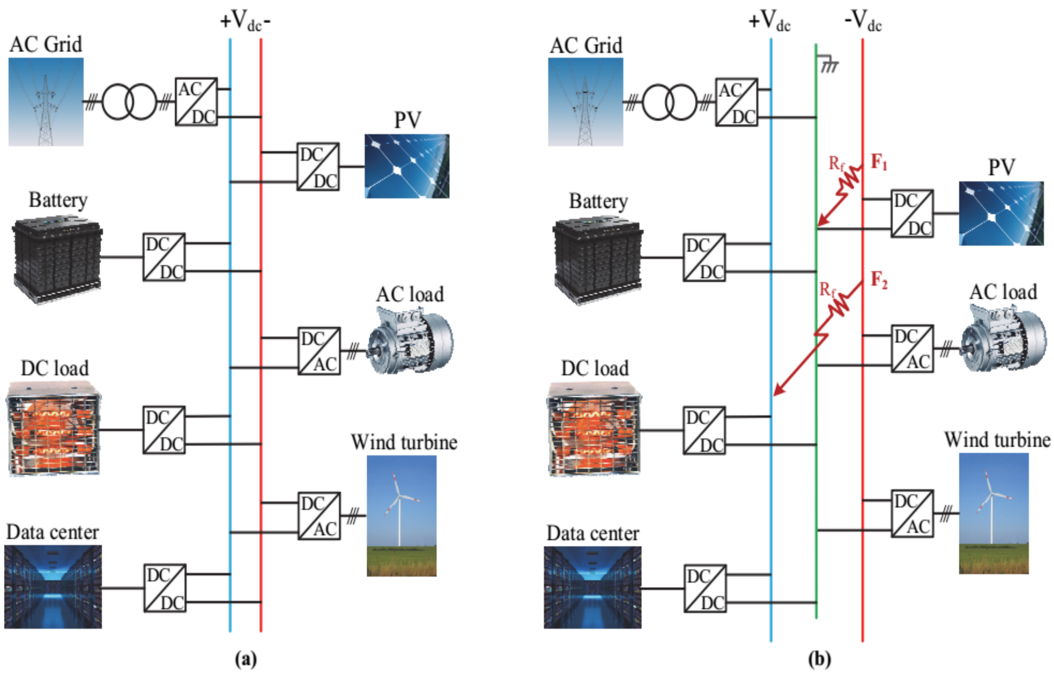

Fig. 1*:* Schematic Diagram of DC Microgrid architectures.

Fig.1. (a) DC bus (Unipolar architecture). **Fig .1. (b)** Bipolar DC bus architecture.

The use of two-cascaded rectifiers on the DC side is one of the topologies that makes the construction of a bipolar DC microgrid one of the simplest. A transformer with twin secondary windings is necessary since the series connection has the potential to cause a DC voltage offset. This may be avoided by using a transformer with this feature. This might result in an increase in both size and expense. Other one-converter based topologies, like VSC with a neutral line connected to DC mid-point and NPC converter, have addressed this issue. When a neutral line is linked to the DC midway, the transformer may become saturated in a VSC due to the DC component of the current [17].However, there is no guarantee that the DC voltage will be balanced under any of the potential operating conditions for the NPC converter due to an inherent problem with voltage balancing [18].The DC bus voltage has to be stabilised by a voltage balancer that has been thoughtfully developed in order to address the problem of voltage imbalance that occurs in any of these two setups. Regardless of the DC microgrid's configuration, the DC failure could occur in the DC bus or the DC cables that connect the various microgrid components. A single point of energy interface between distributed generators (DGs), energy storage systems (ESSs), and loads is what a DC bus and DC interconnections are intended to do.This is because the purpose of a DC microgrid is to make the microgrid as simple as possible. DGs, ESSs, and loads may all be concurrently impacted by a flaw in a DC bus or DC cable connection, which could result in an increase in the fault current. From the standpoint of protection, this is a drawback because it makes it more challenging to pinpoint the issue's origin. Therefore, even a single breakdown anywhere in the protective system could have disastrous consequences if the protective system design is flawed.

A. features of DC faults:

The voltage source converter (VSC), which interfaces with the direct current (DC) side through a capacitor (C) and the alternating current (AC) side through an inductor (Lac), is used in the microgrid. Due to the design of the VSC, when a fault is applied, the DC side capacitor discharges first via the DC network, and the later part of the response is formed by the contribution of the fault current from the converter interfaced sources.This happens while the fault is being applied. The discharge of the capacitor will result in a large current amplitude, which has the potential to cause damage to the VSC components as well as any other components that are in series with the fault. The high peak fault current must *be* considered during all design processes for the system and its components if fault current ride-through is a protective approach component [19]. A fast protection device is needed to stop damage from happening if, on the other hand, the same "breaker-based" protective paradigm used in AC systems is applied to DC systems, where the protective devices mitigate faults and, as a result, eliminate the unmitigated fault current characteristics from the operational scenarios of the connected component.In order to comprehend and study the DC fault characteristics, the nonlinear system is handled by identifying three distinct stages. These stages are the grid-side current feeding stage, the capacitor discharge stage, and the diode free wheel stage.

B. DC-DC Converters Fault Characteristics:

As was said earlier, DC microgrids are made up of power electronic DC-DC converters that are located at the point of source and load. Between DC supplies and loads, these converters act as a bridge. Similar to VSCs, these DCDC converters are prone to malfunctions brought on by DC system defects. Due to capacitor discharge via uncontrolled pathways when the fault occurs, the short-circuit fault current has the potential to grow to 15 times the level of the nominal steady-state current. This was previously described. For instance, in certain converter and converter connection topologies, fault conditions can force diodes to commutate to the on-state, forcing the fault current through the converter in such a way that the fault current is forced through the converter in such a way that the fault current is forced through the converter in such a way that the fault current is forced through the converter in such a way that the fault current cannot be interrupted by any mechanism that is inherent to the converter topology [21], [22]. Because semiconductor switches have a minimal capacity to endure short circuits, this phenomena may be damaging to the performance of these components. Therefore, quick fault identification and the stoppage of fault current are necessary internally to the DC-DC converters in order to avoid failures that are caused by short circuits [23], [24].

Cost constraints might preclude such a strategy, in which case the exterior protective system must be designed to minimise any occurrence that might result in internal converter damage, such as by strategically putting fast-acting fuses or DCCBs in all current-carrying ports. Some DC-DC converters have short-circuit fault immunity due to their construction. In typical buck-boost or multistage buck-boost converters with an inductor at the output, short-circuit current is limited to the maximum inductor current since inductor current cannot vary rapidly [30]. Impedance source-based DCDC converters may also give a buck-boost feature and resist open- and short-circuit defects. Z-source and quasi-Z-source DC-DC converters [31] and Magnetically Coupled Impedance Source (MCIS) converters [32] may be utilised for moderate voltage gain and high voltage conversion ratio, respectively. certain sources of impedance DC-DC converters' major downside is significant step-up voltage stress on the switches. Conduction losses from high voltage semiconductor switches with considerable resistance reduce efficiency. The vast majority of isolated DC-DC converters have a buck characteristic,limiting output current in short-circuit faults. Modular multilevel converters (MMC) with various submodules may be used for high-power microgrid applications. VSC's fault-tolerance, low component count, and affordability make it a viable choice for non-isolated systems. However, most isolated DC-DC converters have a buck characteristic, limiting output current in short-circuit faults. In case of output short-circuit, full-bridge and DAB may restrict cell current. MMC fullbridge and DAB converters manage submodule capacitor current during faults, distinguishing them from conventional current limiting converters. Thus, capacitor discharge no longer causes faults. If the converter is working, abrupt short-circuit fault initiation will not harm any system components.

III. DC FAULT DETECTION METHODS:

Very low line impedance is characteristic of the DC microgrid. As a direct consequence of this, the fault current deviation is very large, and The fault current does not take many milliseconds to reach hundreds of amps. As a consequence of this, the sensors need to have high sample rates as well as high speeds, and the communication system has to be very quick as well as dependable. When it comes to the sensors, communication, and control systems that have been deployed, protection techniques need to be able to detect in a quick, reliable, and accurate way. As of right now, there are a few different DC protection techniques that have been presented to detect and identify the problematic section. These techniques include differential protection, directional overcurrent protection, distance protection, overcurrent protection, and current derivative protection.

The effectiveness of these DC protection strategies may be judged according to the following primary characteristics [23]:

- Swiftness: In order to avoid the machinery from being destroyed, the protection system has to be able to locate the problem as quickly as possible.
- Selectivity is required, and the protection technique should be able to detect the problematic region. And the protection should not be activated in the case of the external malfunction.
- Sensitivity implies that the faults, particularly high-impedance faults, must be detected by the protection system.
- Reliability requires that, in the event that the main protection or communication systems fail to function, the secondary protection system must be able to isolate the malfunctioning area.

A. Overcurrent Protection:

A threshold, much like the one used in the conventional AC overcurrent protection, is evaluated in order to establish whether or not a problem has occurred. The established Overcurrent Relays (OCRs) must be properly coordinated in addition to performing fault detection. Consider the time-current curves (TCCs) of an upstream OCR and a downstream OCR that have been installed in a dc microgrid as an example. These curves are made up of overload and instantaneous features.. After a certain amount of elapsed time has passed, if the currents that were detected by OCR1 or OCR2 are over their respective thresholds Io1 and Io2, A tripping signal will be transmitted to the relevant CB. It is crucial to remember that the downstream OCR's TCC must be lower than the upstream OCR's TCC by a sufficient amount in order to retain selectivity. Additionally, the ultrafast downstream PD turning-OFF speed has the ability to reduce or possibly completely eliminate the amount of mistrips brought on by upstream PDs. For a DC microgrid, where the rectifiers can limit the fault current, overcurrent prevention was devised [18], [40]. However, the application of such a protection technique on more complex DC microgrid topologies may lead to either longer fault clearing durations or the disconnection of larger networks than technically necessary in the event of a crisis.In addition, when it comes to a compact dc microgrid, there is not much of a time gap between the upstream and the downstream protection operation. In this kind of scenario, the upstream OCR may work more quickly than the downstream OCR.

One solution to the problem of poor selectivity is to utilise a communication connection between the overcurrent relays. This link, which is based on the IEC 61850 protocol's standard message, provides selectivity and isolates only the problematic components [41].In the paper [42], the authors present a framework based on the combination of overcurrent protection and unit-based protection, which has high sensitivity, selectivitynand speed, in order to have a quick and efficient operation and to lower the costs of installation.Overcurrent protection has a number of drawbacks, one of which is that it has a poor sensitivity for high-impedance faults. In the paper [43], Each pole gets a parallel LC filter added. so that it may have resonance at a certain frequency even when the system is operating incorrectly. After that, a discrete wavelet transform, also known as a DWT, is used in order to extract this frequency for the purpose of defect detection.

B. Current Derivative Protection:

As soon as the error occurs, the value of the current derivative shoots up from zero to a very high level. One potential use for this function is to pinpoint an issue in a very short amount of time. Nevertheless, the magnitude of the current derivative is dependent on the length of the cable, the line loading, and the fault impedance. Because of this, it is very challenging to identify an appropriate threshold, and any threshold that is identified must be modified to account for the specifics of each operating environment.The first and second orders of the current's Derivatives are taken into amount to discover the low and high fault impedance fault in order to solve this problem [44].Additionally, while working ,sensors need to have a high sampling rate in order to reliably detect the current derivative. When using high sampling rates, noise will be amplified, and the possibility of false trips will increase. In order to find a solution to this problem, an effective filtering strategy will need to not only have a short time delay, but also a strong capacity for odour cancellation.

C. Directional Overcurrent Protection:

It is possible for either side of a sophisticated meshed DC microgrid to be the direction from which current flows. Concerning this matter, the implementation of directed overcurrent protection might result in an improvement in selectivity.A DC microgrid with an existing communication infrastructure has recently been recommended to use directed overcurrent prevention [45], [46]. The suggested strategy claims that once the fault has happened, the fault current's size and direction would change. The communication system is then used to identify the direction of each branch, which will help in identifying the damaged line.

D. Distance Protection:

The impedance that can be measured from the point of measurement (POM) all the way to the problem spot is the basis for the operation of distance protection. If the measured impedance is found to be within a predetermined range, a tripping signal will be delivered to the corresponding CB after a predetermined period of delay time to achieve the necessary level of protection selectivity. If you want to have a rapid distance protection system, there is no need to use a technique that takes a lot of time to properly pinpoint the problematic spot. Instead, a rough calculation of the impedance will be sufficient for making the choice about whether or not to use the relay. Voltage at a closed point, current, and the POM are all measured in [20]. Iterative computation and circuit analysis are then used to calculate the fault distance. Although this method includes a single additional iteration to improve distance accuracy, When the fault resistance is strong, the calculated distance error rises. This is because the fault resistance causes the distance to be calculated more inaccurately. Measuring the resistance from a PD to the problematic point is another way that may be used. This method has a number of advantages, including a low weight of computing and the need of merely inexpensive sensors and filters [47]. After a sufficient amount of time has passed, the value of the line inductance is insignificant due to the fact that it has a large value at high frequency. Because of this, the calculation of the resistance takes place after 10–20 milliseconds, which is a considerable amount of time. This approach also has a poor performance to find faults when dealing with short cable sections that have high impedance defects, which is another of its many drawbacks.

E. Differential Protection:

The differential relay uses a current transducer to measure just the current amplitude on both sides of a certain element. It then uses the value of the current difference to determine whether or not a fault has occurred. In reference number 49, a fault response of converter-interfaced DC systems is analysed to investigate the influence that transient system behaviour, such as poor synchronisation for the high change rate of a faulty condition, has on the operation of differential protection schemes. This study was carried out in order to discover how transient system behaviour can affect the operation of differential protection schemes. The criteria for accurate and quick defect detection are then quantified as a result of this investigation. Finally, in order to accomplish high-speed differential protection, a central processing device that is intended to take use of the inherent features of DC differential current measurements has been developed. A Medium Voltage DC (MVDC) microgrid with various distributed energy sources, such as solar arrays, wind turbines, a fuel cell stack, an energy storage system, and mobile generators, is given significant protection in paper 50. The suggested protection schemes for distribution lines include communication-based differential protection with a solid-state switch, backup DC overcurrent protection for lines, and communication-based DC directional overcurrent protection devices for source and load protection to support bidirectional power flow. These safety features are all intended to guarantee that power can move both ways.

The comparison of commonly used protective devices for imparting reliable protection to the DC Microgrid is illustrated in Table I.

TABLE I: COMMONLY USED PROTECTIVE DEVICES FOR DC MICROGRID PROTECTION

Protective Device	***Disadvantages***	***Advantages***
Fuse	• Unable to distinguish between a temporary and permanent	• Low cost
	Fault	• Simple structure
	• A new fuse must be installed for the operation to be successful.	
Mechanical circuit breaker	• Long operating time (30-100 ms)	• Relatively low cost
	• Limited interruption current capability	• little power loss
Solid state circuit breaker	• Expensive	• Fastest response time (<100μs)
	• High power loss	• Very long interruption lifetime
	• Big due to heatsink needed	
Hybrid circuit breaker	• really pricey	• Low power loss
		• mechanical contacts, no arcs
		• Fast response time (Few ms)
Z-source circuit breaker	• To enable ZSCB activation, a significant transient fault is necessary..	• Natural commutation for critical fault
	• ZSCB could not provide prolonged protection	• Lower cost than SSCBs

IV. CONCLUSION AND FUTURE TRENDS:

Given the unique properties of DC microgrids in the event of faults, a reliable protection mechanism is essential. Grounding , Grid topology, and interactions amongst interconnected converters during fault occurrences are all systemic factors that must be taken into account during system design. The fault current characteristic compounds the difficulties, since the power electronic converters wired into the system and the connections connecting them have a significant influence on how it behaves. The DC microgrid cannot be simply imposed over an existing protective infrastructure, contrary to popular belief, because it has more operational advantages and prospective benefits than the AC microgrid.The design of a DC microgrid must include protection measures. Even though this seems like a drawback, if DC microgrid protection is a crucial aspect of the DC microgrid system design, then it's possible that the right solutions will be found that will allow the DC microgrid to be used in even more scenarios. While discussing the challenges of safeguarding AC microgrids was out of the scope of this paper, it may be possible to eventually create DC systems that are more resilient if the current limiting capabilities of the interconnected power electronic converters that make up the DC microgrids are properly utilised. This study studies the DC fault current in three phases, the capacitor discharge stage, the freewheeling diodes stage, and the grid-side current feeding stage in order to better understand the difficulties involved with DC microgrid protection. Furthermore, both isolated and non-isolated DC-DC converter topologies have had their behaviours studied. Other DC-DC converter types, such as buck, DAB converters and full-bridge have the capacity to restrict the current in the event of a malfunction. While boost converters do not. DAB converters , which providde the bidirectional power flow necessary for future distributed applications and have the electrical isolation and current limiting capacity essential to the electric system, may prove to be a popular choice in DC microgrids. To build a fault tolerant DC-DC converter that can handle the current demands of a DC microgrid, engineers must take into account a number of factors, including power density, efficiency, fault current limitation, redundancy, and cost. A variety of techniques for finding, isolating, and identifying faults are discussed in this work. There are five primary DC fault detection methods: directed overcurrent protection ,overcurrent protection, distance detection current derivative protection, differential protection. Both the benefits and drawbacks of each approach are worth considering. Most of the approaches described are used for grounded, radial, DC systems with low fault impedance. However, a multi-looped ungrounded DC microgrid makes it difficult to identify a high impedance problem, as an example Determining the issue and coordinating the relays in a DC microgrid hence requires the development of a novel fault detection and the communication system , coordination mechanism that is independent of sensor inaccuracy, or even communication latency.

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