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# Fault Management in DC Microgrids: A Review of Challenges, Countermeasures, and Future Research Trends

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**ABSTRACT** The significant benefits of DC microgrids have instigated extensive efforts to be an alternative network as compared to conventional AC power networks. Although their deployment is ever-growing, multiple challenges still occurred for the protection of DC microgrids to efficiently design, control, and operate the system for the islanded mode and grid-tied mode. Therefore, there are extensive research activities underway to tackle these issues. The challenge arises from the sudden exponential increase in DC fault current, which must be extinguished in the absence of the naturally occurring zero crossings, potentially leading to sustained arcs. This paper presents cut-age and state-of-the-art issues concerning the fault management of DC microgrids. It provides an account of research in areas related to fault management of DC microgrids, including fault detection, location, identification, isolation, and reconfiguration. In each area, a comprehensive review has been carried out to identify the fault management of DC microgrids. Finally, future trends and challenges regarding fault management in DC microgrids are also discussed.

**INDEX TERMS** Artificial intelligence, Machine learning technique, DC microgrid, DC shipboard power system, Fault detection, Fault isolation, Fault protection, Fault reconfiguration, Fault location, Signal processing.

## I. INTRODUCTION

The abysmal condition of climate change and the extra-ordinary carbon emission deadline set by the European Union (EU) is planned to minimized carbon emission to about 80% to 90% by 2050 using renewable energy and smart power utilization [1]. In order to enhance future energy sustainability and lower the dependence on the usage of fossil fuels recent research focused on replacing the traditional resources with renewable energy sources (RES) and efficient power management by deploying microgrids. Microgrids (MGs) are localized/decentralized grouping of distributed energy resources (DERs) constituted of one or a combination of units connected to nearby consumers. These units consist of generators; and renewable resources (e.g., wind turbine, PV, tidal power, fuel cells, combined heat and power (CHP), biogas plants, hydropower units, geothermal heat, and biomass energy) that can operate in two operating modes autonomously (standalone mode) or in grid-connected mode [2]. Although, these MGs are commonly categorized into AC, DC, and hybrid (AC-DC) systems; yet the AC-DC MGs are considered to be a promising topology for future grids integration [3], [4]. Besides this, by 2030 approximately 27% usage of renewable energy will result in the evolution of green energy utilization [5]. A DC MG can't solely improve the potency of the DC network by reducing the quantity of power electronic converters (PEC) from DC-based DERs and energy storage systems (ESSs). However, it additionally gives effective transmission capability and power quality compared to AC MGs [6]. In addition, the structure of a DC microgrid is configured so that it does not require synchronization and control of reactive power [7]–[9]. The real-time implementation of DC MGs is getting more attraction because of multiple benefits over AC microgrids like less power conversion stages and the capability of transmitting more DC power through a given cable. Independency of synchronization methods, not only struggle from frequency drifts [10], but also less conversion stage makes the DC systems have less line loss [11], [12] and support with less interfacing power electronics equipment [13] to simplify the system control complexity and unnecessary power conversion stages. Therefore, DC MGs are usually recommended for a distribution system impaled by PEC. Furthermore, a DC MG is preferable as compared to the AC MG due to system reliability, uninterruptable power supply system, better system stability, and better efficiency due to the disappearance of reactive power.

Fig. 1 presents a schematic perspective of DC MGs systems [14]. The DC bus is used as the primary support, which allocates the power supply to the utilities as well as to the households. Other energy resources such as photovoltaics, fuel cells, batteries, wind turbines (WTs), etc., are connected to DC MG for enhancing the delivered power. A buck and boost power converters have been utilized in this system to step up or step down the DC voltage to achieve an appropriate level.

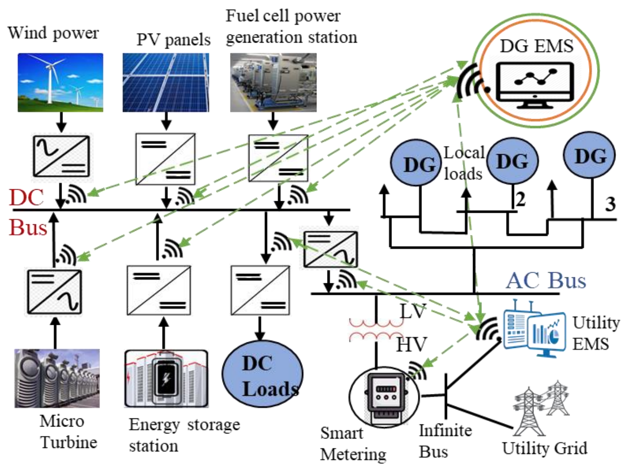


**FIGURE 1. A generic structure of DC microgrids**

In order to handle any faulty condition in the DC power system, the protection of DC MGs can be categorized into three phases: fault detection, fault isolation, and fault reconfiguration. Fig. 2 depicts the existing and emerging methods for fault management (FM). Fault management of DC MGs is essential to understand the system behavior to support the grid stability and fast recovery under various fault conditions such as rapidly rising fault current, arcing, and no natural occurrence of zero-crossing [15], [16]. In order to deal with the challenges for FM of DC MGs, some procedures such as installing protection devices, appropriate grounding, fast fault detection strategies, fault identification method, and proper direct current circuit breakers (DC CBs) are required.

The DC power systems are already utilized in different applications such as telecom data centers and vehicular power systems [17],[18]. The amplification of RES with more enhanced renewable energy storage systems (RESs), electric vehicles and electrical load, acquires power have contributed to the development of the concept of DC MG implementation in residential and commercial applications as well. As a result, developing the DC grid architectures, as well as essential power electronics and protection devices became the recent focus of researchers. In-spite the fact of their plentiful advantages (such as-curtail/minimized power conversion steps, minimum losses, economic, higher energy potency and so forth [19]), the development of economically effective and reliable protection techniques for DC systems with bi-directional power flow is still an important factor for DC MGs implementations. Resultantly, the protection standards and guidelines that can be acceptable to commercial and industrial applications have still not been designated [20]. Some practical standards are developed and designed respectively for the DC power systems and low voltage (LV) DC distribution systems such as European standards ETSI EN 300 132-3-1 [21], IEEE Standards-946 [22], for telecommunication data center and the auxiliary DC power systems. However, these standards have not accepted the long-term high magnitude fault current and the substantial changing rate of fault currents in DC power systems for fault detection and isolation.

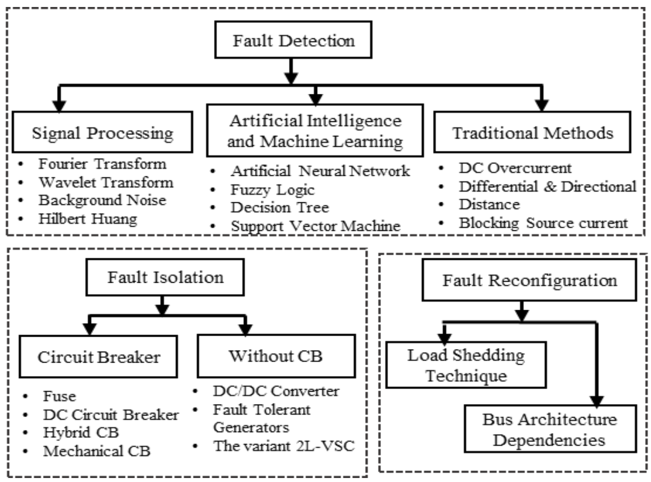


**FIGURE 2. A framework of fault management in DC Microgrid systems**

The main purpose of DC MG protection is to respond to the faults in two operation modes. When the operating mode is grid-connected and the fault occurrence is on the grid side, so the protection of DC MGs must identify the fault, switch the operation mode to islanded and continue power supply to the associated loads. During the system's fault, protection of DC MGs is quite important by detecting, isolating, and reconfiguring the fault [23]. In [11], the protection of DC MGs is accounted with a focus on the influence of the chosen protection devices and grounding technique on LVDC microgrid systems. This method shows that it’s doable to use out the available devices to shield such a system. The issues may arise with high impedance ground faults which may be tough to detect. The high impedance ground fault detection is the main problem for DC MGs protection [24]; for this purpose, the power converter fault current with the DC link capacitor voltage is used to ensure reliable operation [25]. In [26], the zone base DC MGs consist of intelligent electronic devices (IEDs), mainly capable of detecting fault current in a DC bus-segment to avoid system shutdown by isolating the faulty segment. The arc model for fault protection in LVDC MGs is also presented in [27]. In this study, the model is developed from the observed current patterns and arc voltage, allowing the arc voltage to be analyzed in terms of its stability, resistance, and extinguishing conditions to simplify the series fault issue in DC MG.

The protection of DC MGs utilizes various types of overcurrent relay and circuit breakers (CB); the overcurrent relay can produce a current peak of twice the nominal converter's capacity, which according to some researches reaches within milliseconds [28]. The DC capacitor is also able to discharge as a result of any fault detected in the microgrid as depicted by previous literature [29]. Hence, the DC MGs can protect the circuit by detecting the fault before reaching the current limit [12]. Though, to limit the short circuit fault interruption time, DC systems use different protective devices such as Solid-State Circuit Breaker (SSCB), Hybrid Circuit Breaker (HCB), fuse and semiconductor switches such as Insulated Gate Bipolar Transistor (IGBT) and Insulated Gate Commutated Thyristors (IGCT), which can meet the strict time limits. For a reliable operation of DC systems, fast detection and isolation of fault is crucial [28],[30].

The major challenges for fault protection of DC MGs can be elaborated as:

- Challenge due to the system blackout and grounding
- Difficulties in detecting and pointing out the fault location in case of lack of frequency and phase information
- Unintentional islanding and meager-adequate standard in the DC MG protection
- Protection integration issues due to various modes of operation and the disruptive nature of RES
- Increase number-of voltage source convertors (VSCs) and circuit breakers
- Arcing and fault clearing time
- Signal processing and communication delay as well as circuit breaker tripping
- Absence of natural zero crossing
- Power quality issues and cybersecurity of network communication

In order to address the above-mentioned challenges of DC MGs, effective solutions like proper grounding [31], fast and efficient fault detection strategies [32], fault classification [33], current limiting and ease of fault location [34], and a proper DCCB are essential [35]. Grounding in DC MGs is related to various system considerations such as design purpose, grid reliability under normal circumstances, minimize leakage current [24], ground fault identification [24], and maximize the equipment safety under fault conditions [36]. Given that, a novel current grounding method has to be introduced which could emphasize the fault detection capability of the DC system [24]. Based on the current features pertaining to the DC faults, an appropriate and reliable method is the need of the hour to maintain stability and to restrain any damage to equipment. The coordination between protective relays is stringent, in light of a sudden change in DC fault current [31],[32]. For the protection of DC MGs, five main classes of fault detection methods including overcurrent, current derivative, differential current based unit protection, and distance estimation-based methods have been proposed [27]. The fault protection of DC MGs is presented in [25], [26]. In response to a sudden change in DC fault, this study discusses the model-based fault detection, isolation and, controller reconfiguration in detail. For fault detection and isolation, it discusses various model-based schemes to generate the residuals that are robust to unknown disturbance, noise, model uncertainties and various statistical techniques of testing of rapid change in fault current.

Recently, DC fault protection adopts machine learning principles (ML) and Digital Signal Processing (DSP) techniques for event recognition in DC power systems [33], [35]. The wavelet transforms (WT) and short-time Fourier transform (STFT) are amongst-the commonly utilized DSP techniques for frequency as well as time-domain analysis. The STFT systems are limited by the time-frequency resolution. Short windows are used to detect low frequencies while high frequencies are hardly managed in time with a long data window [33]. As opposed to that, the time-frequency resolution breaking down is one of the salient features of WT, which makes it a viable choice to detect DC faults. Fault classification and event recognition are widely used based on the principles applied by WT [33]–[35].

However, WT is susceptible to disturbances and noise production in the DC network. The ML models, among which support vector machines (SVM), Artificial Neural Networks (ANN), decision-tree (D-Tree), and Deep Neural Networks (DNN) are extensively suggested by literature for fault detection in DC power systems [36]–[38]. ML offers the most efficient detection of the DC failures to date, which is unharmed by any other DC network disturbances. Recent literature has also supported the use of various ML principles mentioned above [39]. Another evidence also presented the utilization of ANNs in the DC power system failures [40], [41]. The above-mentioned fault detection methods have resulted in longer detection times and complex ANN configurations.

The fault isolation is accomplished by creating the appropriate DC CB to bring the DC MG to a stable operating mode. Fault isolation mainly includes circuit breaker-based methods and converter based methods by concerning the short-circuit current features. The DC CB must have these main key characteristics like a quick response, high reliability, and low conduction loss [28],[42]. According to the requirement such as long lifetime, economic, and reliability, DC CBs must be selected from the available protective devices. The fault reconfiguration in DC MGs comes after the faults being detected and isolated to recover the resiliency of the system. Fault reconfiguration can respond and detect the occurrence of short-circuit to ensure the safe, satisfactory, and reliable operation of DC power systems. Load shedding methods are efficient in fault reconfiguration after system failure [43], and DC bus reliabilities make them the best option to adopt [44],[45].

The aim of this paper is to provide a comprehensive review of fault management in DC MGs, including cutting-edge prospects and future challenges. In recent years, with the fast increase in the global demand for energy, DC and hybrid MGs are attracting much attention. The authors in [46]–[49]; have summarized the protection challenges and issues in DC MGs, while the authors in [50],[51] have addressed the challenges of DC fault protection and reconfiguration issues. Moreover, the structure and operational protection challenges of DC and Hybrid MGs are conducted in [52]–[55]. Although, these papers addressed the protection issues and challenges, including fault detection, fault location, identification, DC protection devices, and fault reconfiguration techniques; yet some concerns, like localization, reconfiguration/recovery, identification, and design of fault protection techniques in the DC MGs include the DC bus voltage instability during dynamic load fluctuation, have not been adequately addressed. According to the aforementioned literature, this review presents some specific future challenges associated with fault management operation in DC MGs that are not highlighted properly, which are moderately essential from the protection strand. A legitimate future direction cannot be inferred from the opaque analysis. Thus, this review paper broadly spotlights to execute the future challenges, improve fault protection methods, and present a transparent direction for fault management. Consequently, this analysis could be valuable, particularly for researchers, academicians, and engineers in this field.

The basic premise of this review is to analyze and present the detailed fault management techniques for DC MGs by examining works-related to intelligent fault detection methods (signal processing and ML), fault classification, location, fault isolation, fault recovery, and fault integration control strategies. In each protection technique, the technical difficulties with existing issues are highlighted. In addition, fault detection and reconfiguration of the DC MGs are also addressed. The existence of advanced strategies based on signal processing and ML methods opens a new and emerging field of research opportunities. However, unless otherwise, a fault refers to the short-circuit that is applied on any pole to pole (P-P), pole to the ground (P-G), and the fault on DC bus segment are analyzed. The sudden onset of fault current exhibits the most challenging behavior, and appropriate protection approach must be able to address the scenario to minimize system damage, to continue to operate effectively without disabling the whole system. To investigate and identify the various fault occurrence in DC MGs, simulation studies were conducted with MATLAB/Simulink software to analyze the system performance by detecting and isolating the fault in terms of potential challenges and solutions.

The organization of this paper is as follows. Section II describes the characteristics and the types of DC faults. Section III presents the fault detection and classification categories. Fault isolation and reconfiguration are reviewed in Section IV. Section V describes the research challenges with future directions for these issues. Finally, the conclusion is drawn in Section VI.

## II. FAULTS IN DC MICROGRIDS

Understanding and analyzing short circuit fault currents is an essential part of formulating an appropriate fault protection strategy. In addition, the fault current response of the DC power system needs to be analyzed, the coordination relay. High fault current damages the parts of DC MGs such as power converters; therefore, the power converter may lose voltage and current control, as they require a high power rating which increases the cost, and cascades tripping into other protection zones [56].

In DC MGs, short circuit faults occur in two different ways, pole to pole (P-P) (line to line) and pole to the ground (P-G) (line to ground). In the P-G fault, one or both conductors are connected to the ground. Therefore, the P-G fault is either a low or high impedance fault (HIF). The conductors are directly connected to the P-P fault. Therefore, P-P faults are low impedance faults that are more detectable and dangerous [28], [57], [58]. On the other hand, according to the current fault response time, DC MG divides the faults into two different groups: static/steady-state part and transient part. Table I summarizes the main characteristics of the defect in the DC MGs. The cable discharge of DC-link capacitors and power converters injects the transient current, and the DER injects the current into the steady-state [11]. However, a DC fault, depending on the fault location, can be a bus defect or a feeder defect. This defect is crucial for the entire DC system, in particular, the power converter and ESS. Faults in VSCs and energy storage devices can cause a P- P short-circuit fault and this is a terminal defect that usually can't be cleaned quickly. In these cases, the replacement of devices is being done, and using a fuse may be the right choice [59].

Recent literature presented the typical response of a DC fault in detail [12]. Reverse diodes are exposed as a result of the self-blockade of the IGBTs as a way to protect the whole network. The high-fault resources are played by the capacitors that are filter-charged. For instance, the typical fault profile can be overviewed from Fig. 3, irrespective of the fault or short circuit location on the DC cable.

TABLE I
MAIN FEATURES OF FAULTS IN DC MGS

| **Faults in DC Microgrid** | **Key Features** |
|---|---|
| Pole-to-Pole Fault | Impedance is low, and this fault is detectable |
| Pole-to-Ground fault | Impedance is high, not critical compared to pole-to-pole fault |
| Transient fault parts | The cable discharge and DC link capacitors of the power converters inject the transient current. After switching the converters during fault occurs, the energy store in the inductance of the cable will discharge. The transient fault part has three states i.e. a) Fast-state, b) Medium state c) Slow front transient |
| Steady-state fault parts | Need to calculate current of each phase and DER injects the steady-state current |

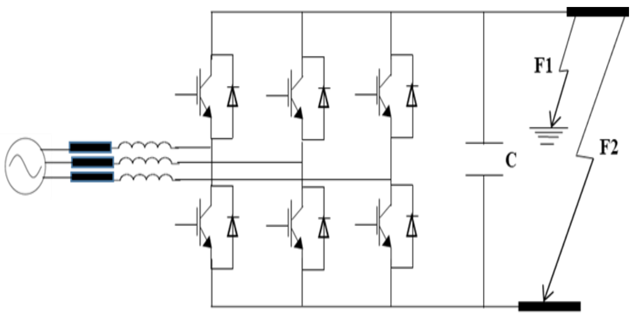


**FIGURE 3. A faulted DC network equivalent circuit**

A systematic review and analysis is presented based on the optimal protection strategy [60], where two separate phases define the natural responses of the whole circuit. These analyses define fault characteristics and help with protection strategies and also propose protection strategies that prevent damage. The capacitor discharge stage, a grid-side current stage and, a diode freewheel stage define the P-P fault in most of the DC MGs. The initial time $t_0$ of the fault, the capacitor discharges in a matter of milliseconds until the voltage drops to zero. At $t_1$ to $t_2$ the freewheel diodes charge when the cable inductances start flowing the current. The diode is vulnerable to damage at that point in time because of the high current flow rate through the semiconductor. The DC and AC current levels equalize after a certain time when the current magnitude drops down. After the freewheeling diode time period, the AC side feeds the network to the fault point. In [61], the P-G fault has been examined in detail. The typical P-G fault doesn't rely on freewheeling diodes. However, the rest of the features remain the same. Furthermore, DC MGs naturally have the absence of zero crossings, so AC CB cannot be applied for DC MGs protection.

Under this portion, the steady-state and transient features of DC MGs during the incidence of P-P and P-G fault are analyzed according to simulations results. These fault features are important for fault detection, disruption, and protection. The P-P fault, i.e., F2 on the terminals of the DC systems, as shown in Fig. 3, can be treated as supplementary load along with low resistance, which relies on the fault impedance, location, and type of fault, DC network having PECs s exhibits distinct fault response. The steady-state and transient fault current paths in DC systems during a P-P fault are described in Fig. 3. The DC line current tendency (IDC) and DC voltage (Vdc) during the P-P fault are presented in Fig. 4. Initially, after the occurrence of fault at 0.5 secs, capacitors start the discharge causing a sudden drop in Vdc as depicted in Fig.4. The discharge of the DC-link capacitor results in a transient current having high amplitude and less rise time. The discharging of the capacitor causes a rapid rise in Idc that can be seen in Fig. 4. The current from the input source rise quickly and flows through the IGBT paths.

The P-G fault, i.e., F1 on the DC network, is highlighted in Fig. 3. A similar response shows by the PECs to that of F2. The time of P-G fault Vdc drop and the freewheeling diodes become forward bias, and the input from the AC grid feed the short-circuit fault along IGBTs. However, if the P-G fault component through grid-connected VSC is high compared to current flowing in the negative pole of DC system into the negative pole terminal of VSC, the direction of current change and the VSC current starts to flow along the negative line of VSC into the negative DC pole. As a result, the input source contributes to the P-G fault, as illustrated in Fig. 3. In the case of the IGBT activation for the self-protection method, the fault current path of RES through the VSC negative terminal is cut off, while; the fault is fed by the AC input source through the freewheeling diode of the power converter. The DC P-G fault current (Idc) and DC P-G voltage (Vdc) trends are depicted in Fig. 4, where it is clearly seen that the waveforms of P-G voltage and P-G current follow the same path during the fault.

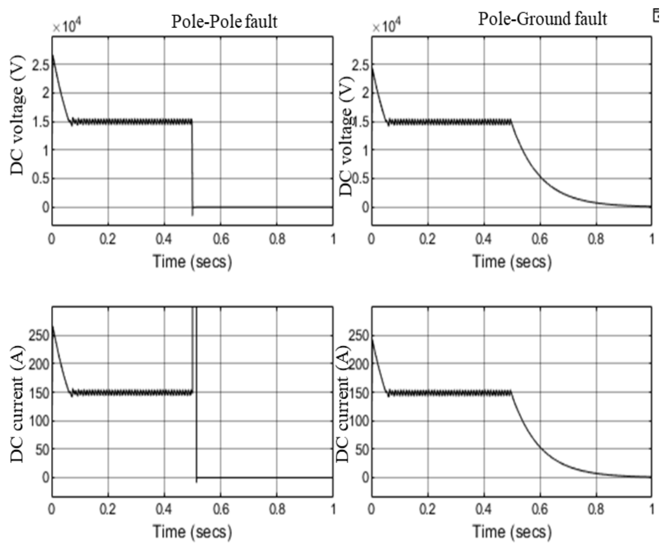


**FIGURE 4. A DC bus voltage Vdc and current Idc trends during P-P and P-G fault in the DC network**

## III. FAULT DETECTION AND CLASSIFICATION

The fault management of DC MG systems is essential to ensure the nominal operation and supports the main grid's stability with fast recovery performance. As mentioned earlier, the FM of DC MG comprises fault detection, identification, location, isolation, and reconfiguration. The detection and the classification of faults are the main part of the FM in DC MGs systems. However, in the conventional DC power systems, the radial configuration [62] and fault protection of DC systems are designed based on unidirectional power flow. Whereas, integration of Distribution Generation System (DGs) in DC system makes fault protection more challenging. DG rises fault current level causes the power flow direction of the DC power system to increase and change. Therefore, it can affect the coordination of defense devices. In addition, many of the challenges associated with the protection of DC systems are low impedance, large DC capacitors, high transient current and voltage.[63].

The CB is one of the fault current interrupters, which interrupts AC fault using naturally occurring zero crossings. As the natural zero-crossing method is inapplicable in DC systems, the application of conventional CB will not be possible. Therefore, the DC systems require a faster and intelligent fault protection technique with an appropriate grounding design [47]. DC MGs fault detection has been discussed in the literature. This review has also managed to include the fault detection and classification (FDC) in DC MGs systems based on employed techniques, like general safety/protection methods (i.e., distance safety operations based on fault calculation from the point of measurement of the defect site [64], direction and differential method [65]). Also, signal processing-based methods [23], artificial intelligence and machine learning-based methods [66], and model-based methods. Table II highlights various fault detection and classification based on signal processing principles.

### A. SIGNAL PROCESSING BASED METHODS

Transmission lines and distribution systems, including DC MGs utilize the DSP. System parameters deviate from normal value during a faulty condition in the DC power system which in turn alters the output accordingly. The signal processing technique is based on analyzing the output signals and does not involve an explicit input-output model of the target system, and the output features correlate with the system faults [76]. The typical signal analysis methods include the fast Fourier transform (FFT), spectrum estimation, and the WT are described in [77]. The key features like fault detection are mainly extracted from the analysis of three signal processing-based methods (frequency domain, time domain, and combine time-frequency domain) [78].

Signals are being transformed from a time domain to an entirely novel domain based on the field transform techniques that offer a clearer picture of the data features. STFT is one of the commonly discussed techniques for the classification and detection of DC MG failures [79]. The STFT is instigated to reduce the limitations of Fourier transform on the confined interval of signal, S-transform [80], [81], wavelet transforms [82],[83], and Hilbert-Huang transforms (HHT) [84],[85]. The various signal processing based fault detection and classification methods are given in Fig. 5.

TABLE II
FAULT DETECTION AND PROTECTION TECHNIQUES BASED ON SIGNAL-PROCESSING

| Methods | Key feature and contributions |
|---|---|
| The Discrete Wavelet Transform (DWT) method was implemented to detect any surges in DC current signal [67] | During the surge, DWT is applied to detect the feature vector from the DC current signal and send it to the neural network. Later it encourages, whether the feature belongs to fault current surge in reason of short-circuit occurring across the DC link capacitor. It determines the irregularity of the signal approaching the fault detection in DC systems |
| Combine WT and discrete transform (DT) [68] | It is used to detect the fault in Microgrids. The fault classification is carried out by including WT-based features. |
| Wavelet transform (WT) and S-transform based methods [69] | Used for fault detection in grid-tied DG systems. It is used to study voltage stability at the Point of Common Coupling (PCC) with a nonlinear load connected during islanded operation modes |
| DWT and Extreme learning machine (ELM) based method [70] | Mostly utilized in the classification and fault localization. It can be utilized for fault management in both grid-tied and standalone modes of operation. |
| The classification of fault in MGs based on WT and ML Techniques [71] | Filters out the best fault localization features in transient signaling utilize the particle swarm optimization (PSO) algorithms. To identify the best wavelet function combination PSO is used instead of using only one wavelet function for fault classification to protect the DC MGs. |
| The Windowed Wavelet Transform (WWT) methods for fault detection and classification [72] | The fault detection method includes bagged D-Tree in which input features obtained from the signal processing techniques are utilized and is selected by correlation analysis |
| DWT based ANN [73] | The DWT based ANN is the most reliable and high effective technique used for the detection and location of the fault in DC MGs |
| The WT based ANN techniques for fault detection and location in DC-MGs [74] | It restricts time limits for the interruption of fault imposed due to the fast-rising of fault currents in DC MGs, and the absence of frequency and phasor information. The WT-based ANN technique is the best approach for the detection and isolation of fault without shutting down the whole system. |
| Hilbert-Huang transform (HHT) and deep learning-based technique for detection process in a sensor of DC MGs [75] | It used the Krill Herd Optimization (KHO) algorithm., HHT and deep learning for detecting cyber-attacks in DC MGs and detecting the attacks in DG units and its sensors. |

#### 1) WAVELET TRANSFORM BASED METHODS

WT is one of the most promising techniques in signal processing that can be applied in the detection of fault. The time frame is adjusted by the WT as per the frequency [86]. It

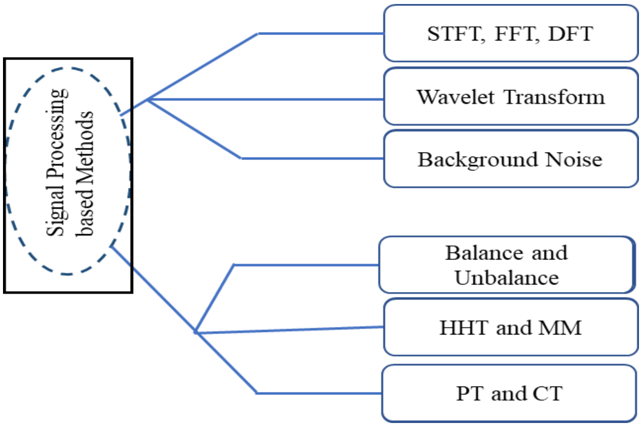


**FIGURE 5.** **Signal processing based fault detection and classification**

analyzes the transient behavior in the current or voltage signal related to the failure in frequency and time domains. WT has the feature to decompose the signals in its frequency components, having a different resolution level, later used for fault detection in DC MGs. Just as the other transform-based protection techniques like STFT, S-transform, and HHT, distance protection based on the WT-based transmission line [87] relies on a single decomposition level that consists of high frequencies for faults localization and bi-level phase estimation, those high frequencies are again utilized for fault estimation. Furthermore, fault in DC MGs is detected by using the WT-based signal processing strategy presented in [88] and traveling wave-based single-ended fault location [89].

The FFT and WT are investigated and presented to extract the signal's faulty feature, in which the disturbing signal is given as input to the ANNs model for the fault analysis depend on the significant time period [90]. WT is used to decompose the signal and parameterize the frequency and time-dependent localized signal. The parameterized features of the low frequency single are called "approximations," as well as a signal having high frequency content is called "details" [91],[92]. A researcher worked on the applications of WT, such as compression of the image, filtering and noise reduction as per DSP principles [93]. A WT-based system for monitoring power quality has been suggested to identify the transient fault in MGs is presented in [94]. Another researcher worked on the features that extract the component that is dependent on time and frequency for the transient signals to deteriorate the signal component is discussed in [95].

Fault detection revolves hugely around WT principles as well as the localization of the faults. A recent study, however, preferred wavelet packet transform (WPF) over the DWT for the accuracy of the information. [96]. The filters (such as low and high pass) are common to WPT and DWT for fault detection. The low phasor component is decomposed every time by the low and high pass filters, which are specific to DWT, while both components are equally regressed in WPT, which renders it more reliable in terms of accuracy. Concurrently, a researcher introduced the WT technique, also known as un-decimated WT, for fault localization [97] and supported WT over the conventional DWT and WPT in case of real-time failure detection pertaining to its specific feature of lower-noise issues.

#### 2) FAST FOURIER TRANSFORM BASED METHODS

Another recent advance in fault detection and localization is the Fast Fourier Transform (FFT). In [98], Fast Recursive Discrete Fourier Transform (FRDFT) is proposed by a researcher for failure detection. The algorithm in FRDFT helps with relay adjustment pertaining to the connected grid as well as the islanded mode in addition to the directional approach. The authors in [99] Communication-assisted fault location is also suggested by authors for classification and detection in DC microgrids. RDFT has also been used for the extraction of features alongside sequence analyzer. A faulty MG is detected by measuring the sequence and phasor and then using them as an FL-based input as per this method. In [100], MG protection from failures is also proposed by DFT techniques. Features that are extracted using DFT are presented by not limited to phase angulation, amplitude, frequency, and signals. At each end of the feeder, these salient factors are used as input for computational differential features. Although differential protection is considered reliable, data mining models are also incorporated in the events of the faulty microgrid.

#### 3) SHORT TIME FOURIER TRANSFORM BASED METHODS

To effectively investigate and understand the application of STFT in consequence of fault detection in DC MGs due to fewer impacts of line inductance affect the sudden rising fault current. Therefore, a DC bus and a power converter are considered as the by-product of input signal decomposition when counted as frequency components. To obtain the frequency feature vector, the STFT is then utilized [101]. The STFT method is suggested for P-P fault detection and multiterminal DC MGs networks rather than FFT. Apart from line-to-line fault detection, selective operation validation frequency profiles to make stable operation and fault identification in DC system based on STFT presented in [102]. The STFT can be implemented for transient and fault signal analysis of the DC power system [102],[103]. The STFT has a limitation in resolution because of its fixed window size. In [104], the STFT and the DWT were integrated for early diagnosis of the fault because the STFT and WT suffer from certain limitations under non-stationery conditions. The STFT can overcome the limitation of Fourier transform on the limited time interval of the signal, and the feature like amplitude frequency obtained by STFT is used for fault detection. The STFT based protection of high voltage (HVDC) against pole-to-pole faults is suggested in [102]. The system monitored and decomposed the DC current into frequency components. The Standard deviation (SD) of the side portion acquired from the amplitude-frequency features is utilized for fault detection.

#### 4) S-TRANSFORM BASED METHODS

Gabor transforms, and WT is another form of S-transform which is considered as an extension to the STFT [105]. S-transform is quite similar to the STFT in terms of providing the frequency range of signals. Islanding detection based on S-transform is presented by a researcher [105]. Energy spectral information is obtained by converting the negative sequence voltage and current. Load changes are frequent but less noticeable in the DC MGs as DG trips produce insignificant changes when studied cumulatively, which in turn determine the threshold. Another researcher proposed techniques for MG protection in both modes [106]. Another reason to prefer S-transform is its ability to provide frequencies that are high in the spectrum and work independently of any parameters towards fault indication. Additionally, a simplified S-transform reduces the computational burden of this method, which makes online calculations a lot easier. For reliable system operation, the DC grid requires high speed and robust fault detection techniques. With this regard, fault detection based on S-transform with adaptive adjustment is suggested in [107]. The improved S-transform is based on frequency-domain and detects the fault within 0.3 ms because the fault current speed is too high.

#### 5) BACKGROUND NOISE BASED METHODS

The interconnected switching operations of DC systems have harmonic sources. It generates a certain amount of high-frequency noise by interacting electronic convertors with the cable insulation capacitances and stray inductances; repetitive switching transients occur in the system. During the occurrence of a fault in DC MGs, high-frequency noise in the repetitive transient switching prevents a good reading of the system impedance at high frequencies. For this purpose, as mentioned earlier, signal processing methods have been suggested for DC power system failures localization and detection such as the traveling waves-based fault detection methods, WT, etc. which measure the incident and reflected waves time difference. Prony-based fault recognition and algorithm based on the background noise of fault detector converter are two of the techniques discussed in [108]. Although the methods provide better results for the detection and location of the fault, and still require investigation for accuracy and hence are in the initial developmental phase. The background noise contains information related to the location of the fault.

#### 6) HILBERT–HUANG TRANSFORM BASED METHODS

HHT is a powerful technique designed specifically for time-frequency representation implemented to any non -stationary information [109]. The implementation of this technique for AC MGs is discussed in [110] and compared to S-transform, where the HHT techniques process the differential currents and counted as a fault detection factor with its differential energy calculations. Fault detection thresholds are set after analyzing of data by considering the fault conditions are spilled into HIF, islanded mode, and the grid-connected mode. After a relative assessment, it is concluded that HHT is as effective as S-transform. In [111] HHT technique is implemented for multiterminal high voltage DC system distance protection, high-frequency features are detected using the transform in transient state. The distance from CB to FL is the voltage input and output. The instantaneous amplitude-frequency is features of the signal component are provided by the HHT, which is used for distance estimation after average. Real-time testing is also implemented using the algorithm to detect a 10% failure. The signal noise is presented without any communication channels, which should be considered when testing in real-time. Furthermore, the application of the HHT technique in power systems for fault detection is studied in [112]. In this study, the HTT technique is suggested to analyze the signals to understand the dynamics of the process and extract the effective feature for fault detection, which are diagnosed by projecting the transient signal into a time-frequency domain. The islanding detection based on the HHT technique and extreme learning machines (ELM) in order to detect an islanding condition in a distribution system with DGs is suggested in [113]. Besides, the HHT technique is also implemented for studying fault detection, including the distributed system network (DSN) and MGs. [114] Another author combined ML with HHT to identify MG failures. The empirical mode decomposition (EMD) is adapted to compute intrinsic mode function (IMF) by measuring phase current at various locations. As a result, these features are used in the HHT process such as the inclusion in the ML model for error detection and classification. In [115], the author presented protection techniques for MGs using HHT techniques.

#### 7) MATHEMATICAL MORPHOLOGY BASED METHODS

The mathematical morphology (MM) is a non-linear DSP technique such that it transforms signal shape to a geometrical structure. The MM provides several applicable tools that extract the desirable signal characteristics under the analysis of the appropriate structuring element (SE). SMEs are the standards for all MM modifications with signal length and shapes based on their use. MM contains two basic variables, namely, dilation and erosion, which are the basis for other modifications [116]. By combining these two modifications, some filters from the other are available for feature extraction from both single and wide markers. Unlike Fourier transform and WT, MM is fully operational in the time zone, and its power consumption plans are enhanced in [117] [118]. Filters designed for MM are used to detect unhealthy/faulty conditions, including HIFs, especially in AC-based systems with size and dimensions [118]. However, DC-based systems have only signal amplitude that provides an appropriate platform to use MM filters to address the time zone factor from deviations from normal current or electrical power signals.

The protection of DC MGs and AC MGs based on HIF detection techniques are examined in [119], [120]. In [119], HIF detection techniques in distribution systems are published based on the DWT of the current signal. However, it is not reliable in different system conditions, for example, within the grid-tied mode, the utility controls the voltage and frequency stability; however, these parameters escape the limits upon islanding, which may result in irreparable damage to the DC MGs. In [120], the heuristic methods concerning with ANNs for HIF detection are proposed. The MM technique utilizes the opening and closing operators, which are non-complex and quickly applicable to high-frequency non-periodic signals. Therefore, a reliable and accurate signal element extraction technique without any distortion is obtained by implementing the MM technique. The erosion filters based on the MM technique are implemented for stand-alone mode detection of DC MGs within a short-period of time are presented in [121]. In DC power systems, the occurrence of the transient situation is caused by the resistor, capacitor, and inductor circuits (RCL) and switching-devices, which are instantly detected by the MM technique [122]. Moreover, the extraction of LIF and HIF detection is the quality of having a superior by implementing MM technique, deploying a regional-maxima based fault detection consequently upgrade the fault detection level of efficacy. Therefore, MM methods were applied for the detection of both HIF and LIF in DC MGs [123]. This study overviews a MM filters-based fault detection feature before damaging the freewheeling diodes of the PEC during the fault without requiring any communication links.

### *B. ADVANCE STRATEGIES FOR FAULT DETECTION AND PROTECTION OF DC MGS*

Advance strategies for the protection of DC MGs mainly include AI and ML-based approaches. The protection and transient stability of DC MGs remains a complex issue [124], [58]. When a fault occurs in the system, it creates a massive current that could affect the entire system operation, and it could shut down the whole system. The possibility of locating faults quickly and isolating faulty sections from the healthy sections of the system would allow the rest of the DC MGs to maintain normal operation mode. For this purpose, the implementation of advanced techniques like AI and ML-based fault detection, location, fault classification, and fault reconfiguration is quite important to restore the transient stability of DC systems. The ANN has already been employed in AC MGs and have proven to be accurate, fast and robust in operation [125]. The capability to demonstrate the accurate performance of this network to protect the system is of utmost importance. The fault detection schemes offer robust responses when integrated with the soft criteria using differential AI and ML models as compared to a high threshold for measuring the uncertainties. Fault detection in power systems have been incorporated using SVM, DNN, K-nearest neighbor, D-Tree and ANN [126] [68], [36], [37], [127]. Intelligent and robust failure localization, which is unaffected by noise and disturbances in the DC power systems, is offered by an ML algorithm with better generalization capability and high computational speed. D-tree, SVM, ANN, and ML are also proposed for fault detection by a few researchers [39]. Fault detection according to its types using ANN is presented in [40], [128]. Longer detection times and complex ANN structures result as these schemes utilize sampled current measurements for the classification and training of failure events. The above-said methods are used to get a faster solution and fewer errors to find the solution of complex multi-objective nonlinear systems. Fig. 6 depicts the existing and emerging fault detection techniques such as ML and AI as well as classification and localization.

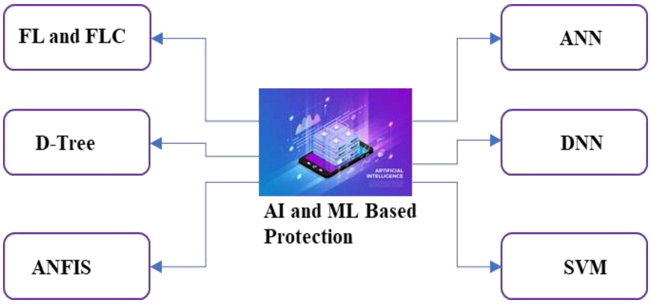


**FIGURE 6. Fault detection, location, and classification techniques based on artificial intelligence and machine learning**

The developing protection techniques and designing control for DC power systems extensively used AI principles [129]. In this study, AI and its application based protection tools describe the control of power systems based on motion control using fuzzy logic and neural network application. The protection of the LVDC system utilizes AL and ML algorithms. Among them, the promising technique demonstrated for detecting and locating the faults in DC MGs is illustrated in [130]. In this study, ANN is applied to obtain the fault classification and location in the MVDC shipboard power systems (SPS). They are using the transient detail in current and voltage signals by integrating a notable amount of data from directly sampled fault features, which can detect and locates the DC fault current compellingly. However, a significant amount of time is required for collecting the data and training the algorithm. To accomplish the smooth operation, the practical implementation with statistical-modeling has to be highly consistent, which required highly accurate collected data to protect the system. In this case, incorrect sampling and signal noise may increase the chance of malfunction under normal conditions [131]. The detection and the classification of fault in MVDC SPS based on ANN are discussed in [36]. Furthermore, the protection of a transmission line based on ANN is presented in [132]. In this study, an ANN-based fault discriminator is described for the protection of the transmission line.

#### 1) FUZZY LOGIC BASED TECHNIQUES

A novel fault detection method using fuzzy logic is proposed for LVDC microgrids [133]. A fuzzy logic system makes the best and most appropriate decision based on several specific rules and conditions for any state of the DC grid. The fuzzy system aims to provide a fast fault detection in microgrids, regardless of the fault's type and current magnitude as well as power supply's feeding capacity, by instantaneous current monitoring that makes faulted section isolated and the remaining healthy section stay in normal operating mode.

The advantage of the fuzzy logic-based fault detection, identification, and classification is its knowledge representation using the simple statement "IF-Then" relation

[134]. The power system's operation in a transient period cannot be described by explicit artificial knowledge; because of many unknown parameters involved and affected the system. Integrating the neural network into the fuzzy logic system makes it possible to learn from the prior obtained data sets. For the identification of fault type in the digital relaying system, the fuzzy set approach is suggested in [135], [136]; and utilized for the identification of fault nature to protect systems. Fig. 7 depicts the existing fuzzy logic systems [137].

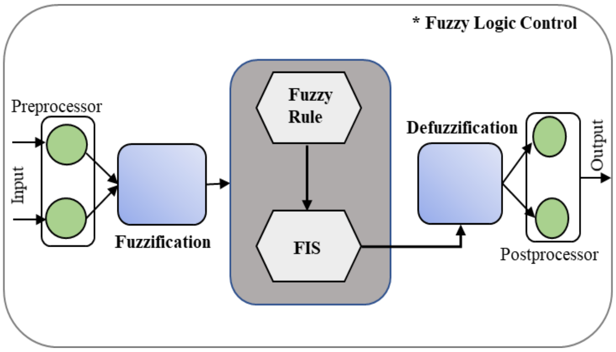


**FIGURE 7. Fault classification based on fuzzy logic** [137]

The fault detection and classification based on the fuzzy logic model is used for the protection of the transmission line [138]. In this study, the fuzzy controller's architecture is developed with the help of the relational neural network (RNN). Furthermore, the fuzzy controller consists of three elements: fuzzification, inference, and defuzzification. However, the classification of transmission system faults using transmission neural network (TNN) schemes has also been achieved in real-time, so it is more favorable for implementation in the actual power system to monitor the fault occurrence and take the necessary action to protect the MGs.

The intelligent fuzzy logic techniques, smart fault detection, and isolation in DC MGs by adopting the concept of fuzzy inference system (FIS) and fuzzy rules are presented in [133]. In this study, the investigation involves the fault detection algorithm in specific conditions, in which the common bus is divided into different segments and monitor each segment continuously. The slave controller measures the currents, speed, and accuracy of the master controller's fault detection depends on its ability to analyze the data and the detection algorithm.

The simulations study is presented for the protection of the DC MGs model consist of energy sources, loads (linear and non-linear), and ESS. The configuration consists of a single bus model. The DC supply input voltage is 250V, and the length of the DC bus cable is 0.5 Km with ground resistance 0.5 Ω. To suppress overshoots voltage caused by the cable inductance, the snubber circuits are connected with the IGBTs. The conditions of simulations are similar to differential-based fault protection. Thus, the P-G fault occurs at 0.8ms. The fuzzy logic-based DC MGs protection algorithm is defined based on logical operators i.e. AND, OR. The obtained results specify that, the fuzzy logic-based controller takes only 20 microseconds for fault detection and send the trip signal to fault isolation parts, which indicates that fuzzy logic is more intelligent and effective as compared to the current differential approach. The smart performance and high potency are the main benefits of fuzzy logic-based protection. The fuzzy logic approach smartly monitored the current and variation in the current value and then trip the system for a few moments after the occurrence of fault. This occur when the currents and their rate of change on the source and load side suddenly increase high and initiate deviation in comparison to differential method. The fuzzy based protection technique speedily observed the variation in current which is above the limit value, and detect the fault very rapidly.

The input and output current of the bus segment considering the fast switching CBs and intelligent controller during the P-G fault are depicted in Fig. 8. It shows that the variation in input and output currents are similar in both differential and fuzzy based DC MGs protection. But, the ML based fuzzy logic controller intelligently/quickly predicted the increasing fault current value before reaching the limit and send the trip signal to the fault isolation parts within 20 microseconds. Utilization of fuzzy logic-based DC protection approach have capability of less damage to DC MGs devices and lesser fault current peak value.

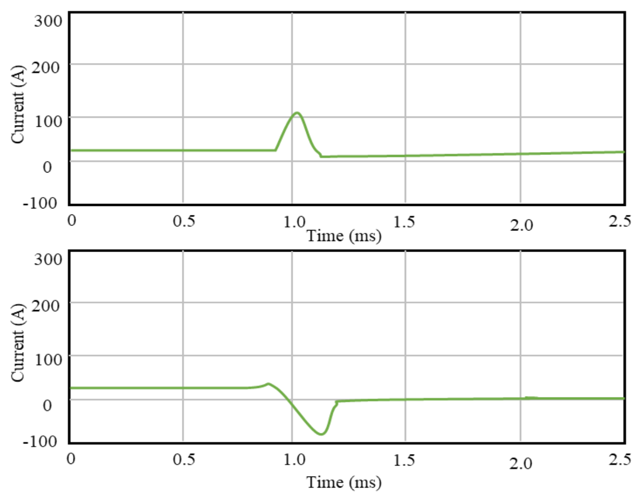


**FIGURE 8. The source side and load side current during P-G fault with fuzzy logic-based DC MGs protection**

The load voltage and freewheeling diode path current in fuzzy logic controller-based DC MGs protection are demonstrated in Fig. 9. It precisely shows that the fuzzy logic technique is capable of restoring and maintain the DC bus voltage for normal operating mode by intelligently detecting the fault and isolating the faulty portion within a short time interval in comparison to the current differential-based method. Through quick detection and interruption of rapidly increasing fault current, the fuzzy logic-based DC systems protection gives diode freewheeling smaller current compared to the differential mode protection, which means that fuzzy logic-based method is more feasible because of semiconductors diode usage and cost of protection is very low. The voltage stress across the IGBT switch is also present in Fig. 9. It is reducing high voltage stress across the diode switch after fault isolation is the main benefit of fuzzy logic-based DC MGs protection. it also minimizes the costs in addition to allowing the utilization of semiconductor switches having less insulation voltage.

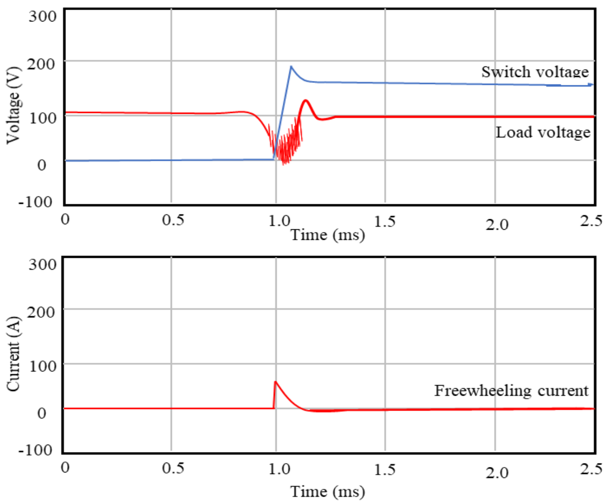


**FIGURE 9. The switch voltage, load voltage and fault current in diode freewheeling path in Fuzzy logic-based DC MGs protection**

### 2) DEEP NEURAL NETWORK

The traditional protection system is not more efficient for the detection and protection of faults in DC MGs. So, to improve the power efficiency, reliability, and system stability during operation and to maintain the energy demands, intelligent fault classification using DNN is investigated in [139]. DC MGs are protected using the DNN which is a type of deep learning (DL). Additionally, it is derived from the ML algorithm [140]. The high-level fault features are extracted using the DNN model [141].

Various challenges like system blackout, signal processing, and delays, CB tripping are dealt with fast and intelligent failure localization, isolation, and classification techniques proposed for the protection of DC MGs [139]. DNN is used to protect the systems using advanced fault detection and classification tasks as described in the study. Desired protection tasks are performed by the currents retrieved at the faulty relaying points. MGs use the AI approach for fault localization and detection [142]. Another author proposed combining DNN with DWT for classification and detection of the failures as well as identification [37]. DNN based fault detection in microgrid systems is depicted in Fig. 10.

DWT-based fault detection is suitable to filter out the desirable data [71], [68]. Data mining, SVM, K-nearest neighbor, and Naïve Bayes are the front-line choices for MGs

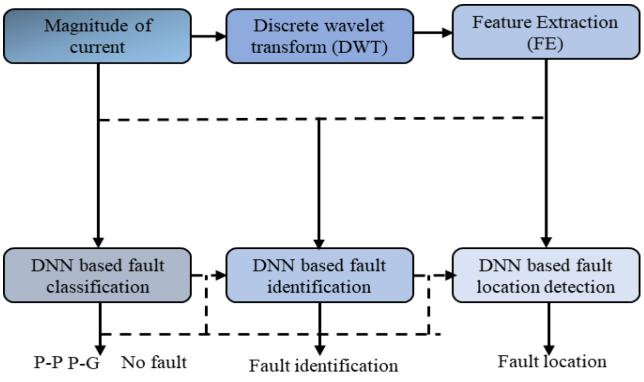


**FIGURE 10. DNN based fault detection in microgrid systems**

protection based on the ML model to develop possible solutions. High computation burdens, however, result in relays' delays which vouches for a need to develop an intelligent relaying system for the microgrid. An author proposed an intelligent differential protection algorithm to help protect MGs [143] which also provides classification and localization of the fault in power systems. By considering possible operating conditions, this technique takes both ends of the faulty line's current data in a microgrid for localization and classification of the failure. DNN based algorithm is developed by assuming the measurement of current, which shows the MG system conditions. Fault detection and fault type classification are two subtypes of fault identification systems [144]. Sub-problems are handled by neurons in the DNN. Current measured is used as input into the algorithm which is measured first at any relay end. Fault identification is assigned by that information to the DNN. Fault type information is provided in case of failure detection then the neurons in DNN give out detailed fault type information. Output details measure the later protective MGs. The main structure of DNN and the techniques employed to construct DNN are:

- Deep feedforward neural network (DFFNN)
- Convolutional neural network (CNN)
- Configuration of DNN

In DNN based fault detection and identification model, initially, the current signal can be obtained from the measuring device; after that, it is processed through the DSP tool for faulty feature extraction of the signal. Later, the DSP signal is given as input to the DNN model for fault detection. Using this technique, the DNN based fault detection in DC MGs can be executed and further continue to achieve the following steps:

- The type of fault in DC MGs
- Pole at which fault appear
- The location at which fault occurs

Thus, to figure out the above mention task, a standalone DNN model is required to handle each problem. The flow chart of DNN based fault detection system for DC MGs is illustrated in Fig. 11. At the time of fault incidence, the first DNN model use for fault detection based on extracted feature input to DNN. After fault detection, a second DNN model is needed for fault classification; to check whether it is an unbalanced/ balance fault. Furthermore, at the same time, another DNN model is used for fault location identification. When the first DNN identifies that the fault is unbalanced, then the third DNN model is implemented for the identification of phase fault. Suppose the first model identifies the fault as balance, whether it is a P-P or P-G fault. The DNN model-based fault detection in DC MGs is very fast and provides a better result, especially for real-time problems. Finally, the information obtained can be utilized for control operation and decision-making process, e.g., isolation and recovery of fault in DC MGs.

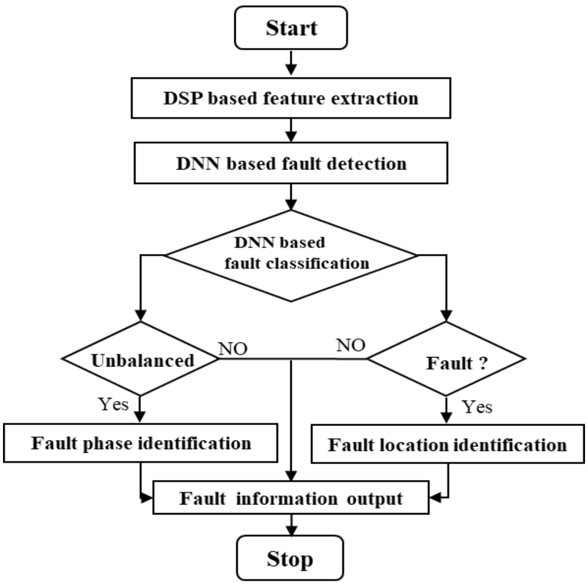


**FIGURE 11. Flow chart of DNN based fault detection system for DC microgrid**

### 3) ARTIFICIAL NEURAL NETWORK

In DC MGs, the power system's protection is of utmost importance, i.e., to prevent the circuit from over flow of current during a faulty event. A suitable protection plan in DC buses is needed because DC bus systems are unable to withstand high current loads. So, the ANN received much attention concerning fault detection, location, and classification in the power transmission network because of its better generalization and adaptive nature of work. ANN train the faulty signal as an input to determine the fault condition as an output [145]. Protection of DC power systems sometimes relies on AI and ML-based schemes to prevent the systems. DC MG fault localization is efficiently dealt with using the ANN-based strategies due to its speed and accuracy rates. [146],[66]. In [146] and [66], fault detection, location, and isolation in the DC bus without shutting down the whole system to attain a reliable DC MG are presented in the above-mentioned articles. LV-based ML techniques are presented in DC MGs [146], while a fault in the DC bus is interconnected with the training of ANN. De-energizing of the system is prevented in the study for DC bus faults which is a lot faster to detect and isolate, resulting in reliable DC MG. Differential short circuit faults are the basis of neural network training in the DC system to maintain validity. Fig. 12 presents the DC MG fault detection and localization based on the ANN modules.

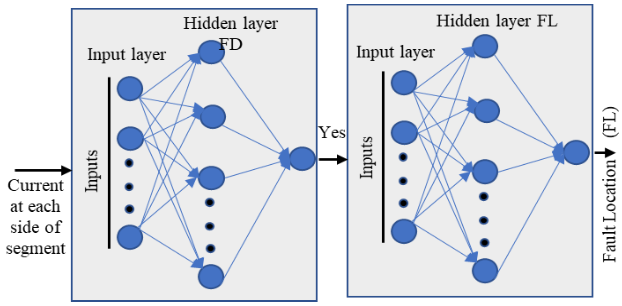


**FIGURE 12. Artificial neural network model based fault detection and localization**

The AI algorithm helps the DC system make the correct decision, tell whether the fault exists, and detect the fault location. To samples of waveforms are obtained for ANN training as presented in the DC fault analysis to detect and locate faults. The fault can be accurately detected and localized using the same input vectors applied in different ANNs. The wavelet multiresolution analysis is based on ANNs used for fault detection and location in DC MG [74]. In this study, ANN is used as a classifier because it provides a smart fault detection capability for a better solution. Above all, the relatively fast calculation time of ANN makes it a good candidate for the protection of DC MG due to the strict time restrictions inherited in DC fault isolation. Fig. 13 shows ANN-based fault detection and classification accuracies by concerning the type of fault. Fig. 13 explains the detection and location of faults (P-P and P-G) on the bus segment using the developed ANN module. In P-P and P-G faults, resistance shows 1Ω, 2.5 Ω, 1.2 Ω and 0.65 Ω, 6 Ω, 0.25 Ω respectively. While, the fault location in each P-P and P-G is detected to train the model which shows 56%, 25%, 89% and 78%, 47%, 11% respectively. The expected results show high accuracy faults detection on bus segments, implementing the train ANN model. After accurately detecting and locating the faults on bus segments, CB is used for fault isolation. Moreover, the error accuracy within 1% for fault location is detected. Fault detection and classification techniques in MVDC SPSs by integrating ANNs with WT multi-resolution analysis technique are applied to protect DCSPS is discussed in [36].

To examine the ANN-based fault detection methods' effectiveness on the impact of noise/error in branch current measurements, time series current signals are added with the

Gaussian noise. For the test data formulation, the feature vectors are extracted from these signals. The typical signal-to-noise ratio (SNR) values of 50 dB, 30 dB, and 10 dB are used. The performance of the network containing error convergence with model accuracy is summarized in Table III. From the result, it is clearly seen that the error in the measurements has a significant impact on the overall fault identification accuracy of 98.5% in only the ANN model. In the considered worst scenario, (SNR of 10dB), the overall classification accuracy is only reduced to 2% compared to the current results with current measurements without noise error. Hence, it is concluded that the signal noise has an insignificant impact on the performance of only the ANN-based fault detection and identification method.

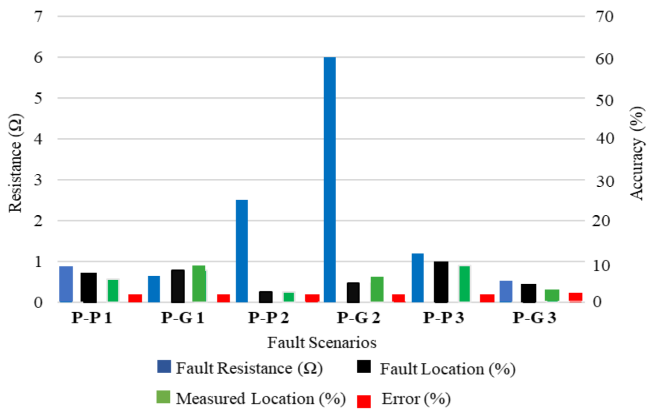


**FIGURE 13. Accuracy comparisons of ANN-based fault detection and classification [75, 146]**

TABLE III
ERROR CONVERGENCE WITH MODEL ACCURACY

| Signal to Noise ratio (SNR) | Model Accuracy |
|---|---|
| Without noise | 99.5% |
| 50 dB | 98.5% |
| 30dB | 98.0% |
| 10 dB | 97.5% |

The flow chart of ANN model-based fault detection in DC MGs is shown in Fig. 14. The input current samples values are pre-processed using DSP methods to extract the fault features in both frequency and time domain [74]. Then, the extracted feature is given to the ANN model for detection and classification. If the fault is detected, then the model classifies the fault. The time series deviation of relative wavelet energy (RWT) in each decomposition level of the time series data embedding for the construction of the feature vector. The DWT-based decomposition method and ANN model for fault detection and classification are also discussed in [73]. In this study, the DWT and ANN models are deeply discussed, where it has been demonstrated that these techniques are very effective and reliable for fault detection and location in DC MGs.

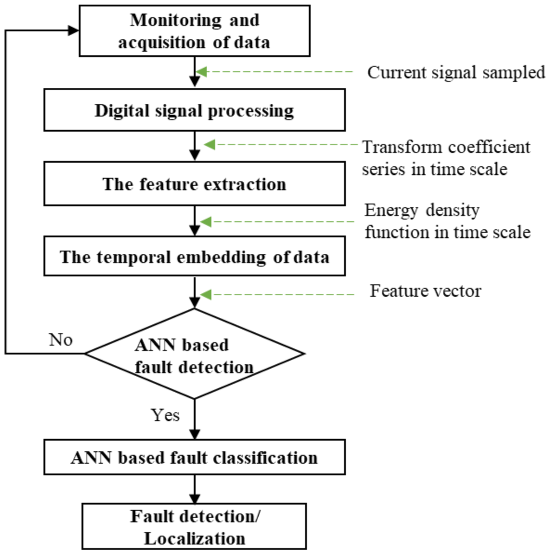


**FIGURE 14. Flow chart of ANN based fault detection system for DC microgrid**

For the stable operation of DC MGs, ANN-based strategy is capable of detecting the fault (P-P and P-G), and disconnect the fault current source to isolate the faulty portion in an effective manner. To restore the operation, reclosing is done after the detection and isolation of fault. The opening and reclosing of CBs and fault detections is controlled on DC bus without any communication link. The effective fault isolation and system recovery schemes for DC MGs are necessary to reduce the main grid blackout voltage to maintain the normal operation. The fault is created at 0.5 seconds during P-P and P-G faults. For the P-G fault, DC system can be isolated within less than 100 milliseconds, but in the P-P fault scenario, the grid outage voltage ranges from hundreds of milliseconds to seconds because it is dependent on fault current decay behavior. The voltage and current signal variation during mitigating of fault in the DC power system are depicted in Fig. 15. The DC fault current has a sudden increasing behavior after 0.5 seconds, while DC voltage decay starts which is associated with efficient fault detection.

The AI and ML techniques are adopted for the protection and power system control in DC MGs due to their error minimization capability, intelligent decision-making capability, high accuracy, robustness, and fast fault detection and classification. Though, ANN and DNN are prominently used in DC systems protection. A DNN is a deep conventional neural network with multiple hidden layers in between the input and output layers. In fact, ANN and DNN both are branches of the ML technique. However, the traditional neural network i.e. ANN can be either shallow or deep, therefore it is also called the shallow neural network (SNN) (i.e. one layer between input and output). The effective performance and high potency of DNN show more superiority as compared to the ANN due to their high network hierarchy and complex structure as depicted in Fig. 16.

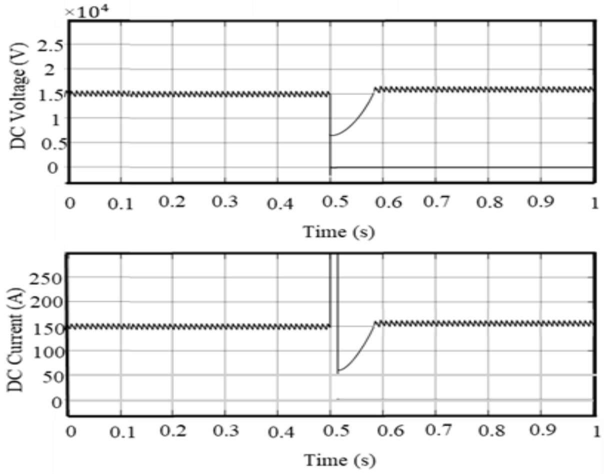


**FIGURE 15. The waveforms of voltage and currents during fault mitigation**

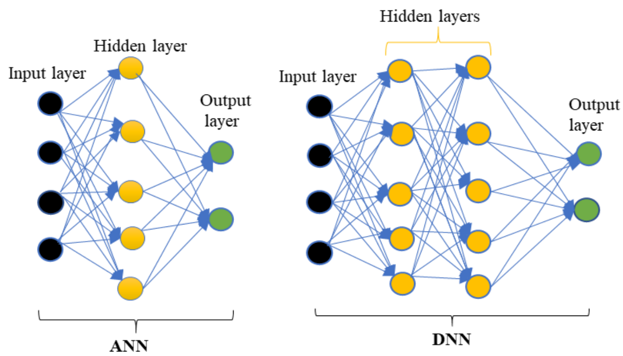


**FIGURE 16. Structures of ANN and DNN**

#### 4) DECISION TREE-BASED TECHNIQUE

The AI and ML-based fault protection techniques have shown exemplary performance in AC MGs, but these protection techniques have not been adequately employed in DC MGs. In [41], an ANN has been utilized to detect and locates the fault, but MGs used in this paper is simple and also ANNs overfits when the number of hidden layer increases [147]. In [74], the combination of ANN and WT are implemented to detect and locates the occurrence of faults, but the proposed technique fails to identify the exact fault location in DC MGs. Also, in [148], the CNN is implemented to detect the faulty device like power converters, but these protection schemes are failing to protect the lines and loads properly. Therefore, the fault detection and location in DC MGs based on recurrent neural network (RCNN) and D-Tree presented in [149], in which the fault location on load feeders with high accuracy is determined by using RCNN. Besides, the D-Tree-based classifier is utilized to determine the overall system condition (whether it is healthy or faulty), as well as whether the fault is on the main DC bus or the lines. In [72], fuzzy logic- adaptive protection with bagged D-Tree-based techniques for fault detection and classification in protection relaying schemes for the microgrids.

The D-Tree algorithms are one of the most powerful ML techniques implemented for regression and classification as well as fault detection and locations by measuring the feeders current load and DC bus voltage continuously [150]. The D-Tree-based transient stability and islanding detection for fault protection using advanced data mining schemes is presented in [151], [152]. The D-Tree-based technique used for constructing optimal classification trees for fault detection and classification is explained in [153], [154]. So, a high degree of accuracy is obtained through a finding of methods resembling more than one tree for detection, locating, and the classification of fault [155], [156]. A D-Tree is an ML technique applied to breakdown complex problems into a hierarchy of simpler ones. While training a D-Tree, all training data is sent into the tree to optimize the internal nodes' parameters. Table IV. provides a summary of fault detection, locations, and classification methods in DC MGs based on AI and ML techniques.

TABLE IV
AI AND ML BASED FAULT DETECTION, LOCATION AND CLASSIFICATION FOR DC MGS

| Methods | Key contributions | Limitations |
|---|---|---|
| ANN based-detection and location of a fault in DC MGs [146] | ANN technique effectively detects and locates the fault on the bus segment. Quickly detection and isolation, without de-energizing the entire system, and more reliable for DC MGs | The robustness of the uncertainty in measurement is not mentioned. |
| DNN [37] | Fast fault detection and location. Faults type, fault location information for DC MGs recovery | Reconfiguration of fault is not mentioned |
| Fuzzy Logic [129] | FL method is implemented for DC MGs protection. | It is used for detecting motion. |
| Fuzzy logic [157] | FL algorithm applied for detecting the unbalance in power and deviation in voltage. It improves the efficiency of the DC MGs. | It is only used for centralized methods |
| Hybrid ANN SVM [158] | It is used for the detection and location of fault for the protection of MGs. It has self-learning and self-training ability. | Complex and need a large number of datasets |
| Adaptive network-based FIS [88] | To identify the fault zone in MGs | Applicable only for the islanded mode operation. HIF is not mentioned |
| ANN [40],[146] | The main contribution is detection, location and isolation of fault in DC MGs and cannot require any communication. | Robustness to uncertainty in measurement is not mentioned. |

### *C. MODEL BASED FAULT DETECTION AND IDENTIFICATION*

DC MGs utilizes the model based fault detection and identification (FDI), which incorporates a detection factor as well. The parameter estimation and analytical knowledge of the DC power system comprise the model-based FDI, parity relationship technique, as well as the observer/filter-based technique for FDI in DC MGs. Moreover, the control technique in DC MGs includes primary control, secondary, and central control functions. The main function of the local controller contained current/ voltage control for each VSC converter. The controller mainly covers the reliability, security, and economical operation for DC MGs at both interconnected DC MGs and proper communication with the main grid, which are suggested in [159]. DC MGs fault is divided into several types, i.e., AC side conventional fault, internal faults (include the switches failure IGBT and IGCT), and DC network faults. For the protection of DC MGs, the different types of protection strategies by detecting the fault in DC MGs, then isolation and configuration of fault. The model-based fault detection in DC MGs is presented in [160], where in this study, the novel model-based fault detection includes fault detection filter and Kalman fault detection filter techniques for fault detection in DC MGs. To design the filter, linear matrix inequalities (LMIs) are used. Fig. 17 depicts the model based fault-detection and isolation-technique.

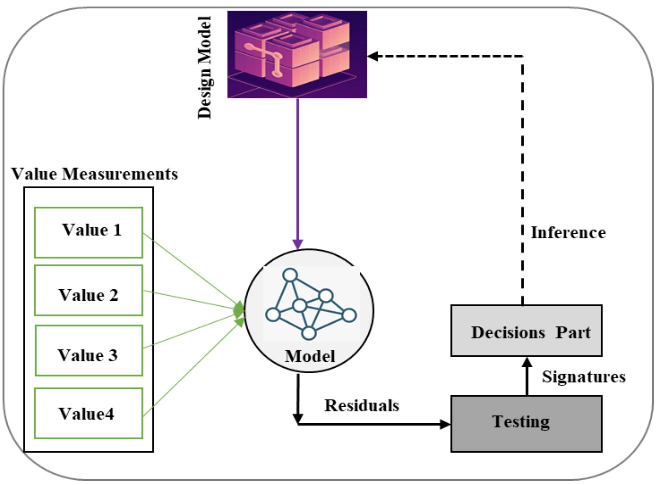


**FIGURE 17.** **Model based fault detection and isolation techniques**

The model-based scheme, which can be effective for fault detection in DC MGs, is presented in [78], and model-based fault detection and isolation in DC MGs are presented in [161]. These methods present the model-based fault management includes three stages like residual generation, statistical testing, and logical analysis of the system's fault. Recently In [162], the model-based FDI strategy has been presented for detecting components or the sensor faults for switching power converters. The model-based techniques are implemented with software, separating the effects of signals, disturbance, and fault on the residual signal, which is the main prerequisite for DC MGs protection. [163] used a model-based FDI to detect a fault in the DC/DC converters within the wind power generation systems. According to that study, a DC/DC converter's fault detection filter was designed and suggested. The proposed fault detection filter consists of a residual signal generator along with an observer. In [164], quantitative model-based fault detection and isolation for a wind power generation system are discussed. Base on that study, a filter/observer is proposed, where the observer's innovation signal has been utilized for system modeling; and to detect and identify the faulty conditions. Moreover, the fault detection in MGs, smart MGs, along with model-based methods and their type, are presented in [165], [166], respectively.

### *D. A COMPARATIVE STUDY OF DIFFERENT METHODS OF FAULT MANAGEMENT IN DC MG SYSTEMS*

The fault management of DC MGs poses many challenges such as (inception of the sudden increase in fault current and high peak fault current discharging from the DC-link capacitor, lack of appropriate DC current breaking equipment, lack of high preferential fault detection approaches, the long delay in fault isolation time as well as the physical experience of fault current measurement. Hence, the occurrence of a fault (P-P and P-G) and fault on the DC bus segment threaten the DC MGs operation). Despite their significant advantages of DC MGs protection and there are no written standards, experience or solution exist with regards to DC protection [11]. In DC MGs based on DGs and RESs, the potency of intelligent fault detection provides us some valuable benefits such as quick recovery, and fault restoration, which leads to a reduction in power interruption time [167], [15]. Various fault protection solutions have been proposed for DC MGs including overcurrent-based protection [11], [168], [169], current derivative-based method [11], and direction and under voltage-based protection [168]. However, the current and voltage dynamics have not been considered, and this technique causes unnecessary outage of sources and load in DC MGs.

The fault detection and isolation in low voltage DC bus MGs were presented in [58]. The limitation of this techniques is that; fault detection uses a specific threshold value, which means that fault occurs when the DC line current exceeds the threshold. Based on the operators experience the fault detection limit value is determined, which is the defecting factor. The present study aims to correct the limitation that occurs in [58], so that consideration and human actions do not affect the detection of the fault. Intelligent fault protection based on a Fuzzy logic system introduced for fault detection in DC MGs, where after the fault is erased, the whole system remains stable [134].

The fault protection performance and summary of different fault management techniques in DC MGs with the conducted fault protection techniques are provided in Table V. Thus, and it can be conducted that the proposed method has the potency to detect and isolate the fault smartly. Moreover, the suggested technique strongly locates the fault for isolation of the faulted section instantly by carefully monitoring the currents, and their deviation at both points on the faulted DC bus and systems will trip for few moments after the fault inception. When the input currents and their rate of change on both points increased steeply and it results in a deviation, which was not possible in the other fault protection methods of DC MGs. The presented fault protection systems quickly detected change in the current rate that increases the threshold limit, and detect the fault instantly as an intelligent expert, which was not available in the compared protection methods.

TABLE V

A COMPARATIVE STUDY OF DIFFERENT METHODS FOR FAULT MANAGEMENT IN DC MICROGRID

| Methods | Key Protection Challenges | Protection Remarks |
|---|---|---|
| Wavelet-based Multi-resolution Method ANN-based Analysis [74] | Influence of current branch ratings with noise, the current signals of the time series were supplemented by Gaussian white noise. Effective detection accuracy; and robustness to the measurement uncertainty like noise and smart detection of fault are the main protection challenges. | 98%-99% of overall fault classification accuracy. Intelligently fault detection without any communication. It is featured by a quick fault localization and selective isolation. |
| Overcurrent with differential method [26] | Not able to detect HIF. The communication is link required to provide a quick and accurate method for the detection of the current direction. Dependency on differential current on line loading, wire length, and noise generated due to high sample rates. Robustness to uncertainty was not mention | To locate the fault and isolate the faulted section, it uses communication links between digital relays-measurement of error during transient coordination, system design issue, system architecture, and complexity of algorithms. |
| A Differential-based DC Protection [12] | Not proper measurements of current and misjudgment of direction. Primary protection failure. Reliability is less due to the small-scale deployment of fast CBs to have selective location and isolation of fault. Problems associated with unbalance load transient switching. The communication channel is required | For fault detection, it relies on a communication channel installed between the protection device on each side of the protected section. The drawbacks include, unable to provide backup protection. Robustness to uncertainty is not mentioned. |
| WT based method [170] | The drawbacks of WT-based DC protection method are; only frequency domain analysis and a high sample rate. Synchronization and transient analysis of the signal, issues of inertia and control of VSCs, and solution for transient state second-order derivative. Fault detection and localization are the main concerns. | WT technique is implemented for decomposition of common-mode current to detect and locate the ground fault at different network points. It requires a communication link. Moreover, the effectiveness of uncertainty was not mentioned |
| ANN Method [40], [128] | It has intelligent fault location and isolation capability. Challenges include more time consumption to estimate the signals criteria of the model without any communications, and it requires smart measuring algorithms. For fault detection, classification, and isolation this method requires data handling and burden reduction. | The sampled current measured values are directly implemented to classify the fault. For fault detection and location, it utilizes two ANN models. Within 1% error, the fault location can be detected. The fault classifier structure is complex. Though, it leads to long detection and training times. The ANN integrated with IGBTS to provide more efficient results with an overall classification accuracy of 99%. |
| The proposed Method | The fault detection in DC MGs based on the differential method [58] uses a specific threshold value, which means that when the DC bus line current is above the threshold value, the fault may occur. The limited value is determined based on the operator's experience, which is the main defect in the current differential-based methods | The fuzzy logic-based DC MGs protection takes less than 20 microseconds for fault detection and sends the fault isolation commands. The protection performance with high accuracy is the main concern of the fuzzy-based approach over the current differential methods. |
| | In the current differential method for DC systems protection, it takes a long delay of 250 microseconds to detect the fault based on the current difference value and send trip command for fault isolation. | Quick detection is important to maintain the stability of DC MGs without waiting for a long delay to send a trip signals |

## IV. FAULT ISOLATION AND RECONFIGURATION

The fault isolation schemes are mainly used to stop the high short-circuit fault flow in the DC MGs by disconnecting the faulted part from the healthy one. As fault detection and locations are completed, the next step of fault management in DC MGs is fault isolation and fault reconfiguration to maintain systems reliability and stability. Whenever the fault is detected, it should be isolated from the rest of the healthy section. Different isolation techniques like DCCB, fuse, SSCB; and modular multilevel converter (MMC) configuration are the emerging breaker-less fault isolation devices. Recently, due to advancements in power electronic technologies, the researcher is focusing on breaker-less isolation. There are two types of fault isolation in DC MGs that are breaker-based fault isolation and breakerless based fault isolation.

In the DC system, the steady-state fault currents can damage the interfaced converters [103]. It is thus required that the fault detection and isolation must be completed within <10 ms. Furthermore, in the absence of natural zero crossings in DC systems, additional arrangements are required while extinguishing the DC fault current for the protection of the DC MGs. For this purpose, different CB-based fault isolation techniques like DCCB, mechanical CBs, SSCB, and HCB used in DC power systems are discussed in [171]–[175]. In this study, the DC grids use voltage source converts and mechanical CBs. While "Breaker-less/converter-based" techniques are used for fault mitigation and eliminate the need for DCCBs in accordance with fully controllable PECs that coordinate with no load contactors or separate contactors to isolate fault [15], [176], [177]. The most indistinguishable protection is also closely related to the implementation of the DC power transmission system to minimize power loss to healthy parts of the system during the classification of potential errors and sequence recovery of the system. Another type of DC converters like a buck and boost type converter used for the limitation of fault current in DC power system presented in [178], [179], to reduces the harmonic distortion on phase current to a low level as well as the communication is required for the control purposes of the DC power system. The main efforts include switching losses, output power losses, efficiency, and total power losses.

The fault reconfiguration becomes an important aspect of the fault management in DC MGs after the fault detection and isolation. It ensures the continuity of power supply to the DC system during complicated operations such as cruising [180], ice-breaking [181], and dynamic positioning [182] for a marine mission to ensure the power flow to the critical load. In [183], the reconfiguration of the system network technique by considering the system reliability to control the power loss in distribution systems. While, In [184], the reconfiguration of a system network determines the minimum power loss in a network of distribution systems with uncertain load and renewable generation. The reconfiguration of fault in DC MGs mainly consists of load shedding selection strategies for reliable bus architecture to ensure the DC power supply from the generator to load. However, during the fault scenario, instability arises between the load and generator; this instability may cause the system blackout during operation. For this purpose, the protection of the system is quite important by implementing the fault reconfiguration methods [185]. The analytical hierarchy process to prioritize the load is presented [186]. In this study, expert control action determination modules have been developed to prioritize the load. The DC bus architecture dependencies including single bus architecture [20], multi-bus system [44], and DC zone-based fault isolation and reconfiguration presented in [187],[45]. The poor fault reconfiguration capability of the traditional DC bus makes it the least preferred choice for marine carriers such as ships. As mentioned in [26], the ring bus seems to have lower transient over-currents despite high power losses. Moreover, the resistance varies, which results in electromagnetic interference at switching frequencies. However, higher transient over currents with minimal losses are offered by the radial network. Multiple bus frameworks can provide increased reliability of the DC SPS [44]. The impact of losses such as de-energizing of the DC bus could also be reduced by integrating ESSs in the converters, which would also improve fault detection, localization, isolation, and reconfiguration.

## V.RESEARCH CHALLENGES AND FUTURE DIRECTIONS

The most challenging issue in DC MGs is fault management because of the lack of frequency and phasor information. Subsequently, lack of adequate standards in DC MGs protection, unintentional islanding, excessive circuit breakers, and protection coordination problems due to the intermittent nature of renewable energy sources and modes of operation. The other challenges include steep transition in DC fault current, direction, arcing, fault clearing time, and signal communication issues. Cogently, the power quality issue and cybersecurity issues are the prime challenges prose to the fault detection in DC MGs. It is pertinent to note here that the increased usage of renewable energy sources indigenously renders the researchers put forward new techniques to detect the fault in DC MGs.

The future research directions are as follows:

- Through innovating the communication network stability such as Local Area Network (LAN), Wide area network (WAN) and Field Area Network (FAN) and information security
- Intensifying a combined protection and control technique in future DC MGs can be effective in resolving the challenges like low voltage right through (LVRT) and self-healing ability to provide fast fault recovery and resilience in response to the short-circuit situation.
- The intelligence control and protective devices like Solid State Transformer (SST), which mainly consists of high-power semiconductor components, high-frequency transformer (HFT), and the control circuits, which not only have the capability to Step-up and Step-down the voltage level but also have advantages like a) the power flow control (PFC) b) the short-circuit current limitation and c) seamless transition between the operating mode of DC MGs.
- Future efforts to protect DC MGs are expected to boost system intelligence by accomplishing effective integrated coordination between power-generation (PG), energy conservation, and end-user to maintain systems stability.
- To secure the upstream and downstream appliances would be one of the futuristic aspects of DC MGs. The development of DC MGs. The integration and protection of upstream and down stream devices will be an important factor in future research. With the growth of DC MGs, fault protection as a result of short circuits would be better handled. The controlling factor would be the first-line defense which would result in the advanced use of coordinated controls as opposed to the conservative protection schema.

- Implementation of computer vision-based deep learning methods and genetic algorithms (GA) for DC MGs to detect errors and their configurations enables full control of the secondary distribution network (SDN) using IoT-based sensors that will improve the reliability and potency of power systems. This research work will involve the development of a deep learning algorithm to include multiple types of DC short-circuits, the actual transmission of the model to the sensor node, and to improve its accuracy and efficiency so that it can be more accurate and faster, and error-corrected.
- By deploying the application of smart technologies like the internet of things (IoT) in the energy sector to monitor and control the power transmission, distribution, and supply system.
- By expanding the blockchain technology and smart IoT including cloud computing in the energy sector. Presently, IoT devices rely on centralization with the synchronization of multiple applications and machines. Security concerns regarding hacking have always been challenging. With the advent of blockchain, these issues can be dealt with effectively to help the end-users.
- Blockchain can help to resolve the need for multiple interfaces and foreign interference. Decentralization and democratized platforms also make it easier to synchronize a number of devices

The integration of IoT vision cloud and blockchain technology immensely acquires the advanced development and smooth shift towards the protection and secure control of load demands in DC MGs. By integrating RES, ESSs, and all-electric vehicles (EVs) into the smart grid, develop a broad research area on control techniques to address the challenges concern to DC power systems. The expedient feature of IoT vision and blockchain technology with wireless communication links initiate a productive fascination by investigating and adapting this recent technology in microgrid systems. Fig. 18 depicts the applications of IoT and blockchain technology in smart grids. The future research trend of emerging technology could be used as a new cyber layer that supports the operation and development of microgrid with various DGs. The cyber-physical security blockchain shall be responsible for handling security and data protection issues in smart grids.

In the coming era, IoT vision technology in smart power grid discussing the open issues, challenges, and future research trends which are classified into the following layer (i.e. physical layer, network layer, transport layer, application layer, miscellaneous issue, and the security issue) which has the ability to handle the hurdles in DC power system and we can apply this nascent technique in various smart grid applications such as energy acquisition, data fusion, congestion, huge data handling, devices integration, big data analytics, and other security issues. Apart from these issues and challenges, the backward capability, device-level power usage limitations, multi-network providers, smart aggregation, interoperability of cross-domain IoT-based DC grids, smart meter configuration, prototyping, and scalability, which are the most important future research directions.

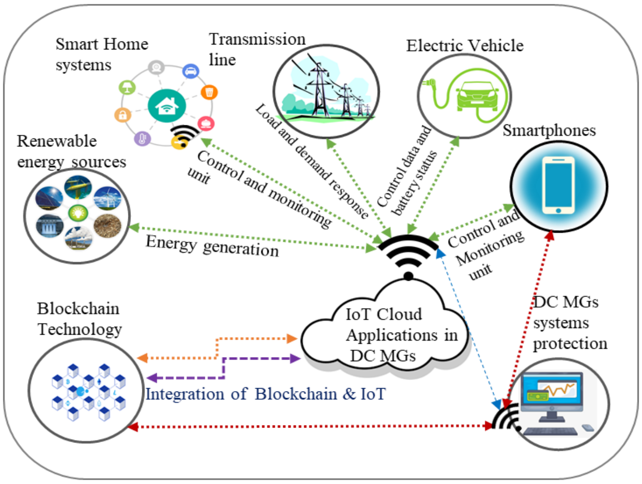


**FIGURE 18. Integration of IoT and cloud computing technology in DC microgrids protection**

## VI. CONCLUSIONS

According to the distinct-characteristics of DC MGs during fault scenarios, proper fault detection in DC MGs becomes the prime focus of researchers after increasing dependency on renewable sources' usage. DC electric flow lacks many important features like frequency and phasor information, which pose a challenge to managing fault. However, signal processing based fault detection, wavelet based fault detection, background noise-based fault detection, and several other techniques discussed above are the prominent methodologies to manage fault in DC MGs. It is evident from the fact that dependency on DC MGs increases due to the excessive use of renewable sources of energy domestically as well as industrially. However, after detecting a fault, the fault location is being done in order to identify the fault. Once, the fault is identified, then the respective optimum methodology is used to restore the fault. Thus, in the future, fault management in DC MGs will be among the prior research fields

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