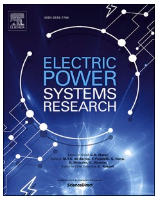
Electric Power Systems Research 210 (2022) 108051

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



A comprehensive review on DC Microgrid protection schemes

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ARTICLE INFO

Keywords:
DC microgrid
Protection schemes
Challenges with protection schemes
Protection devices
Research gaps

ABSTRACT

The attractiveness towards the DC Microgrid is mounting rapidly due to self-sustained arrangement that consist of distributed energy resources (DERs) which can also work in an islanded mode at the time of grid failures. DC Microgrid provides significant benefits, such as cost-effectiveness, reliability, safety, simplicity, better energy efficiency etc. but at the protection aspect, DC Microgrid has to face some severe issues. Hence this paper tries to focus on the challenges related to the protection schemes for DC Microgrid along with the loopholes of present schemes. The paper mainly focused on the traditional protection schemes and Special Techniques based Protection Schemes of DC Microgrid. Thus, the current study first reviews different DC Microgrid protection scheme and challenges and then overviews various technical and common issues presented in literature, all carried out in a comprehensive manner. Finally, this paper offers a scenario of the current state of DC Microgrid protection, and discovers research gaps along with the suggestions for future research directions.

1. Introduction

DC microgrids have high efficiency, better reliability and compatibility and simple controlling strategy [1,2]. The use of DC microgrid for direct feeding of DC loads eliminates the utilization of inverters in power grids that prevent approximately 7%−15% of power loss of intact system [1]. Dc microgrids are robust, resilient and having very simple control design with higher efficiency. Thus, the applicable area of dc framework is extended on shipboard power system and aircraft technology [2]. It is providing a suitable, efficient and affordable platform for faster growth of power generation using renewable energy sources, storing of energy and use of electronic loads [3]. The DC microgrid structure also provides a reduced per capita cost in energy market compared with AC counterparts when renewable energy generation and energy storage system both are present [4]. The implementation of DC microgrid in the power system is beneficial as it can provide better power density and efficient power flow between renewable energy sources comparing to the conventional AC power grids. In addition, use of DC microgrids can make progressive development into the system efficiency and it can shrink the cost of electrical communications network compared to the AC microgrid. It is seen from the studies that DC microgrids can provide better out comes than AC microgrids [4]. The power loss is also decreased while using DC system and this system allows approximately 1.414 times more flow of power compared to the AC system, as AC system suffers from reactive power drop and skin effect issues [5].

Implementation of DC microgrid in the power system increases the use of electronic loads, electrical vehicles and energy storage system for modernization of energy market [6]. Thus, for ensuring a secure and reliable power supply DC microgrid protection is very essential. On the other hand, the converters, made by power electronic devices also having capacitive filters, are caused for tremendous increase of transient current. This current of high value probably sufficient enough to damage the converters and also it may have faulty situation in the micro grid system. Hence a standard DC microgrid protection scheme which will take the lowest time to operate is important to design [7]. The main challenging part is to maintain the stability of the system during faulty circumstance and integration of the DC microgrid with conventional grids (i.e., AC distribution system). Hence, developing a protection scheme for DC microgrid is a key area for research [1].

Though the use of DC micro grids for reliable power supply is in trend, several issues are accumulated with the technology. As there is no zero-crossing waveform in the dc current, DC microgrids always faces a risk of arc faults. The regular used circuit breakers are unable to overcome the arc faults. The DC microgrids also faced other protection issues like quick rising of fault current, lack of standards, practical experiences, information and guidelines [8]. Besides, the amplitude of fault current and its direction at the faulty condition varies due to presence of distributed generators. A high-speed differential protection scheme is obtained to deal with the situation in DC microgrids. However, when the

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https://doi.org/10.1016/j.epsr.2022.108051
Received 1 December 2021; Received in revised form 27 March 2022; Accepted 26 April 2022

magnitude of short circuit current is extremely transient and the synchronization error lasts for few microseconds only, the mention protection scheme faced problems regarding stability issues and mal-functioning of the relays are observed [3].

The distributed energy generation develops its interest with the integration of large solar photovoltaic (PV) plants to the conventional utility grids that enhance the DC power generation infrastructures such as DC micro-grids [22]. The DC microgrids can restrict the power losses. It also beneficial because of low operation and maintenance cost of microgrids. Besides, DC microgrids are suitable for direct supply on DC loads that eradicate the requirement of more power electronic inverters [9]. Microgrids are acting as an eventual framework that interconnects RESs, loads and energy storage structures. Microgrids can perform as local distribution system as they have distributed generators. Moreover, they can improve the efficiency, reliability and quality of power in both islanded and grid connected mode separately. But the implementation of the system to the existing power network faces several challenges including severe protection issues [10].

Though the implementation of DC micro grid can provide several significant advantages, the main obstacle is lack of in-depth analysis of the issues and certain challenges related to the protection schemes [11]. Thus, a dynamic protection model is needed to be design that can offer better security, sufficient redundancy, selectivity and sensitivity. But to design this type of protection model, some important factors need to consider, such as: 1. Arc fault analysis, 2. Proper grounding system, 3. Better sensitivity of converters especially during faulty situations, 4. Changing of fault current (short-circuit current) while the microgrid is operating on different modes, 5. Lack of standardization and 6. Quick increase of current peak during transient fault condition [12].

1.1. Contribution

In this paper, an effort has been thru toward massed numerous papers with both review and full-length research papers accenting issues related to DC microgrid protection vantage point. The facts of consequences from this review are offered comprehensively with a serious study. Secondly, an ephemeral discussion is specified on the current DC microgrid protection issues and their old-style protective resolutions. The paper also offerings an inclusive survey and review of current advanced techniques proposed by several researchers on DCMG protection schemes. The execution challenges of those systems are conferred and suggestions for the future are given. Thirdly, the paper highlights the advantages and limitations of existing protection schemes, which are highlighted in this paper to foresight the future scope for designing the smart and advanced protection schemes for DC microgrid systems. This content of the paper will significantly help the researchers to improve the inadequacy and exhume new methods to enhance the DC microgrid protection scheme with advance technology in the future. Finally, the article concludes with some future recommendations for advancing the DCMG protection system.

1.2. Structure of the paper

The paper is arranged as follows. Section 2 presents the DC microgrid architecture. The Section 3 discussed about the available microgrid protection schemes. Challenges regarding the existing DC microgrid protection schemes are discussed in Section 4. Section 5 deals with the protection devices in DC microgrids. The research gaps and future research directions are represented on Section 6 and 7,respectively. Finally, Section 8 draws the conclusions part.

2. Architecture of DC microgrid

A sufficient knowledge about the DC microgrid architecture is very important to deal with the predicted and certain challenges associated with the grid. The DC microgrid can operate in grid connected mode and islanded mode according to the need [49]. The main challenging part of protection scheme is the interconnected of dc microgrid with the ac grid, as several topologies are there for interconnection [11].

Thus, a detailed overview of DC microgrid skeleton is required for better understanding. The dc microgrids have to deal with sudden load change, change of operational mode, multiple generating units etc. Hence different types of topologies are implemented in it, such as single buses system (suitable for voltage regulation), and multiple buses system (for reliable power sharing). Different types of reconfigurations are also present here to interface the dc microgrids with ac microgrids and utility system [16]. The architecture of DC microgrid is shown in the Fig. 1.

3. Available DC microgrid protection schemes

3.1. Review of previous works

Li et al. in [3] proposed a novel solution to deal with the protection instability issues due to the error in time synchronization with differential relays (high speed) in dc microgrid. The fault current of dc short-circuit are extremely transient. Thus, a delay of few microseconds due to synchronization error may introduce instability in the protection model. A multi-sample differential (MSD) protection scheme is used here to deal with the external faults and internal faults. Sahu et al. [9] present a new scheme for real time monitoring of micro-grid phasors by implementing firefly algorithm which uses time-frequency responses (TFR) helps in power management and coordination of the micro-grid. For achieving least time in micro-grid monitoring this new approach is very suitable as it uses selective frequency scaling. It reduces the tracking time of different harmonic disturbances that appeared in DG (distributed generator) integrated operations. Nougain et al. [13] proposed a centralized protection for micro grids based on percentage differential current approach. A local Running Autoregressive Smoothing Average (RASA) algorithm is used as backup protection. The approach of percentage differential current based technique reduces the need of any RSG (restrictive signal generator) unit. The proposed scheme is useful for avoiding any mal-operation in the system in case of CT saturation. This proposed work provides a feasible protection of a MVDC radial microgrid and uses an amalgamation of the two types of intelligent electronics (IEDs) devices in a topology of sub-microgrid (SMGs) in the radial microgrid. The scheme represents reliable, secure and selective approach that can effectively reinstate the microgrid function ensuring its normal action within 100 ms. Dhar et al. [14] present a new fault detection scheme for DC micro grid depending on differential current-based approach. It can calculate the fault distance accurately with very fast response. The scheme also able to measure the distance using non-iterative calculation that provides fast computation. Additionally, this proposed scheme of fault detection is effectively designed for detecting arc faults (like as series, ground arc fault) in PV system. Manditereza et al. [15] proposes a microgrid protection approach based on the application of voltage relay. Analysis of sensitivity and active power differential calculations depending on the data collected from measuring voltage in a specific protection zone of the micro-grid system is utilized here for making relay algorithm to build the protection scheme. The performance of this protection relay is explored under different fault conditions. The relay is operated efficiently and accurately while detecting and identifying various faults in both meshed and radial topology in the microgrid system. Sarangi et al. [16] make a detail review of conventional and existing protection schemes of solar PV system. The review also includes different grid-connected algorithms of the PV system in various operational modes. The major loop holes and limitations along with the future possibilities of solar grid protection system are listed here. It also provides an idea for making an efficient, reliable and secure hybrid grid in future courses of action. Gashtero odkhani et al. [17] designed smart scheme to detect and classify fault for a microgrid (MG) system that have numerous distributed generations (DGs). The scheme is based on the sensitivity analysis of the differential

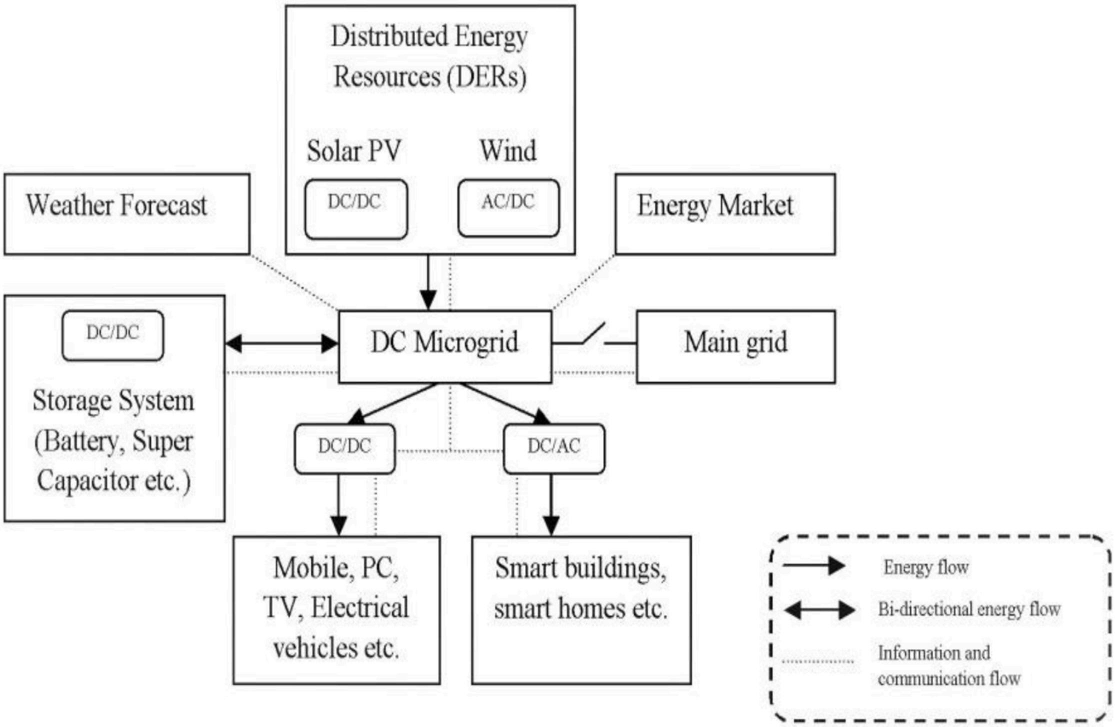

Fig. 1. Physical architecture of DC-Microgrid [50].

power. The performance of this scheme is compared to the different data-mining models, conventional relays used in other microgrid protection purpose and radial-loop topology. The robustness, quick response and accuracy of this protection scheme confirmed by 25 kV IEC standard MG. Beheshtaein et al. [18] investigated the issues related to DC microgrid protection from different features, such as various protective devices, characteristics of dc fault current, fault location methods ground systems and different fault detection methods. Future trends for making protection schemes of DC microgrids are discussed briefly at the last. Tan et al. [19] proposed a master-slave control scheme for microgrid protection with virtual inertia. The scheme is useful for overcoming the downsides of conventional inverter-based distributed generator systems that have lack of inertia. The traditional controllers (such as Proportional-integral controller) are replaced by recurrent probabilistic wavelet fuzzy neural network (RPWFNN) for improving the controlling capacity of reactive power in both transient response mode and grid connected mode of micro-grids at the time of switching either islanding or grid-connected condition or between both of them. The RPWFNN based control strategy is also improving the steady-state and transient responses of controlling voltage in the microgrids. Shamsoddini et al. [20] designed a protection scheme for Low Voltage DC microgrids that uses only simplified equation of fault current to make estimation of equivalent inductance. By implementing artificial line inductance (ALI) at the both ends of each line, the end equivalent inductance estimation is improved. The main advantage of this approach is that the performance of the protection scheme is not hindered with the changing topology of microgrids. This protection model is able to detect any type of faulty situation in less than 0.2 ms while the sampling frequency is 8000 Hz. This scheme also provides back-up protection. Hubana et al. [21] designed a station protection algorithm with the help of artificial neural network and discrete wavelets transform method. The protection scheme is designed in MATLAB Simulink and real data are used to demonstrate its operation. This scheme also includes isolation of defected feeder after proper detection, identification and classification of fault location.

3.2. *Traditional protection schemes*

The section of this paper mainly highlighted the issues and challenges of the existing protection schemes for dc micrograms. A good number of research papers are reviewed and presented in this section to find out the present scenario of the traditional protection schemes as well as the advance protection schemes. Some of the concerning features for making a better protection strategy are selectivity, reliability, speed and sensitivity of the system [16].

In this section traditional dc microgrid protection schemes are reviewed and the findings are presented in Table 1. All the methods used to make protection schemes are mentioned here with their advantages and limitations.

3.3. *Special techniques based protection schemes*

In Table 2 the developed special techniques for microgrid protection are highlighted with their advantages and limitations.

3.4. *Operational mode of grids and software tools used in protection schemes*

In Table 3 the microgrid operational modes and software tools are summarized for different microgrid protection schemes.

3.5. *Microgrid protection methods*

In Fig. 2 the methods associated with Microgrid protection are briefly summarized. These methods are collected from literature reviews which are recently used for making protection schemes of microgrids.

4. Challenges of DC microgrid protection

The protection strategies of DC microgrids are facing several types of challenges due to insufficient standards. To design a protection scheme for better performance, proper attention is required on the common and

Table 1
Overview of traditional protection schemes.

Refs. no.	Developed schemes	Strengths	Limitations
[3]	A multi-sample differential protection (MSD) method.	• To deal with the issues related to instability due to the time synchronization error in a high-speed differential relay-based protection model for DC distribution system in DC microgrids. • It can deal with both external and internal faults.	•The MSD protection strategy may be used to ensure that the operation of relays do not confuse for a sudden change in motor power.
[9]	Real time monitoring of micro-grid based on firefly algorithm.	• Less tracking time of different harmonic disturbances. • Least microgrid monitoring time.	• Only frequency components are considered
[13]	Microgrid protection scheme based on percentage differential current approach.	• Very fast response. Reduces the need of RSG unit. • Avoided mal functioning in the system when CT is saturated.	•It is a centralized protection scheme. Thus, any problem on central zone can cause to collapse the whole system. • Different types of power electronic devices are used, which may increase power loss during power conversion. • Only nodal voltage and segment current magnitude is used for centralized communication.
[14]	Fault detection scheme based on differential current.	• Higher accuracy on calculation of fault distance. • Very fast response. • Distance of fault is calculated using non-iterative method.	• Worst case is seen during DC arc fault condition when proper grounding is absent.
[15]	Voltage relay based Micro grid protection scheme.	• Accurate and efficient detection and identification of faults. • It is suitable for both meshed and radial topology based micro grids.	• Voltage of the system is only used for measurement of the relay. • For each node one relay is required.
[17]	Differential power-based sensitivity analysis for fault detection and classification of faults in DC micro grid.	• Robustness, quick response and accuracy are the main benefits of the scheme.	• Misdetection of fault which causes false alarm at no fault condition in the islanded mode of microgrid. • Machine learning can be implemented for making a better protection scheme.
[19]	Micro grid protection scheme based on Master slave control with virtual inertia.	• Improve the drawbacks of lack of inertia in conventional inverter based distributed generator systems. • Improving the steady state and transient responses of controlled voltage in micro grids.	• Main focus is given only voltage control and reactive power control.
[20]	An efficient and advanced protection system is designed based on estimation of equivalent inductance for Low Voltage DC microgrids.	• Very less detection time (<0.2 ms). • Fast response and better selectivity. • The threshold value is Independent of any changing microgrid topology. • Probability of back-up protection and communication less operation.	• The system is operated on fault resistance 0.6 ohm and 2 ohms. • The response time of the model is less than 0.2 ms in both cases. But further modification may require.
[23]	A new protection scheme of anti-islanding protection strategy based on support vector machines (SVMs) for low-voltage-sourced microgrid.	•Commanding capability of classification for SVMs. • Independent of power quality (PQ). • Better performance on accuracy, authenticity, precision effectiveness, and selectivity.	• Seven inputs are monitored by the sensor. • Detection and discrimination of different types of faults in grids are not considered here.
[24]	An islanded microgrid protection strategy with coordination of LFC, OUFR and VIC based on a new swarm intelligence optimal PID controller. LFC-Load Frequency Control, VIC-Virtual inertia control, OUFR- Digital Over/ Under Frequency Relay.	•It can operate at high power penetration of wind/PV with robust frequency stability.	•To deal with the sudden mal-operation of the system the setting of OUFR is need to be readjusted for traditional VIC and LFC. Thus modified VIC is required.
[25]	A protection scheme for DC microgrid of low voltage is designed based on adaptive droop algorithm.	• Threshold values of voltage and current are used to identify the fault. The fault clearing time is 60 μs.	• Classification of faults and the transients is unable to obtain by this scheme.
[26]	Time-Time (TT) transforms protection strategy based on the value of current of synchronized measurement for each line end.	•The protection scheme has high accuracy, better robustness for any to changing faulty conditions, and shows good performance even in highly noisy conditions.	• The application of this scheme is restricted up to only two cycles between the signals of two ends. The tripping signals are sometimes delayed due to larger time difference. .
[27]	An inverter-dominated microgrid protection scheme that designed by making interconnection between iterative filtering-based empirical mode decomposition (IFEMD) and extreme learning machine.	•The scheme is suitable for dealing with the changing operating modes of microgrid at different topologies. •It also provides protection for both arcing and non-arcing faults. •Higher accuracy (98.667%).	•The performance is better up to noise level 30 dB (SNR).
[28]	A microgrid protection strategy depending on sine-cosine optimization (SCA)-based MPPT algorithm for detection and classification of distribution line faults at both islanding and	•At lower solar irradiance, the system can provide good protection and the time required for tripping signal is 11 ms.	•The trip signal produced by the relay is at 4.511 s. •And with ANN integrated protection scheme the time required for trip signal is 16.67 ms. Thus, the work can be extended to minimize the tripping signal time.

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Table 1 (*continued*)

	grid-connected condition.		
[29]	Low Voltage (LV) DC microgrid protection scheme is designed based on the natural characteristics of the fault current. To select the threshold value artificial line inductance (ALI) technology is used here.	•Fault detection time is very low (less than 250 µs. •This protection scheme has quick fault detection ability, adaptivity, and independent from different microgrid topology and communication. •No extra exclusive apparatus or high-speed microprocessor is required. Thus, it is also a cost-efficient protection scheme.	•The performance of the model is obtained with 8 kHz sampling Frequency. •Only fault current is considered here.
[66]	Centralized microgrid protection scheme based on voltage source converter (VSC). HIL approach is used for real-time validation of the scheme. HIL- Hardware in the loop.	•Required a smaller number of DC circuit breaker that makes quick operation. •Backup protection based on communication failure. •Self-healing properties.	•The system restoration time is within 100 ms-300 ms that needs to modify. •Additional differential relays-based protection is required for improving communication infrastructure.
[67]	Directional overcurrent dual setting-based relay type protection scheme for microgrid (MG). The scheme can operate both forward and reverse direction.	•Minimum time required for relay operation. •Independent of the communication signal for its primary operation.	•High bandwidth communication signals are not considered here. •There is some non-linearity in the programming of the protection scheme that needs to modify.
[68]	A protection scheme of DC microgrid by using local measurements and the characteristics of the system parameters. The scheme is independent of the communication network of the MG.	•Quick discrimination of faults of DC micrgrids. •Variation of the communication system in the DC MG is not affect the protection scheme. •Reduced the breaker rating and the overall cost.	•Time taking for fault detection is 500 µs that need to modify •Only loop type DCMGs system is considered here.
[69]	Combination of two fault detection methods to make a new protection scheme for DC microgrids. PSCADE software is used in this protection scheme.	•It can detect and localize the low resistance DC faults very quickly. •It also able to deal with high resistance DC faults accurately.	•Malfunctioning of the DC microgrid operation is avoided here at the time of changing the grid mode.
[70]	A central protection centre (CPC) MG protection scheme based on Prims aided Dijkstras algorithm.	•Continuous monitoring of MG. •Identifying the exact fault type and its location in the MG system.	•The scheme is applicable for small bus system. Large bus system is not considered here.

technical challenges related to the existing protection schemes. The section tries to investigate the main issues with DC microgrid protections. Those issues are categorized in two sections i.e. (i) Technical issues, and (ii) common issues.

Technical issues:

- Communication failure [37].
- Cyber-attacks [37].
- Low tolerance of the microgrid converters during high fault current [37].

Table 2

Overview of special protection schemes.

Refs. no.	Developed schemes	Strengths	Limitations
[20]	Inductance based fault detection approach.	•Only local measuring data is used. •Does not affect with the change of microgrid topology.	•Communication system is not considered.
[21]	ANN based microgrid station protection scheme.	•Identification and detection of fault, isolation of faulty unit	•False fault tripping time.
[30]	Sensor based energy fault detection.	•Sensor data is easily available. •A Virtual sensor is created to reduce manual works.	• Cannot use for different PV based faults identification.
[31]	Deep belief network (DBN) based on machine learning approach	•Can provide an accurate classification by learning the microgrid non-linear features. •Can identify short circuit fault from effected line.	• Load type is ignored • Three-phase voltage and current waveform is required.
[32]	Deep recurrent Artificial Neural Network based strategy.	•Significant prediction accuracy and computation loads	•There is no direct method to incorporate future data. • Intermediate layer is restricted at two numbers.
[33]	Unsupervised approach-based PV protection system.	•Anomaly detection of PV system, increasing system efficacy and less maintenance.	• Fault free environment is required for training the data, about its normal behavior. • Experiment with real faulty condition yet to be done.
[34]	A machine learning (ML) based intelligent technique for fault detection (FD) in microgrids using the local measurements.	•Better accuracy performance (greater than 95.7%). •Implementation cost reduction.	•The scheme has considered only low impedance faults for detection. •There is no device coordination process. The scheme does not deal with the microgrids stability issues.
[35]	A constant power load based localized protection strategy for DC microgrids having radial configuration.	•The location of fault is determined accurately. •The scheme also provides quick response and robust behavior. •The scheme is impervious against system configuration disturbances	•The margin of error for the developed scheme is maximum 3.2% during practical situation.
[36]	DC microgrid protection scheme based on bidirectional Z-source circuit breaker that has an O-shaped impedance network.	•The requirement of component is low. •The efficiency of operating power is increased. •The scheme also offers automatic interruption of fault, less reflection of fault current, common ground for all loads and power sources etc.	•At the time of fault interruptions an amount of fault current is reflected in the feeding source. •The MOV snubber should operate bidirectional with Z-source circuit breakers (ZSCB).
[37]	Blockchain based differential	•To protect the DC microgrid from cyber-	•The time taken to detect the cyber-

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Table 2 (*continued*)

	microgrid protection scheme.	attacks and communication failure.	attacks is less than 2.5 ms, which can be improved.
[38]	It is a non-unit line protection model that includes the voltage traveling waves (ILVTWs) of initial line-mode operation.	•The sensitivity and reliability are very high with good accuracy. •The threshold value of the protection model is independent of simulation.	•Only current derivatives are used for determining the forward faults. •The sampling frequency is considered based on critical frequency.
[39]	A microgrid protection scheme based on the positive sequence currents.	•Synchronization of data is not necessary at the time of exchanging information between the lines of the relays. •This scheme provides immunity to harmonics, communication at lower bandwidth and flexibility.	•This scheme is mainly focused on minimizing the communication cost during the microgrid protection strategy using the differential relay.
[40]	Kernel Extreme Learning Machine (KELM) based Hilbert–Huang Transform (HHT) protection scheme for distributed generation (DG) integrated microgrid system.	•Superior security, robustness, dependability, reliability and accuracy for detection of fault conditions.	•Line-Line (LL) faults are considered as more critical for identification at different topologies.
[41]	Artificial Neural Network based decentralized communication-less DC microgrid protection scheme that uses cuckoo search metaheuristic.	•The scheme provides back-up protection. It has more than 96% accuracy values and dependability of 99%.	The Artificial Neural Network enables each classifier to detect faults with only local voltage and current measurement.
[51]	Protection scheme for DC microgrid with recurrent neural networks (RNNs) that can identify exact location of fault on the load feeders. For designing the microgrid.	•Fault detection with higher accuracy. •Only feeder current and main bus voltage is used. •The overall condition of the microgrid system is also determined by using decision tree-based classifier (DTC).	The total error for both RNNs (i.e., grid connected and islanded) is less than 3% that can be improved.
[52]	Robust detection scheme for DC microgrid cyber-attack based on Parity method.	•Designing is easy. •Less computation complexity. •Only local information is used. •There is no coupling between the residuals of unknown load and nearer voltage variations. •It can applicable in DC microgrid clusters.	The detection of cyber-attack is depending on the threshold point at higher residual. Thus, the designing of threshold point is needed extra care.
[53]	Support vector machines (SVMs) is used for locating faults in DC microgrid clusters.	•Localized the high impedance faults with local measurements. •The scheme is not directly affected by the disturbances (like: bad calibration, noise etc.). •High accuracy, cost effective and less error.	•Other parameters (such as voltage, power etc.) are not considered in this scheme. •Signal-processing, deep-learning tools can be used as combination for development the scheme.
[54]	Travelling wave (TW) based microgrid protection scheme, to calculate high frequency components.	•Higher accuracy for large number of training data. •Communication free single ended protection scheme.	•The time taking for finding out the fault location is 200 micro-second, which can be modified.
[55]	A travelling wave (TW) based protection scheme for detection, classification and localization of various types of DC faults in MVDC microgrid. MVDC- Medium voltage DC	•Fast and communication less techniques. •Both primary and backup protection is provided. •Robustness against higher resistance faults up-to 200 ohms. •Independent from voltage level and system configuration.	•The time required of the TW is not considered here. •The maximum error limit for fault zone is (+-) 38 m, which can modify. •The scheme avoids the communication failure.
[56]	An adaptive overcurrent relay protection scheme based on both sequence components of fault current.	•Real-time microgrid operation. •Reliable performance with different critical faults in various fault resistance.	•The overcurrent relays are not operating in low fault current. Thus, super imposed component of current is required.
[57]	WiMax based protection strategy with wide area wireless communication network is proposed here.	•The scheme is able to integrate smart grid and microgrid with better communication network. •The scheme is very up-to-date.	•Real time implementation is not considered here.
[58]	A wavelet transforms based fault detection scheme for microgrid with deep neural networks. CERTs microgrid and IEEE-34-bus system is used for evaluation of the proposed scheme.	•It can identify fault type and provide faster response of faulty phase with its location. •Service recovery is also provided with the scheme. •The scheme is robust against measurement uncertainty.	Here three-phase current magnitude is used for measurement. But for real time validation some fault resistance values are required.
[59]	An adaptive protection scheme based on over current protection strategy is developed here for microgrid network. ANN based control strategy is also used to train the system with real-time data. ANN- Artificial neural network.	•Smart and reliable operation. •The total error obtained from all the system is less than 1%. •This quantity of error is acceptable in the state estimation strategy.	•Two ANN method is used here that makes the system more complicated.
[60]	A combination of differential and adaptive overcurrent relay is designed for microgrid protection.	•Protection of individual feeders, the interconnecting buses, DC sources, backbone feeder and load points. •Less infrastructure upgrades.	•This scheme is only operated on the particular zonal faults.
[61]	Multi-agent strategy based microgrid protection model which architecture is based on the three relay agents (such as selectivity, configurator, and coordinator.	•It is working on both online and offline mode. •This scheme provides quick protection, assortment and centralizing key information. •Back up protection is also included.	•Multi domain modeling is not considered here. •The proposed scheme is not tasted on different sorts of communication systems.
[62]	A combination of MPC & ANN to make protection strategy for detecting and	•Faster response and smaller overshoot. •The scheme also provides secure	•MPC based models are responsible for increasing the computational burden.

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Table 2 (*continued*)

	removing the false information injected in the DC microgrid system. MPC- Model Predictive Control.	detection of cyber-attack.	• Artificial intelligent based strategy is needed to deal with different types of cyber-attacks.
[63]	Adaptive droop-based control strategy for mitigating communication faults in DC microgrids.	•Detection of missing or failure link in the communication system. •Quick maintenance microgrid operation.	•Real time approach is not considered here. •And the proposed scheme is unable to deal with complex communication.
[64]	An attack index-based DC microgrid protection scheme for detecting stealth attack using the information from current sensor.	•Calculation of attack index is only depending on the low bandwidth communication and system's local measurements.	No real time validation of the proposed protection scheme is discussed here.
[65]	Combination of traditional and an adaptive protection scheme for microgrid protection with a preemptive switching algorithm.	•Increase the accuracy and precision of protection scheme. •Reduced overall communication rate.	•Real time experiment is avoided.
[71]	An adaptive protection strategy (that operate automatically) to provide reliable and secure functioning of microgrid. The scheme is based on pre-calculated setting of overcurrent relays.	•Reliable protection scheme. •Reconnection of microgrid after fault recovery is easy.	•Any change in the microgrid topology needs special analysis.
[72]	An adaptive protection co-ordination strategy based on numerical directional overcurrent relays (DOCRs). Here commercial AMPL based IPORT solver is used to make the scheme more efficient. (AMPL- A Mathematical programming Language. IPOPT -Interior Point Optimization)	•The scheme can handle different operating situations of microgrid, like-generation, line & load loss conditions etc. • In this scheme real-time data is used. •Miss-coordination in the microgrid system at the time of distribution generator installation also handled by the protection scheme.	•The scheme is tested on IEEE-14 bus system. Larger bus system is not considered here.
[73]	An adaptive protection scheme based on real-time changing of over current relay setting. The scheme is tested on IEEE-13 bus feeder system.	•Misoperation issues of relay are trying to solve. •Proper co-ordination of devices in the microgrid at the time of changing the modes (i.e., islanded and grid connected modes).	•The scheme is depended on the reliability of communication network. •For large scale microgrid system latency and data congestion problems are needed more attention.
[74]	Differential current based protection scheme that is able to detect fault and its location very quickly for DCMG of multiple solar PV system	•Calculating the accurate locations of fault at very less time for DC cables. •Location of series arc fault in solar PV system is also detected by the scheme. •It is a non-iterative and discrete time	•The scheme is working on low voltage, while connected with utility grid.
		frame-based protection strategy.	
[75]	An adaptive protection scheme based on quadrature & zero sequence components of fault current.	•Improvement of speed of relay operation. •The numbers of protection channels are reduced. •The total cost and size of the protection scheme is reduced.	•The proposed scheme is designed for rural villages only. •All Loads are inductive. Only the components I^0&I^q are used.
[76]	An adaptive microgrid protection scheme based on central protection unit (CPU). Practical scenario of Sri Lankan Power system.	•It is a reliable protection scheme. •The scheme helps to develop self-operated microgrid that reduced the involvement of human for microgrid operation, calculation and designing Continuous monitoring of microgrid.	•The scheme is designed with the consideration that there is zero distance between relay and fault location. •Only single microgrid connection with the utility grid is considered here. •Failure of communication and disconnection of load at that instant is not discussed in this scheme.

- Blockchain based energy marketing strategy of microgrids are hindered because of recent regulations that are not allowing for running local peer-to-peer energy markets in most of the countries [42].
- Different types of protection configurations and settings for different microgrid topologies [43,48].
- Lack of controlling configurations specifically designed for managing grid-connected condition of DC microgrids [44,47].

Common issues:

- Load types are ignored for better accuracy [31].
- False positive rate of detection [45].
- Difficulties to find out exact fault locations [17].
- Different types of shading faults [46].
- Presence of harmonics due to power electronic converters switching [9].
- Inverter noise, very low fault current, zero current crossing etc. [11].

5. Protection devices in DCMG

To isolate the faulty section from the healthy section in the DC microgrids several protection devices are used. In Fig. 3 the protection devices used in DC grids are presented with their advantages and limitations [11,16].

6. Research gaps

In DC microgrids small disturbance may cause major faults. So, this factor should consider for designing a reliable and secure protection model. Here some research gaps are listed out from the literature review of DC microgrid protection.

a The most important factor for digital microgrid protection is uninterrupted and secure communication network. But from the literature review it is shown that no perfect scheme is developed to maintain the communication network correctly.

b Sensitivity of the protection schemes is very important as the tripping signal is directly depends on it. But in most cases false tripping signal is appeared that indicates weak protection scheme.

Table 3
Overview of grid modes and software tools.

Refs. no.	Microgrid (MG) mode of operation	Microgrid topologies	Software tools
[3]	Grid connected	Radial, Tree and multi-terminal circuit	MATLAB/Simulink
[9]	PV based grid connected MG	Not mentioned	MATLAB/Simulink
[13]	Grid connected and Islanded MG	Radial	MATLAB/Simulink
[14]	Islanded MG	Not mentioned	MATLAB/Simulink and TMS320C713 digital signal processor.
[15]	Grid connected and Islanded MG	Radial and Meshed and integrated inverter-interfaced DER (Distributed Energy Resource)	DigSilent power factory
[17]	Grid connected and Islanded MG	Radial and loop	Real time digital simulator (RTDS) with integrated MATLAB.
[19]	Grid connected and Islanded MG	Not mentioned	An online trained RPWFNN controller
[20]	Grid connected and Islanded MG	The scheme is independent of MG topologies.	Not mentioned
[21]	Grid connected and Islanded MG	Not mentioned	MATLAB/Simulink
[23]	Standalone Islanded	Not mentioned	MATLAB/Simulink
[24]	Islanded	Not mentioned	MATLAB/Simulink
[25]	Grid connected and Islanded MG	Not mentioned	MATLAB/Simulink
[26]	Grid connected and Islanded MG	Radial and loop	PSCAD/EMTDC
[27]	Grid connected and Islanded MG	Can applied for different topologies	MATLAB/Simulink
[28]	Grid connected and Islanded MG	Not mentioned	OPAL-RT digital Simulation platform.
[29]	Grid connected and Islanded MG	Not mentioned	Simulation
[30]	Grid connected and Islanded MG	Not mentioned	Python and MATLAB.
[31]	Grid connected and Islanded MG	Radial and loop	MATLAB
[33]	Islanded	Not mentioned	MATLAB/Simulink PSIM with Sim Coupler modular.
[34]	Grid connected and Islanded MG	Not mentioned	DigSilent Power factory
[35]	Grid connected and Islanded MG	Radial	Time domain DigSilent Power factory.
[36]	Grid connected and Islanded MG	Applicable in different topologies.	Simulation
[37]	Grid connected and Islanded MG	Not mentioned	MATLAB/Simulink
[38]	Grid connected and Islanded MG	Not mentioned	PSCAD/EMTDC
[39]	Grid connected and Islanded MG	Not mentioned	Simulation
[40]	Grid connected mode only	Radial and loop	MATLAB/Simulink
[41]	Grid connected and Islanded MG	Changing of topology does not affect the scheme.	DigSilent power factory and Python
[51]	Grid connected and Islanded MG	Not mentioned	MATLAB/Simulink and DigSilent software.
[52]	Microgrid cluster for both Grids connected and Islanded mode.	Not mentioned	dSPACE-based microgrid platform
[53]	Microgrid cluster for both Grids connected and Islanded mode.	Not mentioned	Python
[54]	Grid connected and Islanded MG	Radial and meshed	PSCAD/EMTDC
[55]	Grid connected and Islanded MG	For all topologies	MATLAB/Simulink
[56]	Grid connected and Islanded MG	Not mentioned	Real time digital simulator (RTDS)
[57]	Grid connected and Islanded MG	Not mentioned	OPNET modular software
[58]	Grid connected and Islanded MG	Radial and loop	CERTS microgrid system of time series simulation.
[59]	Grid connected and Islanded MG	Radial and loop	MATLAB
[60]	Grid connected and Islanded MG	Not mentioned	EMTP-RV software
[61]	Grid connected and Islanded MG	Not mentioned	PSCAD software is used.
[62]	Grid connected and Islanded MG	Not mentioned	MATLAB/Simulink.
[63]	Grid connected and Islanded MG	Not mentioned	MATLAB/Simulink.
[64]	Grid connected and Islanded MG	Ring connected	MATLAB/Simulink.
[65]	Grid connected and Islanded MG	Not considered	MATLAB
[66]	Grid connected and Islanded MG	Not mentioned	OPAL-RT based Real time simulation and MATLAB/Simulink.
[67]	Grid connected and Islanded MG	Not mentioned	MATLAB
[68]	Grid connected and Islanded MG	Loop type	Real time digital simulator (RTDS)
[69]	Grid connected and Islanded MG	Radial, ring and meshed	PSCAD
[71]	Grid connected and Islanded MG	Not mentioned	DIgSILENT Power factory
[72]	Grid connected and Islanded MG	Not mentioned	IAMPL based IPORT solver is used.
[73]	Grid connected and Islanded MG	For all topologies	ETAP
[74]	Grid connected and Islanded	Not mentioned	MATLAB/Simulink
[75]	Grid connected	Radial and loop	MATLAB/Simulink
[76]	Grid connected and Islanded	Not mentioned	Not mentioned

c Digitalization of DCMG structure and interconnection of DCMGs with traditional grids is facing several challenges.

d Some faults such as arc faults, DC short-circuit faults etc. that are not noticed as the initial stage can cause severe damages of the total grid system.

e Integration of DCMG to traditional grids for supplying AC loads needed more power converter devices that make the overall energy cost high and more power loss. Thus, DC loads are now needed to be in the limelight.

f In case of AI-based approaches while implementing for DCMG protection a fault free and secure platform is required for collecting, normalizing and processing the data. The whole operation of AI-based schemes is directly depending on the data.

g Malfunctioning of the microgrid parameters at the time of changing the operating mode is avoided in most of the protection designing cases.

h Most of the microgrid protection schemes are used the grid parameters (such as current, voltage, frequency etc.) separately, i.e., either current or voltage or frequency, not all together.

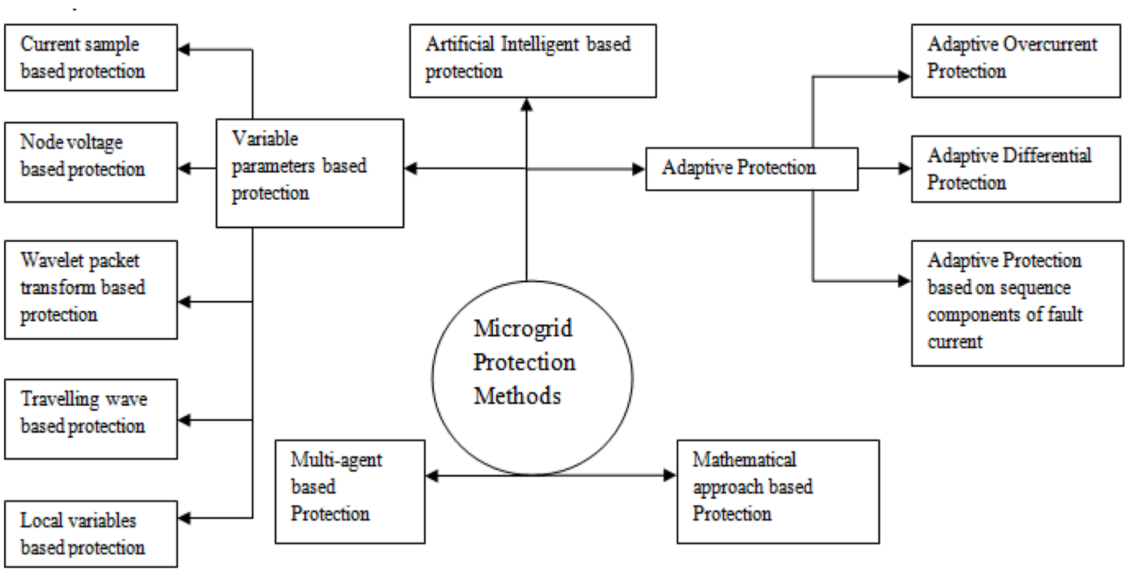
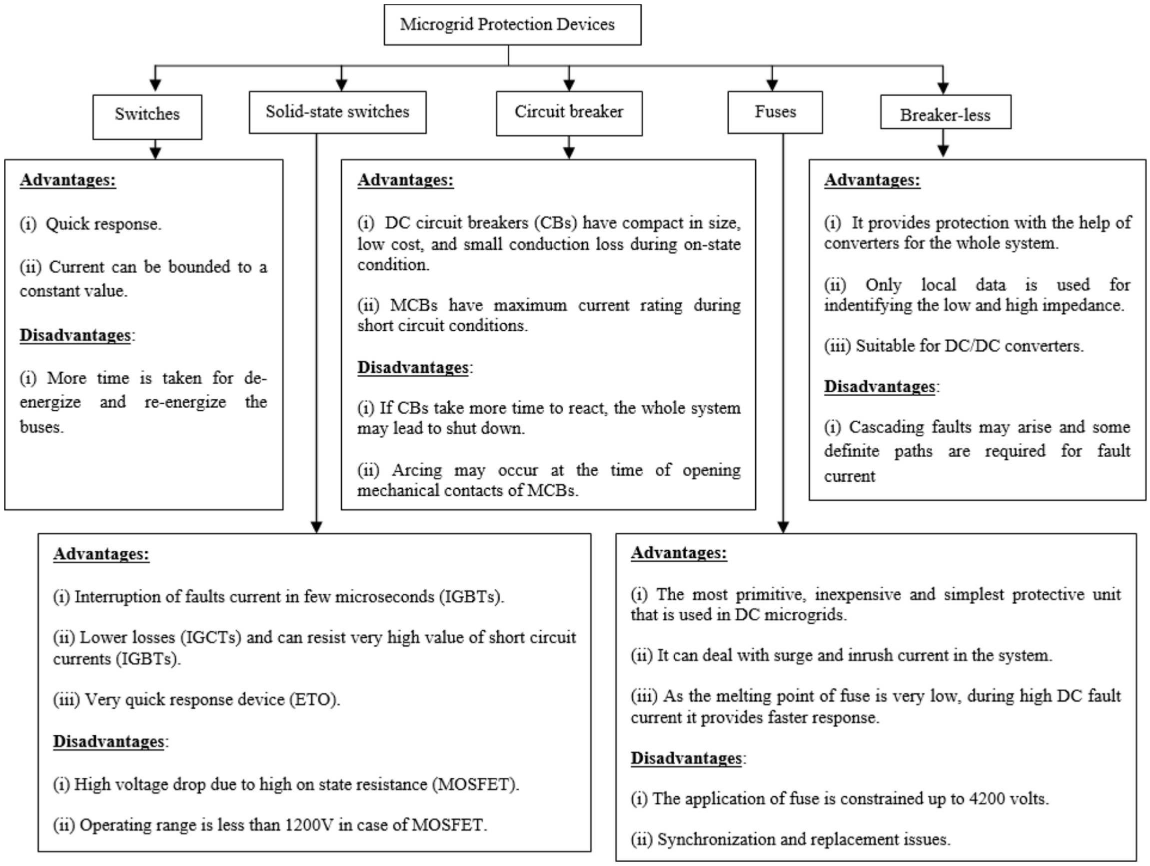


Fig. 2. Microgrid protection methods.



Advantages:

(i) Quick response.

(ii) Current can be bounded to a constant value.

Disadvantages:

(i) More time is taken for de-energize and re-energize the buses.

Advantages:

(i) DC circuit breakers (CBs) have compact in size, low cost, and small conduction loss during on-state condition.

(ii) MCBs have maximum current rating during short circuit conditions.

Disadvantages:

(i) If CBs take more time to react, the whole system may lead to shut down.

(ii) Arcing may occur at the time of opening mechanical contacts of MCBs.

Advantages:

(i) It provides protection with the help of converters for the whole system.

(ii) Only local data is used for indentifying the low and high impedance.

(iii) Suitable for DC/DC converters.

Disadvantages:

(i) Cascading faults may arise and some definite paths are required for fault current

Advantages:

(i) Interruption of faults current in few microseconds (IGBTs).

(ii) Lower losses (IGCTs) and can resist very high value of short circuit currents (IGBTs).

(iii) Very quick response device (ETO).

Disadvantages:

(i) High voltage drop due to high on state resistance (MOSFET).

(ii) Operating range is less than 1200V in case of MOSFET.

Advantages:

(i) The most primitive, inexpensive and simplest protective unit that is used in DC microgrids.

(ii) It can deal with surge and inrush current in the system.

(iii) As the melting point of fuse is very low, during high DC fault current it provides faster response.

Disadvantages:

(i) The application of fuse is constrained up to 4200 volts.

(ii) Synchronization and replacement issues.

Fig. 3. Overview of protection devices.

7. Future directions

Several protection strategies are reviewed in this paper to highlight the present status of DC microgrid protection schemes. But most of the concepts are not implemented on the practical basis. Therefore, some important factors are considered here to make robust protection scheme in future:

- To make the protection scheme more reliable, it is necessary that the structures of grids are designed especially.
- Modern digital protection devices (like PMU & IDM based protection devices, DC circuit breakers etc.) need to be introduced in microgrids.
- For real-time and continuous monitoring and data collection from the grids IoT (Internet of Things) based approaches can apply in the protection schemes.

- The time taken for fault detection need to be improved along with the relay tripping time.
- A secure communication network is required for having true information regarding the data transfer.
- To deal with cyber-attacks advance protection technologies such as blockchain based approach, need to implement,
- Inverter based microgrids that operate in islanded mode are required modern fault detection techniques with or without communication.
- Some special protection issues such as high impedance faults and meshed network need better analysis.
- There is a lack of configuration, smart communication, software and orchestration for microgrid system that required improvement.
- To maintain the privacy of MG is a big challenge while the grid is connected with utility grids.

8. Conclusions

The paper presents research status of the several existing DC microgrid protection schemes. This paper has summarized the recent research articles related to the traditional and advanced protection schemes of DC microgrid to identify the limitations, challenges, pros and cons of the existing works. In study it is observed that MATLAB/Simulink is the most popular software choice among researchers. Others options being PSCAD, RSCAD (the one which comes with RTDS). There are many other simulation platforms like OPAL-RT digital Simulation platform, dSPACE, Python, DigSilent software etc. are used by researchers.

From this review it is shown that maximum protection schemes are used for both mode of DCMG (islanded and grid connected) although both the mode has different faults issues. To develop a cost-effective intelligent protection scheme continuous research is required on this domain, The novel protection scheme includes accuracy, sensitivity and faster response, low power loss, compact size, long life time, cost effective while detecting the faults and isolate the faulty unit from the healthy system. The management of upstream and downstream devices with protection units is also a significant research topic for future. As the DC microgrids have a large number of electronic devices like converters, communication networks etc., the research on protection (area like converter topology, IOT, Blockchain Technology, AI, Machine learning, Deep Learning) could be extended towards this. But, due to a lack of standards and involvement, more effort is still required to overcome the boundaries of existing protection schemes for all circumstances and scenarios.

From the review, it is clear that most of the existing protection schemes (advance and traditional) have more or less limitations, which need to improve for better performance of microgrids. The traditional protection schemes make the microgrid system bulky. The time for trip signal is also high and cannot detect low voltage faults. In case of advance protection scheme implementation cost is high, as the grids are needed to be digital. But in practice scenario, the total cost of energy is reduced compared with other traditional schemes. So, DCMG system is fronting problem for its alteration. So, the researchers have much more opportunity to exertion in this area.

The dynamic changes in microgrid need to be handling carefully. Hence artificial intelligent (AI) based approaches are suitable in this regard. In AI based techniques the protection system trained with a large amount of data where maximum variation is included. The ANN based protection models have less development cost and calculation time. It also has reduced complexity in designing that prefers real-time implementation. There is barely any paper talking the execution of AI based in precise zones of DC micro grid protection. The study addressing these precise zones of AI based protection schemes application. In DC microgrid protection is deceptively nominal and hedging an extensive choice for additional consideration by researchers. In adding, we have offered numerous crucial challenges those are focused in the direction of some open research opportunity. We hope that this review will be supportive for the researchers.

Declaration of Competing Interest

We declare that we have no conflict of interest.

Acknowledgments

This study is based on an independent research work from the Tripura University, “Research on the DC microgrid protection”.

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