A Review on Challenges in DC Microgrid Planning and Implementation

Kolampurath Jithin, *Graduate Student Member*, *IEEE*, Puthan Purayil Haridev, Nanappan Mayadevi, Raveendran Pillai Harikumar, *Member*, *IEEE*, and Valiyakulam Prabhakaran Mini

***Abstract*—DC microgrids are gaining more attention with the increased penetration of various DC sources such as solar photovoltaic systems, fuel cells, batteries, etc., and DC loads. Due to the rapid integration of these components into the existing power system, the importance of DC microgrids has reached a salient point. Compared with conventional AC systems, DC systems are free from synchronization issues, reactive power control, frequency control, etc., and are more reliable and efficient. However, many challenges need to be addressed for utilizing DC power to its full potential. The absence of natural current zero is a significant issue in protecting DC systems. In addition, the stability of the DC microgrid, which relies on inertia, needs to be considered during system design. Moreover, power quality and communication issues are also significant challenges in DC microgrids. This paper presents a review of various value streams of DC microgrids including architectures, protection schemes, power quality, inertia, communication, and economic operation. In addition, comparisons between different microgrid configurations, the state-of-the-art projects of DC microgrid, and future trends are also set forth for further studies.**

***Index Terms*—Architecture, communication, DC microgrid, economic operation, inertia, protection, power quality.**

I. INTRODUCTION

ELECTRICITY has been the cornerstone of the industrial advancements that have taken place since the early 20th century. The improvements in electrical technology are the prime reason for the enormous strides in the scale of progress made by humanity over the past century [1]. Electricity, as a valuable form of energy, has been generated and transmitted in the form of AC or DC since its inception. Though DC was prominent initially, indicated by the establishment of 58 localized DC power plants in the United States of America by Thomas Alva Edison in the early 1800's, over time, AC took over the lead and dominated the electricity generation and transmission [2].

The ever-increasing demand for fossil fuels due to explosive growth in automotive and other industrial sectors has rendered the earth lack of fossil fuels. Furthermore, the excessive use of fossil fuels has resulted in an escalation in pollution levels on the planet [3], [4], which demands a change or rather replacement in the electricity generation procedure. The prime contender, i.e., renewable energy sources (RESs), are primarily DC. Even though DC power generation was limited initially by its voltage drops and reduced generation voltage, the advancements in power electronics and allied sections of electrical engineering have resolved these problems [5]. Subsequently, the focus on electrical power generation has shifted from fossil fuels to RESs [6]-[8]. Unlike conventional energy production, localized generation becomes possible with RESs [9]-[11], which is economically advantageous [12] and is a promising step towards sustainability.

The conventional grid requires a transmission and distribution infrastructure for distributing the generated energy. The losses in the transmission and distribution network are huge, especially in countries like India [13], which demands a persistent solution. The initial gaze falls upon distributed generators (DGs), which generate power at locations close to the load centers. It offers many technical, economical, and environmental advantages [14]. The technical benefits are reduced line losses, improved voltage profile, increased overall efficiency, and improved system stability and reliability. The economic benefits include reduced operation and maintenance costs along with increased productivity [15]. It also has low infrastructural requirements in comparison with the actual power grid [16]-[18]. Moreover, the public's keen interest in environment-friendly energy production and rapid growth in demand for power has necessitated the usage of DGs. Microgrids thus emerge as a better solution by operating various distributed energy resources (DERs), loads, and storage devices as a single controllable unit. Microgrids can operate in both grid-tied and islanded modes [19]. Microgrids reduce the burden of main grid by supplying a share of its loads [20]. A microgrid is different from the conventional grid in the aspect that the sources are close to the load centers and offer a bidirectional flow of electricity [21]. As most of the DGs associated with storage devices and the

Manuscript received: January 26, 2022; revised: May 4, 2022; accepted: June 17, 2022. Date of CrossCheck: June 17, 2022. Date of online publication: July 19, 2022.

K. Jithin (corresponding author), N. Mayadevi, R. H. Kumar, and V. P. Mini are with the Department of Electrical Engineering, College of Engineering Trivandrum, APJ Abdul Kalam Technological University (APJAKTU), Thiruvananthapuram, Kerala, India (email: d-tve19jan029@cet. ac. in; maya@cet. ac. in; harikumar@cet.ac.in; minivp@cet.ac.in).

P. P. Haridev is with Tata Consultancy Services (TCS), Kochi, Kerala, India (e-mail: haridevrono288@gmail.com).

DOI: 10.35833/MPCE.2022.000053

connected loads are DC [22], DC microgrids are acquiring more attention. Figure 1 shows the general configuration of a DC microgrid. Due to the increased penetration of various RESs into the system, the system inertia reduces [23]-[25] as these RESs are coupled to the grid using power electronic converters (PECs) [26]-[28] which do not possess any rotational inertia. As the number of PECs in the system increases, the inertia issue will aggregate, leading to drastic stability issues. This will also make the converter control more tedious [29], [30]. Hence, the disturbances easily affect DC bus voltage, causing unwanted tripping and load shedding. Thus, various energy storage devices such as batteries, supercapacitors, flywheels, etc. have to be integrated with the system for adequate inertia support [31]-[33]. Battery is the storage device mainly used with microgrid [34].

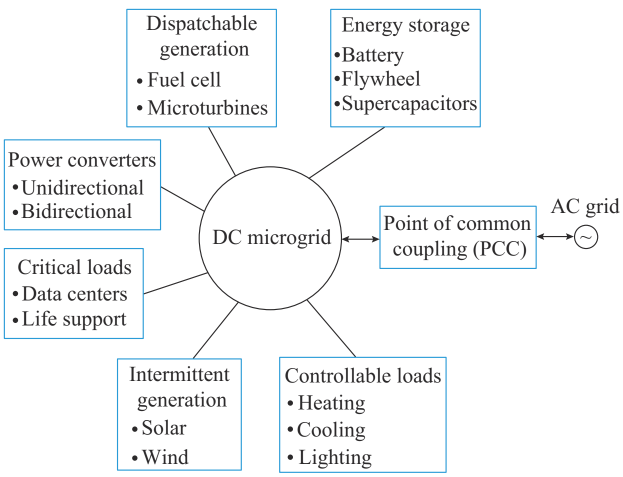

Fig. 1. General configuration of DC microgrid.

But the overcharging and discharging scenarios associated with the battery compel the battery integrated system to operate in an insecure zone [35]. Other factors of concern include the capital cost, maintenance cost, and the size of the battery [36], [37]. Interconnecting multiple microgrids to form a cluster can reduce the overall size of the battery in the system [38], [39]. Thus, the interconnection of neighboring microgrids will improve the virtual storing potential and discharging efficiency of the system [40], [41]. Figure 2 depicts the structure of an interconnected microgrid with *n* buses.

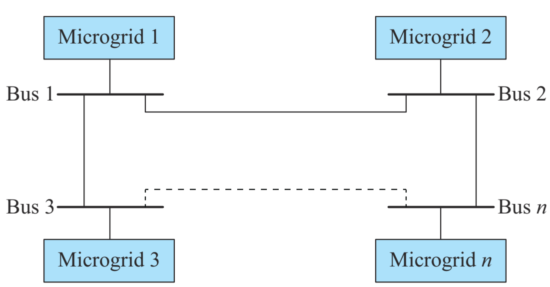

Fig. 2. Structure of interconnected microgrid with *n* buses.

This paper takes DC microgrid as its focal point and explains various benefits and challenges in implementing a DC microgrid system. The rest of this paper is organized as follows. Section II explains various DC microgrid architectures and their comparison. Different types of faults in DC microgrids and protection schemes are discussed in Section III. Power quality (PQ) issues and inertia issues in DC microgrids are presented in Sections IV and V, respectively. Section VI gives an idea about various communication challenges. Economic operation and control of DC microgrids are described in Section VII and various applications of DC microgrids are depicted in Section VIII. Section IX portrays the comparison between different microgrid architectures and Section X lists the latest DC microgrid projects around the world. Section XI lists the future trends in the DC microgrid research. Finally, conclusion is given in Section XII.

II. DC Microgrid Architectures

The hardware topologies for a DC microgrid are decided based on practical requirements. The main factors to be considered are the robustness, flexibility, and reliability of the microgrid [42]. For industrial applications, the most robust structure is the microgrid with storage devices directly connected to the main bus [43], [44]. The most commonly used energy storage device is a battery stack [45]-[48]. Such architecture is used in telecommunication networks [49] or rural microgrid networks [50], [51]. So, by interfacing storage devices directly, issues related to the converters can be avoided [52], [53].

The system flexibility gets enhanced by the introduction of various PECs, as voltage regulation and control become much easier [54], [55]. Based on this, various configurations such as transformer-enabled DC networks [56]-[58], bipolar networks [59], [60], and DC grids with redundant bus structures [61], have been proposed. The classification of DC microgrid architectures is portrayed in Fig. 3.

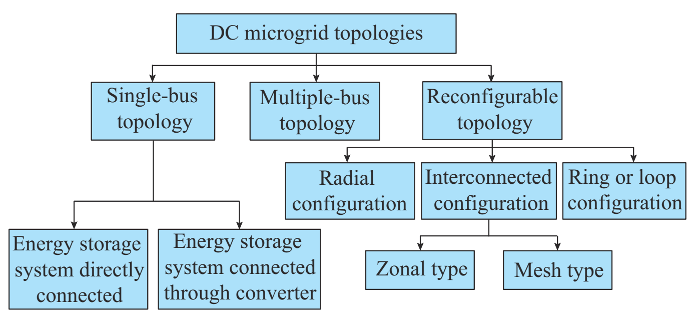

Fig. 3. Classification of DC microgrid architectures.

A. Single-bus Topology

Single-bus topology can be considered as the simplest microgrid structure. The system will have only one common bus, and all components such as sources, loads, storage devices, are connected to the bus using various converters [62]. Direct connection of storage devices is also possible. Figure 4 shows the structure of a DC microgrid with a single-bus topology and battery directly connected to the bus [63]. Even though this structure is robust, the poor regulation of bus voltage due to variation in battery current and state of charge (SoC) makes it less reliable [64], [65].

The overall system performance in this configuration can be improved through the converters in the system, which make the voltage control much easier and more flexible. Figure 5 shows the DC microgrid with a single-bus topology and battery connected via a PEC. However, there are issues like difficulty in designing the control circuits and the availability of only one bus in the network to supply power for multiple units [66]-[68].

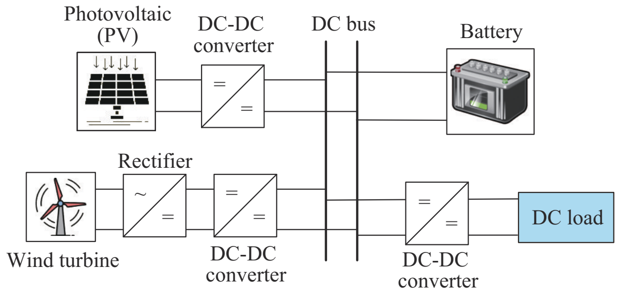

Fig. 4. Structure of DC microgrid with single-bus topology and battery directly connected to bus.

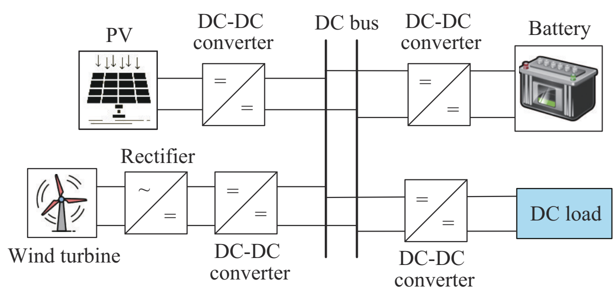

Fig. 5. Structure of DC microgrid with single-bus topology and battery connected via a PEC.

B. Multi-bus Topology

The reliability and flexibility of the system can be improved by extending single-bus topology to multi-bus topology with more voltage levels. A DC microgrid with multi-bus topology and improved system performance is developed in [69], as shown in Fig. 6. Various approaches to selecting the most suitable bus for the interconnection of the load are presented in [70], [71].

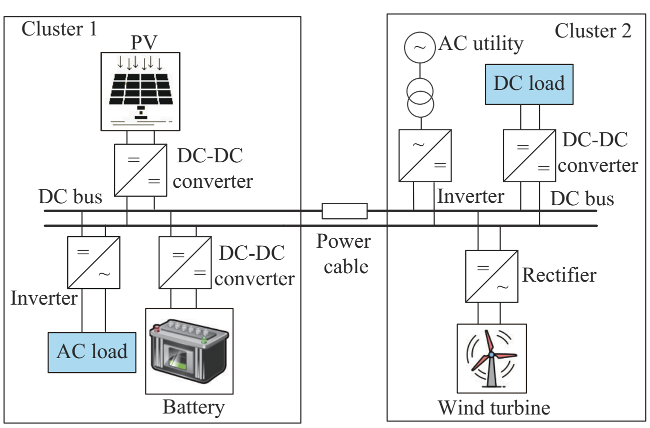

Fig. 6. DC microgrid with multi-bus topology.

In microgrid cluster configurations, each microgrid can inject or absorb power, during power surplus or deficit, respectively. Moreover, diverse units in the system support each other and can be controlled accordingly [72].

C. Reconfigurable Topology

Various reconfigurable architectures have also been proposed for DC systems to address the intermittent nature of RESs [73]. The DC systems are connected with conventional AC systems to ensure the reliability of the system. The interface between the systems is categorized in different ways.

1) Radial Configuration

In this architecture, the AC system is interfaced with the DC system at one end. The path available for the power flow to the load is limited to one. Figure 7 shows the DC microgrid with radial configuration. The configuration can be a single bus or multiple buses as explained in the Section II-A and II-B. Radial configuration can be series or parallel based on the requirements. Compared with the series radial type, the parallel radial type is the most preferred configuration as it makes the isolation of faulty sections easier and is more flexible as power-sharing is possible between various units in the system [74], [75]. However, the design is much more complex as the single bus has to manage the overall power flow. The distribution losses in this configuration are comparatively negligible and it is mainly used for low voltage applications such as domestic loads [76].

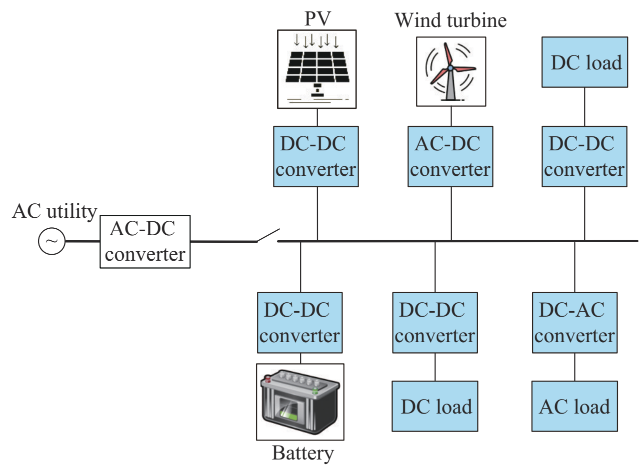

Fig. 7. DC microgrid with radial configuration.

2) Ring or Loop Configuration

The main drawback of radial configuration with one path for power flow is eliminated by providing multiple paths, for customer and grid interface, in a ring configuration. Figure 8 shows a DC microgrid with ring configuration. During fault conditions, an intelligent electronic device (IED) provided in the system isolates the fault section by operating the sectionalizing switches [77], thereby improving the system's reliability. Also, the entire DC part of the system gets isolated from the AC power grid during contingencies.

3) Interconnected Configuration

In interconnected systems, the DC microgrid is provided with multiple AC supplies, ensuring the availability of at least one AC supply in the system during all fault conditions, thereby improving the system's reliability. Interconnected configuration has two architectures, i.e., mesh or zonal type. Mesh-type architecture is the most suitable for high-voltage DC systems, which provides better operational reliability compared with previous configurations [78].

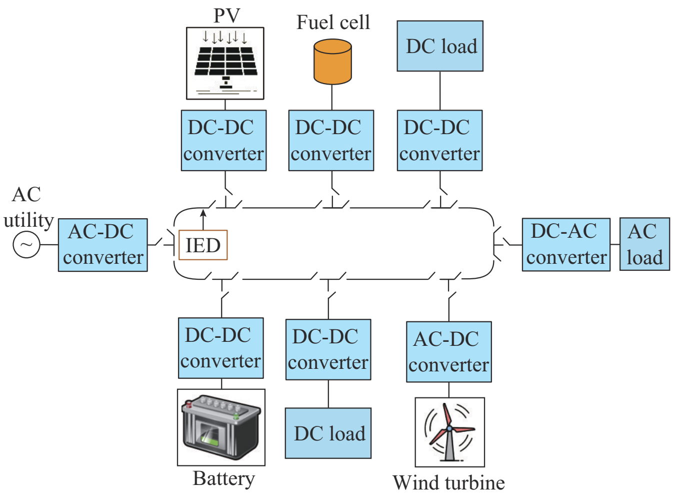

Fig. 8. DC microgrid with ring configuration.

AC utility is interfaced with DC through converters, as shown in Fig. 9. In a mesh-type system, the effect of the fault on the system operation will be less as multiple AC feeders are available for supplying various sections in the system. One of the methods by which the faulty bus gets isolated is a technique called handshaking. Various fault detection techniques in multi-terminal DC systems are explained in [79].

The second configuration, zonal type, is mainly used in shipboard integrated power systems [80]. In zonal type, there are multiple options for the load to get powered. The supply to the load can be provided simultaneously, sequentially, or from only one bus at a time. Since there are multiple buses for the load to receive power, the most suitable bus is decided based on the bus selection method. According to the requirements, loads can be switched between various buses. Figure 10 shows a DC microgrid with zonal-type architecture, where the entire system is divided into multiple zones. Each zone in the system has various components like sources, converters, loads, and energy storage devices. Multiple switches are provided in the system to isolate the faulty sections and ensure continuity of supply to non-faulty sections in the event of fault [81]. Even though this system is more reliable than the mesh-type, a disadvantage of the system is complex. Due to the electronic revolution in this era, most end-user types of equipment based on DC have conquered the markets. Various domestic loads, data servers, communication systems, etc., are DC systems nowadays [82]. The major requirement of these systems is a stiff bus voltage even with variations in load and generation [83].

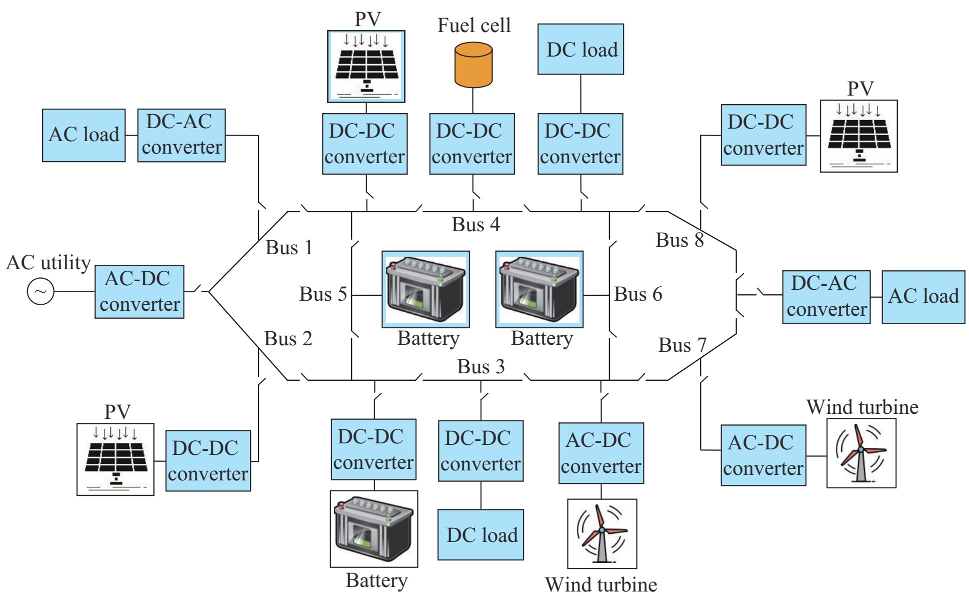

Fig. 9. DC microgrid with mesh-type architecture.

Supercapacitors have grown as a major solution to the issues associated with the fluctuating bus voltage in DC systems. A DC microgrid architecture with a supercapacitor is developed in [84] and is shown in Fig. 11, where a supercapacitor is connected as the DC link capacitor, thereby eliminating all the output capacitors of different sources and storage devices. This configuration ensures constant bus voltage under all operating conditions. Table I gives the summary of the features of different DC microgrid architectures.

III. DC Microgrid Faults and Protection Schemes

DC microgrid faces several challenges in the protection sector and the major area of concern is the fault. DC microgrid architectures are still evolving and this proves to be another barricade in devising a proper protective strategy in a general context [85]. The protection challenges come in a variety of forms. Issues in a DC microgrid arise mainly due to load variations, input power fluctuations, maximum power point tracking (MPPT) controls with DERs, the occurrence of temporary faults, delay in communication, etc. [86].

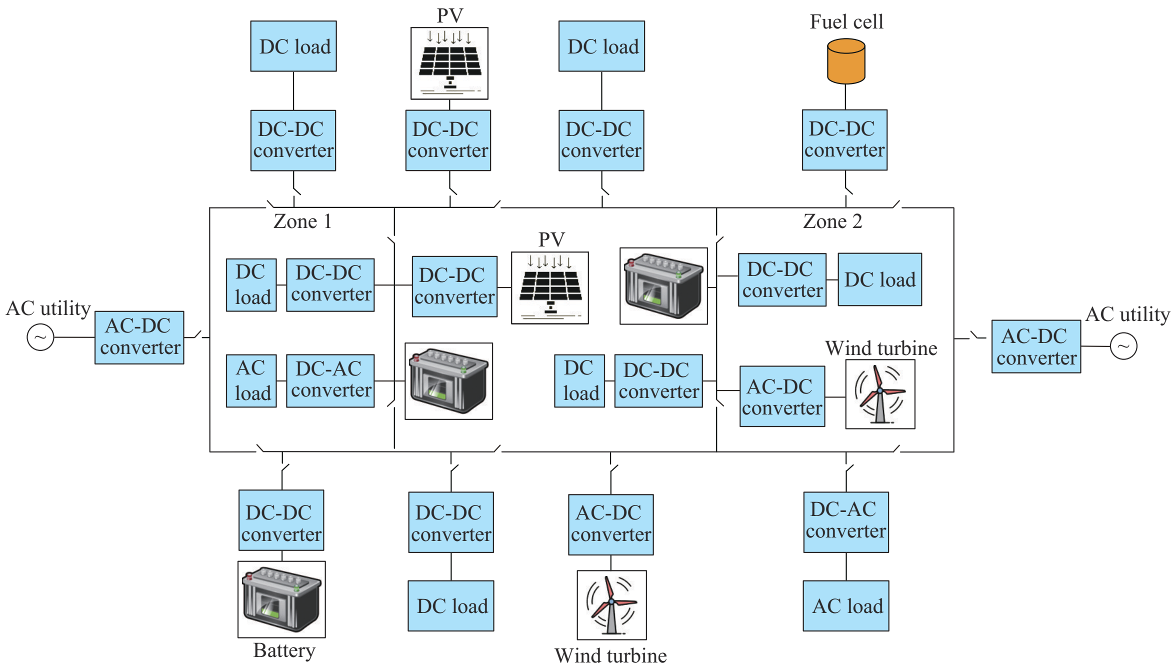

Fig. 10. DC microgrid with zonal-type architecture.

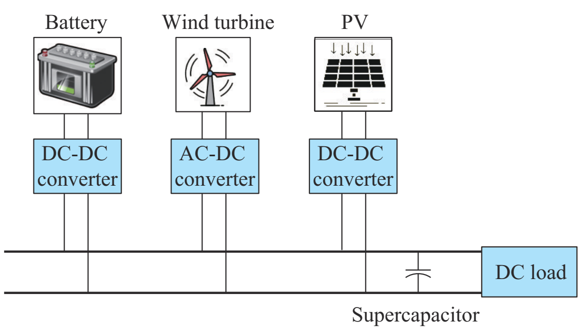

Fig. 11. DC microgrid architecture with supercapacitor.

Unlike AC microgrids, DC microgrids have no natural zero-crossing, and hence the arc quenching in the case of open contacts is censorious [87]. In [63], a review of the types of DC microgrid faults and challenges associated with protection is provided, and the classification of the faults is given in Fig. 12. There are a large number of converters associated with the DC microgrid. The capacitors associated with these converters, either in the form of harmonic filters or other purposes, discharge to produce a sharp spike in current values and hence is a challenge to the smooth operation of the DC microgrid. Apart from that, it demands increased ratings of the protection devices [88]. Furthermore, the lack of proper standards and an excessively large number of sources add to this difficulty. DC circuit breaker (DCCB) implementation is hindered by loss in the system, speed requirement for operation, accuracy in fault current management, and overall cost [89]. The details regarding the challenges in the protection of DC microgrid in the event of faults and the methods to for overcoming these challenges are discussed in this section.

TABLE I
FEATURES OF DIFFERENT DC MICROGRID ARCHITECTURES

Architecture	Overall cost	Protective system design	Reliability of supply	Interconnection with AC grid	Redundancy level	Voltage level (V)	Applications
Radial	Low	Easy	Low	One	Very low	380, 500, 600, 760	Best for low-voltage DC, domestic applications
Ring	Medium	Moderate	High	One	Moderate	240, 350	Telecommunication networks, data centers
Mesh	Very high	Very difficult	Very high	Multiple	High	50-350	Telecommunication networks, data centers
Zonal	High	Very difficult	High	Multiple	High	50-800	Shipboard system

The fault current sources in the DC microgrid are the DGs, storage devices, and associated AC grid. The magnitude of the fault current depends on the methods for power control, bus voltage, location of the fault, fault type, fault impedance, and techniques adopted for grounding. The severity of fault is high for a line-to-line (L-L) fault compared with a line-to-ground (L-G) fault. The discharge current from capacitors in L-L faults causes spike in voltage [90]. In L-G fault, the grounding system has a major influence on the severity of the fault. Faults can also be associated with DC feeders and sources [91]. The sequence involved in the fault management of a DC microgrid is shown in Fig. 13. The major challenges in terms of protection include voltage transients, current surges that are caused by improper grounding systems, arc-fault clearing time, and no natural zero-crossing, etc. [92].

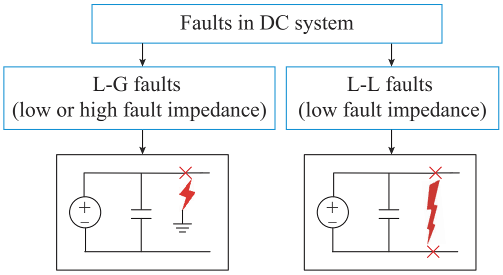

Fig. 12. Types of DC microgrid faults.

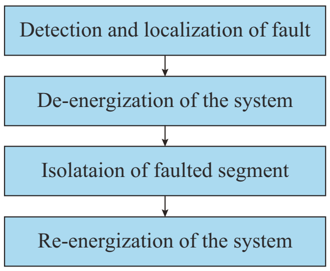

Fig. 13. Sequence involved in fault management of a DC microgrid.

The problems regarding voltage transients occurring during turn-on and turn-off of the system can be minimized by using metal-oxide-semiconductor field-effect transistor (MOSFET) or insulated gate bipolar transistor (IGBT) based solid-state devices. Power relays are capable of protecting over-voltage, over-current, under-voltage, variation in current/voltage, ground faults, etc., and ultra-fast protective action can be achieved by using solid-state circuit breakers (SSCBs) [93]. The faults arising due to the dynamic behaviour of the DC fault current magnitude bring some problems for over-current relays (OCRs) with fixed settings [94]. The curtailment of current by converters leads to a major problem for OCRs. The dynamic nature of fault currents can be caused by constant power loads or even the bidirectional nature of the current. DC microgrids lack a natural zero-crossing, which, in combination with transient over-voltage, poses major challenges to the operation of fuses [95], [96].

Proper operation of the protection devices involves accurate data being sensed. Inaccuracies in the sensor measurements can bring huge problems for protection devices. The sensors can be calibrated using the methods mentioned in [97]. In [98], different cable fault types in a PV integrated DC microgrid are discussed. According to the earlier mentioned classification, the faults considered are L-L and L-G faults. L-L faults are divided into three different stages, i.e., the discharging stage of the capacitor, the comprehensively feed stage, and the reactor freewheel stage. The most vulnerable DC faults are due to uncontrollable power electronic devices and diodes. Bidirectional DC-DC converters and controllable electronic equipment are proposed as solutions to the protection of diodes and other devices. Normally, fault current peak falls rapidly with increased fault distance and causes severe problems for protective devices. In an L-L fault, the magnitude can even be negative, but due to the very short duration of faults, the diodes in the system will not be damaged. Another challenge to DC microgrid protection is the transient resistance [99]. Fault location in the case of a DC system is far too difficult due to the much lower values of the DC line resistance and reactance [100]. In the events of fault in DC microgrid systems such as ships, reliable systems need to be incorporated to quickly identify the fault location and restore normal power distribution [101]. This normally requires expensive communication equipment and allied devices.

In high-voltage DC transmission, traveling wave based time-dependent fault identification methods are adopted, which locate the fault by analyzing the traveling waves that propagate along the transmission line [102]. Even though advantageous, these methods face a fair share of difficulties such as the need for highly accurate detection of the time of arrival of the surge and high-performance data acquisition equipment [103]. Another issue is reflected wave detection and discrimination [104]. A non-iterative method for identifying the fault using a probe power unit is provided in [105].

The protection devices used in DC microgrids are classified as fuses, DCCBs, protective relays, SSCBs, hybrid circuit breakers (CBs), and arc fault interrupters (AFIs), and their types are listed in Table II. DC microgrid protection can be designed by considering the directional element [106] that ensures the possibility of adjacent protection devices communicating with each other and taking combined actions to ensure safe operation. Fuses, though commonly used, are unsatisfactory from the perspective of their usage in a DC microgrid due to the constraints regarding the transients in microgrid voltage [107]. Various protection schemes [108]-[122] in DC microgrids are summarized in Table III.

TABLE II
TYPES OF PROTECTIVE DEVICES IN DC MICROGRID

Protective device	Type
Fuse	- Conventional type - Semiconductor type
DCCB	- Molded case - Vacuum CBs - Hybrid-solid or vacuum CBs
Protective relay	- DC relays - Digital type relays
AFI	- Arc fault circuit interrupter - Combination arc fault interrupter (CAFI)
SSCB	- Gate turn-off thyristor (GTO) - IGBT - Insulated gate commutated transistor (IGCT) - Coupled inductor SSCB (CISSCB)
Hybrid CB	- Combination of DCCB and SSCB

IV. PQ ISSUES IN DC MICROGRIDS

The PQ of a system is defined by several international standards. The scope of definition varies from one standard to another. According to IEC 61000, PQ is defined as "PQ encompasses the characteristics of electricity at the given location in a system, analyzed by comparing with a set of reference parameters" [123]. PQ can be considered as the combination of the voltage quality and the current quality. Thus, PQ is associated with variation of voltage and/or current from the ideal waveform. This is another definition of PQ in an electrical system [124].

TABLE III
PROTECTION SCHEMES IN DC MICROGRID

Protection scheme	Features
Over-current protection	- Modern converters have OCRs, which operate as an efficient current limiting CB [109] - The fault in the system is identified within milliseconds - The strategy based on directional over-current improves the redundancy
Current derivative-based protection	- Fault detection using rate of change of fault current - Calculated current differential is compared with a threshold for operation [110] - For fault in DC loop, the rate of change is calculated considering inductor voltage drop
Differential current protection	- Unit protection is preferred over non-unit for better fault management in the system [111] - Differential current protection can be used as backup with over-current for more reliability [112]
Voltage-based protection	- Voltage-based protection is based on the magnitude of voltage and comparatively fast in action - Fault resistance characteristics are one of the important factors evaluated for the scheme
Impedance-based protection	- By checking the impedance of the power electronic module, it will be different during fault conditions as compared to the designed value [113] - Active impedance estimation technique is adopted for the impedance calculation [114]
Traveling wave-based protection	- Fault location is estimated by analyzing various features of a traveling wave such as polarity, magnitude, and time interval [115] - Wave trap and GPS signals are combined for better fault identification - Off-line analysis is carried out by developing the network graph - Surge arrival time is evaluated for the fault detection [116]
Algorithm techniques with time-frequency transform	- Fault estimation is carried out by analyzing the frequency along with the time domain information related to the signal using various transform tools like wavelet transform or Fourier transform - It avoids the requirement of tripping set point and the method depends on the window size
Protection based on converter control action	- Converter operation is controlled to develop a breaker-less configuration [117] - Various methods like hand shaking [118], fault isolation and network reconfiguration [119], and DG interfaced converter protection [120] are adopted
Other protection schemes	- A non-iterative fault location technique employing probe power unit (PPU) [121] - Current injection techniques to overcome the drawbacks of fault detection using PPU [122]

The DC systems are nearly oblivious to power frequency variations and harmonics as the entire system operates on DC voltage [125]. Even though the absence of harmonics and power frequency disturbances is proven to be useful in a wide variety of ways, in terms of energy savings [126], DC microgrids also have a set of PQ disturbances associated with them. As indicated in [127], the PQ disturbances are broadly classified as events occurring for short and long periods, as shown in Fig. 14. Short duration events or transient events are sags, swell, interruption, oscillatory transients, and impulsive transients. Long duration events or steady-state events are noise, notching, voltage fluctuations, under-voltage, and over-voltage. Most of the disturbances associated with voltage in DC microgrids are due to transients in voltage from AC grids [128], inrush currents [129], and circulating current within converters [130]. Transients, which are subdivided into impulsive and oscillatory, are defined in IEEE Standard 1159 as "sudden non-power frequency changes from nominal conditions of voltage and current or both, that include both positive and negative polarity values" [131]. DC voltage fluctuations may result from providing power to the AC grid, or from low-frequency power fluctuations [132]. Voltage transients occurring in DC microgrid can reach up to 194% of the working voltage [128]. This is extremely large and causes equipment damage and several other consequences.

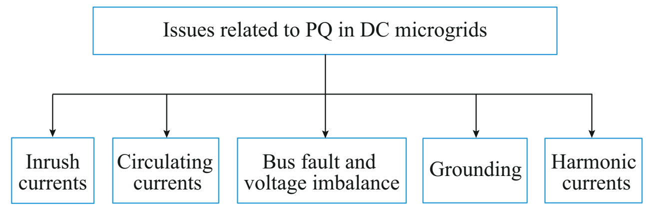

Fig. 14. PQ issues in DC microgrid.

Faults occurring in the bus is another major PQ issue in the DC microgrid. Fault currents with low power can develop issues in voltage at different locations in the system. Thus, the protection system gets confused between real faults and overload conditions in the system [133]. As the DC system does not offer a natural zero-crossing point, arc extinction is a tedious task in the event of a fault. Voltage sags and swells are mainly due to capacitor switching, which involves capacitors in DC-DC converters. Other causes include the equipment being turned on and off. In DC microgrid, poor voltage regulation leads to under-voltage and over-voltage. The impacts of these events vary in terms of their effect. The voltage sag and under-voltage trigger devices to turn off, while voltage swell and over-voltage cause serious effects such as insulation breakdown. Under-voltage can lead to increased losses as the increases of current deliver the same amount of power [134].

Inrush currents are drawn by capacitances associated with the electromagnetic interference (EMI) filters in converters [135]. Current harmonics in the DC bus cause voltage oscillations and unwanted EMI. Thus, a detailed harmonic analysis is to be performed while designing the DC distribution system. The factors affecting inrush currents are capacitance, resistance, reactance, and DC bus voltage [136]. The size of the capacitor is decided by considering the EMI standards that are to be met by the system. When a load is energized, the capacitance draws inrush current, which leads to voltage sags that affect the operation of various types of equipment. [137]. To address the issues due to inrush current that develops with converter capacitance, pre-charge circuits or other soft-start methods in Fig. 15 are adopted [138].

Inter harmonics are generally the waveforms that occur in the frequencies that are not integral multiples of fundamental frequency [139]. Inter harmonics form as a result of the current injection of switched-mode converters. Inter harmonics affect the customary operation of protection devices such as arc fault detection devices and residual current devices. Inter harmonics can arise at frequencies near power frequency though they are also observed to occurring at much higher frequency range of 1-100 kHz [140]. Even though the fundamental frequency of a DC system is 0 Hz, the oscillations of current and voltage in a DC system are similar to AC system harmonics. The harmonic contents arise, as a result of the operation of the converters required to interface DERs with a common DC bus, or the converters required to connect the DC microgrid with the utility grid [141].

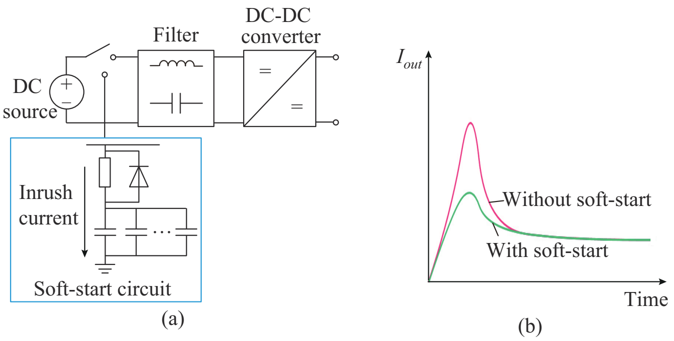

Fig. 15. Inrush current suppression with soft-start circuit. (a) Soft-start circuit. (b) Output current I_{out}.

Though inevitable, the harmonic content of the current and thereby the total losses associated with harmonics can be practically reduced using SiC MOSFET [142]. Smaller current harmonics of the converter based on SiC MOSFET produce output with better PQ and improve the efficiency of DC microgrid. Oscillations associated with the DC microgrid can be damped out by using electrical springs [143], [144].

The PQ and safety of the system are based on the configuration selected for grounding. The major grounding schemes for DC systems are shown in Fig. 16. For low-voltage (48 V) systems used in communication networks, TN-S grounding configuration (T means terra signifying a direct connection to earth; N means neutral; and S means seperate), where either a positive or negative pole is connected to the ground, is used. $+V_e$ and $-V_e$ are the positive and negative voltages, respectively. For higher voltages (380-400 V), IT grounding configuration is adopted [145] (I means isolated). Therefore, the flow of fault current depends on the adopted configurations and the effect of fault current on the system can be minimized by selecting the most appropriate scheme. Also, the selection depends on the availability of suitable cables, connectors, etc. [146]. Various IT grounding schemes in a DC system are classified in Table IV [133].

V. Inertia Issues in DC Microgrids

The inertia in DC systems will be less due to the presence of a large number of PECs compared with conventional AC systems [147]. In the case of a DC microgrid, the inertia is supplied by the kinetic energy of wind turbines and energy storage units. This inertia is not sufficient to support the system during load switching and variation in generation due to intermittent sources in the system [148].

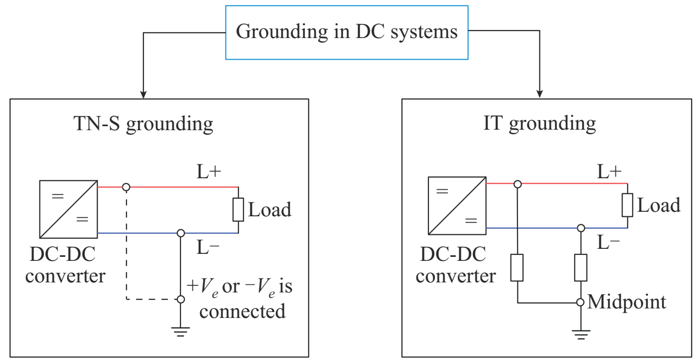

Fig. 16. Major gounding schemes for DC microgrid.

TABLE IV
Classification of IT Grounding Schemes

Type	Description
Non-isolated grounding	- Positive or negative pole of the DC bus is connected to the ground (normally negative) - The intensity of fault current depends on the loop impedance and DC link voltage
Non-isolated grounding with midpoint	- It is widely used for bipolar DC networks - Midpoint is connected to the earth - The fault current flowing in this arrangement is minimized due to the midpoint connection
Isolated grounding	- DC bus return is isolated from the ground of the equipment - Fault current cannot be accurately measured due to current flow in EMI filters even after isolation of the circuit

The inertia in a DC system can be provided using capacitors or supercapacitors, but both have their advantages and disadvantages. DC capacitors are used to support the system by reducing voltage fluctuations. However, the stability of the system will be affected [149], [150]. Capacitor size cannot be increased beyond a limit as it has less power density, larger size, etc. The cost of supercapacitors is another issue [151]. The power variations in the DC microgrid get eliminated when they are in grid-connected mode as large inertia is provided by the synchronous generators in the grid. But for an islanded DC microgrid or cluster of DC microgrids, the problems due to inertia will be severe. The power balance equation can be written as in (1) [152].

$$P_i - P_o = CV_{bus}\frac{\mathrm{d}V_{bus}}{\mathrm{d}t} \tag{1}$$

where P_i and P_o are the input power and output power of the DC bus, respectively; V_{bus} is the bus voltage; and C is the sum of parallel capacitance in the DC microgrid. In (1), C is analogous to the inertia constant of the AC system. However, the inertia control with capacitors is effective only up to an extent. Various inertia control techniques have been implemented in DC microgrids to improve their stability. A flexible virtual capacitance control strategy shown in Fig. 17 for DC microgrid is developed by analogizing the corresponding variables in both AC and DC systems [153], [154]. Overall dynamic response of the system is improved by implementing a model predictive control (MPC) based virtual inertia scheme by eliminating the multiple control loops for the converter [155]. The virtual synchronous generator

(VSG) scheme is widely used in AC systems which provides the rotational inertia and damping properties of synchronous generators. Similarly, in the DC system, the virtual DC machine (VDCM) strategy provides the inertia of DC machines by the energy storage units and its control scheme improves the PQ and stability of the system [156]. A virtual capacitance control integrated power management mechanism is developed in [157], where both the inertia control and power-sharing are based on MPC. Virtual inertia required for the system is provided along with an admittance type droop control scheme in DC systems. The transient response and stability of the system are improved as all the energy storage devices in the system contribute some amount of inertia [158].

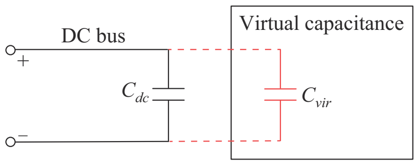

Fig. 17. Virtual capacitance control strategy.

Based on the charging and discharging characteristics of the battery, the inertia and damping control are proposed in [159]. Both the damping control coefficient and virtual inertia control coefficients are calculated based on stability analysis. Among the various components in the DC microgrid, energy storage units are much costlier compared with others. So the management of each energy storage unit in the system is of great importance. SoC-based virtual inertia control scheme improves the power-sharing as well as SoC control simultaneously [160]. Considering the economic aspects, the rotating wind turbines can act as a virtual inertia source that imitates the synchronous machines in the system [161], but the response is much slower. In addition, as the variable-speed wind turbines are interfaced to the grid via converters, there will be a reduction in the system inertia [162]. Due to better efficiency, insulation strength, and soft switching characteristics, dual half-bridge converters are used in DC microgrids to provide inertia along with a virtual super-capacitor. The bus voltage stability of the system gets enhanced with this control scheme [163]. VDCM has attained significant importance in improving system stability by providing adequate inertia in the system. However, to achieve this, both the performance and structure of this VDCM must be optimized [164], [165]. A battery along with its bidirectional converter can suppress the variation in load-side voltage and enhance the entire system response [166]. Even though the capacitor in the system discharges to compensate for the power gap that occurs, the value of the capacitor is limited. A virtual inertia control with an exponential change that delays the oscillation is given in [167]. As inertia is a crucial factor that affects the stability of the microgrid and the inertia is considerably less in DC microgrid, an appropriate inertia enhancement scheme must be selected to ensure that the system is in stable operating state.

VI. Communication Challenges

The communication networks employed in DC microgrid include home-area network (HAN), neighborhood-area network (NAN), and wide-area network (WAN). The structure of the communication network in the DC microgrid is shown in Fig. 18, where BAN means building-area network; and IAN means industrial-area network. HAN is used for low-bandwidth two-way communication between the appliances in a load center such as a house, whereas NAN acts as a gateway. HAN uses Zigbee, Bluetooth, Wi-Fi, etc., whereas NAN uses Wimax, Wi-Fi, etc. Table V shows the features of various communication networks [168].

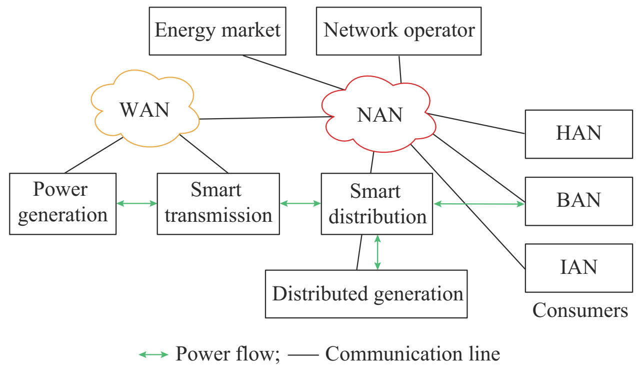

Fig. 18. Structure of communication network in DC microgrid.

TABLE V
Features of Various Communication Networks

Type	Feature
Consumer-side networks (HAN, BAN, IAN)	- These networks include industrial, residential, and commercial areas - Since all the components in these networks are closer, a high-frequency communication system is not required - Coverage area is between 1 to 100 m at a data speed of 1 to 100 kbit/s
NAN	- A high-speed communication network is required to communicate or receive data from grid-connected equipment - Service provider gathers pieces of information regarding energy consumption using smart meters which requires a sophisticated communication structure - It has a higher coverage area of 100 m to 10 km and data speed up to 10 Mbit/s
WAN	- More developed technologies are required for monitoring the system with WAN - Compared with conventional supervisory control and data acquisition (SCADA) systems, WAN requires higher data resolution and faster decision-making - It has coverage area up to 100km and with a data rate up to 1 Gbit/s

DC microgrid control, as well as protection, relies heavily on the accuracy and speed of the communication infrastructure. The establishment of a DC microgrid system thus requires high-speed communication [169]. As the interconnection of various controllers is done via internet or wireless network, grid security also becomes an element of concern [170]. In the hierarchical control scheme, with primary, secondary, and tertiary controllers [171] usually employed in a DC microgrid, latency in communication can be detrimental to the smooth operation of the system. Also, stability is affected by the communication delays [172]. DC microgrid control strategies commonly adopted are the active current sharing technique and droop control scheme [173], [174].

The active current sharing can be further classified into centralized, master-slave, and distributed control strategies [175]. Communication delays pose several difficulties in the proper implementation of these control strategies. The greater the communication delay in the system, the greater the voltage deviation and error in the controller, leading to substantial spikes [176]. In [177], the effects of communication delay on the system performance are studied. Here, the maximum allowable communication delay for a DC microgrid is computed using a mathematical model. The control method under consideration is proportional-integral (PI) control. In a real-world system, the control strategies, as well as the number of elements will be huge. Thus, the effect of communication delay will be more pronounced. Reference [178] studies the effect of wireless communication delay in DC microgrid.

The importance of coordination of DC microgrid design and selection of communication technology is emphasized in [168]. Reference [179] discusses the secondary controllers and their dependence on communication. An expression is developed to represent the delay margin and to compare their performances. However, it is nearly impossible to calculate the delay margin accurately by using simulation or experiment and validate the proper operation of a controller. The conclusion drawn is that the delay margin is independent of the controller used; and the greater the number of communication links, the less the delay margin.

In [180], communication delays from 2 to 300 ms have been reported, thus confirming the possible inaccuracy that may arise while evaluating the delay margin. Reference [181] emphasizes the importance of information exchange for distributed secondary controllers, while evaluating the distributed optimal control of the DC microgrid. Reference [182] studies the operation of microgrids under various conditions, using the low-voltage microgrid based on the CIGRE and IEEE benchmarks, and focuses mainly on communication delays. One case study includes a system with a transient fault with delay in communication systems and it is found that the system cannot achieve stable operation beyond a level of delay. Reference [183] discusses load sharing considering the delay. It also highlights that the power control information being sent over the same wireless channel with other system information can result in loss or corruption of data. A time-varying delay in communication is studied and a controller for mitigating the problem is specified in [184]. The unified Smith predictor is used to introduce delay in local feedback and remote signals of LC for conducting the study. The communication delay affects the reference parameter generation, generally reference voltage, for proper load sharing. The outdated power information used to generate reference values disrupt the operation of microgrid. Reference [185] describes various adverse effects due to limitations of communication technology on microgrids and discusses different control strategies and lays out the challenges posed by communication delays and other limitations of communication technology.

A list of suggestions is also proposed, which includes various analyses regarding the significance of adopted communication technology, degradation in the microgrid operation and resilience, the definition for control architectures based on communication, risk assessment of communication technology on the hardware, critical analysis of the Internet of Things (IoT) technology and a lot more. The results show that the communication delay causes deviation in reference value generation and thereby adversely affects the operation of controllers. Moreover, the smoothing inductor used to improve PQ also adversely affects the delay. References [186] and [187] consider the effect of communication in the secondary control of autonomous microgrid. The system under consideration is an AC microgrid and it is shown that if the islanding operation is delayed, the frequency oscillation associated with the system also increases. Sources of noise in a communication network are generally processing and queuing, propagation, and delays due to other external activities [188], [189]. Reference [190] analyzes the effect of communication delay of DC microgrid during both grid-tied and islanded modes. It is shown that the impact of the communication delay can be minimized by designing the system in synchrony with the selection of communication networks or systems. Several studies on mathematical modelling and evaluation have been conducted considering the communication delay in microgrid systems [191]-[193]. Experimental works are present but are less in number. Hence, a proper emphasis on practically realized systems can be explored further.

As DC systems are designed with different communication topologies and technologies, the integration will be easier only if the technologies are formulated with proper protocols and standards [194]. Since the modern grid is integrated with various IEDs, existing communication technologies based on SCADA will be less effective. Thus, the modification of existing infrastructure to accommodate the latest technologies is a major challenge. Even though the communication networks will have many advantages, cyber security and data privacy issues are also major threats [195]-[197].

VII. Economic Operation and Control of DC Microgrids

With the rapid proliferation of DC microgrid, the economic operation and control are essential to provide high-quality, economical, and reliable electricity [198]. The economic operation is achieved by improving efficiency, reducing the operating cost, or by economic dispatch [199]. Multi-objective optimization-based scheduling is performed to ensure the economical operation of the DC microgrid in [200], but the line losses, which contribute to 5% of total losses in the system, are neglected. A stochastic approach is proposed in [201] for the optimal operation considering the effect of intermittent energy sources in the DC microgrid. In [202], the economic operation is achieved by using a consensus algorithm that calculates the generation cost of the individual as well as neighboring units and re-routes the power flow accordingly. An optimal operation with high penetration of various sources and energy storage systems is achieved in [203] with a mathematical optimization model for the economic dispatch using semi-definite programming. An optimal scheduling model that provides the economic power strategy for the generators in the DC microgrid is developed in [204] considering operation costs, emission costs, and power loss costs. In [205], the optimal load sharing in a DC microgrid is obtained by considering fully distributed control with various equality and inequality constraints. The distributed control shares the details of estimated voltage and operating costs with neighboring grids using a communication network. In [206], the optimization problem aims to reduce the operating costs in microgrids containing the sources with uncertain power output, utilizing the power predictions and technical constraints. In [207], a modified economic droop scheme with DG generation cost and the utility tariff as major factors is proposed for cost minimization. In [208], a cost function that considers the cost of various microgrid components, as well as the utility demand response, is utilized to achieve improved system efficiency. The total operating cost is reduced with optimum droop control parameters obtained using a genetic algorithm. Reference [209] focuses on the minimization of generation cost in DC microgrid during both grid-connected and islanded mode using a combined sub-gradient algorithm and incremental rate criteria. The economic operation and planning of DC microgrid clusters are much more complex than autonomous systems. Lagrange multiplier-based online power flow optimization technique for a DC microgrid is developed for economic operation in [210]. As the adaptation of the DC microgrids is on a rise, extensive research needs to be carried out on the economic operation and economic control strategies dedicated to DC microgrids.

VIII. Applications of DC Microgrids

Observing the numerous features including energy efficiency, DC microgrids can be utilized for different applications in power systems, especially for future smart grids. This section explores the various applications of DC microgrids.

A. Household Applications

Nowadays, the majority of household loads and energy sources at the utilization point are in DC form [211].

Therefore, the conversion stage can be avoided by using DC instead of AC, thereby improving the system efficiency [212]. Also, the energy management schemes associated with DC systems are much more flexible compared with AC and hybrid grids [213]. Various researches related to DC-powered highly efficient homes, which are the key enablers of future smart grids, are ongoing in various countries across the world [214]-[216]. The major requirements of various smart grid road maps are improved flexibility and reliability for household consumers with renewable integration [217]. The reliability of such systems gets improved with the addition of more storage devices and smart appliances. To reduce the amount of storage, increase reliability, and facilitate power management, the individual houses can be operated as a cluster [218]. Figure 19 shows the schematic diagram of a DC-powered home.

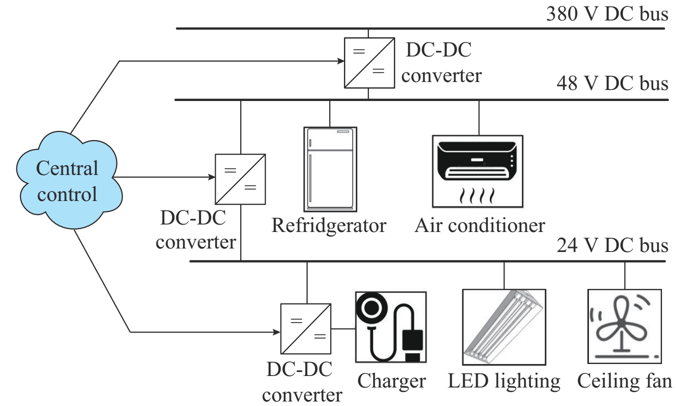

Fig. 19. Schematic diagram of DC-powered home.

B. Renewable Energy Parks

Renewable energy parks are formed by clustering various sources to a common DC bus. Here, multiple solar PV systems or wind generation systems are connected in parallel. These systems are also called collector grids, which is a better option for PV and wind power applications [219].

The structure of a solar park is depicted in Fig. 20 and the top 5 solar parks and the top 5 wind parks around the world are listed in Tables VI [220] and VII [221], respectively. Compared with household applications, the control and management of such grids are much more complex and the operation must be supported with various ancillary services based on existing grid codes [222]-[224]. The stability of a DC-based park with hybrid energy sources is explained in [225] and the optimal allocation of energy sources in an energy park is depicted in [226].

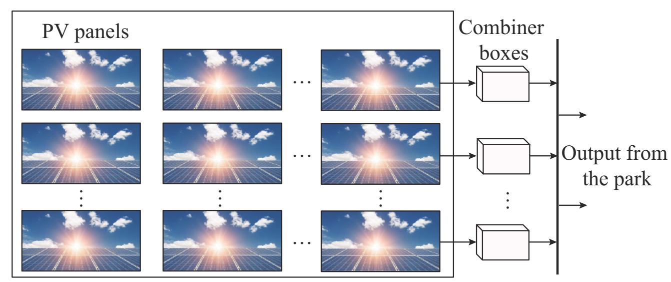

Fig. 20. Structure of solar park.

TABLE VI
Top 5 Solar Parks Around the World

Name of park	Location	Capacity (MW)	Area (km^2)
Bhadla solar park	Jodhpur, Rajasthan, India	2×2245	2×57
Pavagada solar park	Tumkur, Karnataka, India	3×1850	3×53
Huanghe Hydropower Golmud solar park	Golmud, Qinghai, China	3×1800	
Benban solar park	Benban, Egypt	1650	37.2
Tengger desert solar park	Zhongwei, Ningxia, China	2×1547	2×43

TABLE VII
TOP 5 WIND PARKS AROUND THE WORLD

Name of park	Location	Capacity (GW)	Number of turbines
Gansu wind park	Jiuquan, Gansu, China	2×8	2×7000
Jaisalmer wind park	Jaisalmer, India	1.6	24
Alta wind energy center	Kern County, California, USA	3×1.57	3×600
Muppandal wind farm	Kanyakumari district, Tamil Nadu, India	3×1.50	3×3000
Los Vientos wind farm	Texas, USA	2×0.912	2×108

C. Electric Vehicle (EV) Fast Charging Stations

EVs and plug-in hybrid EVs (PHEVs) are being investigated as possible solutions to power backup, emergency power for buildings, and improving grid stability [227], [228]. The interest in EVs is also increasing worldwide drastically as it is an effective solution to the recent concerns connected with fossil fuels [229].

As the adoption of EVs increases, the number of charging stations must also increase. Unlike conventional AC charging stations, DC fast charging is one of the promising technologies that can charge most vehicles to 80% within 15-45 min, thereby enabling EV users to charge on the go [230]. Apart from the EVs, a variety of DC energy resources are also interfaced with the charging stations that operate in vehicle-to-grid (V2G) and grid-to-vehicle (G2V) modes to enhance the reliability of the system [231]. Energy storage devices like flywheel, battery and sources like PV, wind are considered as viable options for this [232]. Figure 21 shows the structure of a typical EV charging station with RES support.

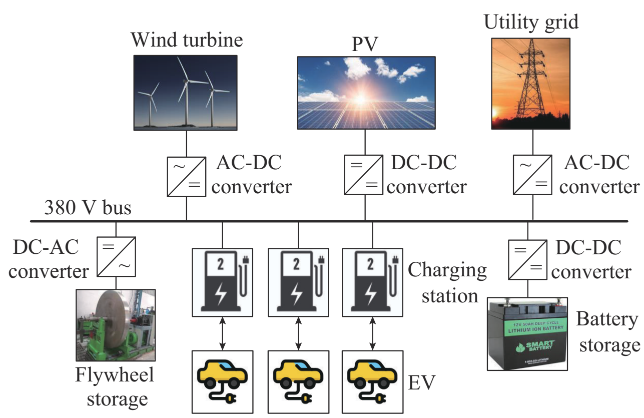

Fig. 21. Structure of a typical EV charging station with RES support.

D. Data Center Support Systems

Data centers possess various complex networks that power different computing devices and the supporting infrastructure [233]. The critical energy end-use in data centers includes the computing equipment and the energy end-use infrastructures like high-voltage AC (HVAC), uninterrupted power supplies, lighting, and communications [234]. The efficiency of data centers is as low as 30%. The studies prove that data centers distributing DC to the IT equipment avoid multiple power conversion stages and reduce electrical power losses [235].

E. Remote Microgrids

DC microgrid is a promising solution to remote applications. The major challenge to a remote microgrid is that there is no external energy support as in other microgrids. They operate as autonomous systems, almost all the time, and hence, energy adequacy is a major concern [236]. Uneven geographical conditions or less populated or isolated communities are the major bases of remote microgrids [237], [238]. Renewable sources will be the appropriate generation sources for such grids [239] as fossil fuel based power generation remains uneconomical due to comparatively less load [240]. Batteries also play a crucial role, especially in providing power during nighttime [241].

IX. COMPARISON BETWEEN DIFFERENT MICROGRID ARCHITECTURES

Microgrid systems can reduce energy costs, and enhance overall system efficiency and reliability. Microgrids are mainly classified into AC, DC, and hybrid AC-DC ones. Each architecture has its own advantages and disadvantages. Table VIII and Table IX [242]-[244] depicts a comparison between DC and AC microgrids, and DC and hybrid AC-DC microgrids, respectively, on the basis of a list of of value streams of microgrids including economics, efficiency, reliability, PQ, and protection.

TABLE VIII
COMPARISON BETWEEN DC AND AC MICROGRIDS

Factor	DC microgrid	AC microgrid
Conversion efficiency [245]	- The conversion efficiency is high as only minimum conversion stages are required to feed the load - DC LED driver has an efficiency of around 97 percent - It is 6%-8% more efficient in PV utilization	- The conversion is less efficient as multiple conversion stages are required - The conversion efficiency of AC LED driver is about 93%
Converter cost [246]	- The cost is reduced for the converters along with the cost reduction due to renewable sources	- Costs of converters are more
Control complexity [247]	- Only bus voltage is the main parameter for control	- Various factors such as the voltage, frequency, reactive power, and harmonics have significance - Synchronization is a major task
Supply reliability [248]	- It is more reliable with provision for remote location power supply	- It is less reliability and difficult to provide adequate power under adverse conditions
Protection system [249]	- An immature protection system with more risk factors	- Cost-effective and well-structured protection systems are available
Integration with existing grid [250]	- More arrangements are required to integrate with the utility grid	- It is easy to integrate with the existing utility grid
Transmission efficiency [251]	- More efficiency is achived due to the absence of reactive current	- It is less efficient

TABLE IX
COMPARISON BETWEEN DC AND HYBRID AC-DC MICROGRIDS

Factor	DC microgrid	Hybrid AC-DC microgrid
Converter cost	- Reduced converter cost	- More converter cost since a large number of converters are involved
Control complexity	- Less complexity in control	- More complex controls as both AC and DC components are interfaced
Supply reliability	- More reliable system	- Increased reliability by reducing the converter stages
Protection system	- Still in a developing stage	- A wide range of protection schemes available
Integration with existing grid	- Majority of components being DC and easily integrated	- Separately designed converters for both AC and DC parts
Voltage conversion	- DC-DC converters to obtain various voltage levels	- DC-DC converters for the DC part and transformers for the AC part which make the system more complex
Synchronization	- Only bus voltage required to be considered while synchronization	- Easy synchronization for DC part and complex for AC part

X. MICROGRID PROJECTS AROUND THE WORLD

Various DC microgrids have been established to supply power, or have been developed at the research centers to analyze the working and performance of DC microgrids. A large portion of the studies conducted by researchers focus on control, reliability, and protection, while operating in islanded or grid-connected mode. The details about various currently running microgrid projects around the world are provided in Table X [252].

XI. FUTURE TRENDS IN DC MICROGRID RESEARCH

The depleting fossil fuel and increased penetration of renewable sources have transformed the DC microgrid into a hot topic for research with huge scope for future works. Currently, many research works are ongoing around the world on DC microgrids and related topics. Various architectures are available in the literature for the interconnected DC microgrids which operate in grid-tied or islanded mode. Even though each of them possesses various advantages, more research needs to be conducted to design a better DC microgrid architecture that ensures a reliable, flexible, and simple operation. The control strategies available today for reliable operation of the DC microgrid cannot be accomplished with simple controllers. Research needs to focus on implementing various hybrid controls that include both centralized and distributed controls at different levels to improve reliability.

DC microgrids are mainly PEC-dominated systems. The precise design and control of these converters are of greater importance. Topologies for converters incorporating solutions to the challenges related to various PQ issues like circulating currents, inrush currents, and inter harmonics are the best topic for future research. The protection of microgrids is also a crucial topic for future researchers. Even though the standards for DC microgrid integration and interconnection are in the developing stage, a well-designed CB and effective grounding schemes are essential for their flexible operation. Different energy management schemes can be designed for DC microgrids by considering various factors like response time of storage devices and controllers, associated losses in converters, etc. By developing a more transparent and effective strategy, the economic operation of the microgrid, optimum sizing of resources, etc., can be improved.

Another area related to DC microgrid with vast scope for future research is stability. Various works address the issues of low-inertia DC microgrid and virtual inertia strategies for stability enhancement. Mainly, the inertia support for such weak grids is provided using converters. But the size of storage devices, their protection, and issues due to overcharging and discharging are major concerns. Interconnection of DC microgrids forming various clusters can be the best solution to these issues. Various pieces of literature explain the power management and control of DC microgrid clusters. But still, it lacks clarity in the factors like criteria for interconnection with neighboring microgrids, selection of the most suitable microgrid for interconnection, stable interconnection via proper synchronization, and best topology for interconnection and the dynamic operation of such microgrids.

XII. CONCLUSION

Even though the DC microgrid is a major topic of discussion due to its potential benefits, it still faces several challenges in design, operation, and proper control. The main issues arise due to the increased penetration of RES, grid power balance, energy management, and DC link voltage control. This paper brings out a comprehensive review on various issues related to DC microgrid implementation. Various architectures for DC microgrid, protection schemes, protective devices, issues due to inertia that affects the system stability, PQ issues, and communication-related issues have been reviewed. Also, applications, economic operation, and control of DC microgrids, comparison between different microgrid configurations, the state-of-the-art DC microgrid projects around the world, and future trends in the area of research related to DC microgrids have been briefly explained.

TABLE X
MICROGRID PROJECTS AROUND THE WORLD

Name of microgrid project	Scope of project
ABN Amro bank's circle pavilion in Amsterdam	- Very efficient sustainable circular building in Amsterdam - Office having 3000 m^2 of meeting rooms with a 350 V DC microgrid support
Highway N470	- The most efficient road in the Netherlands - A special project for the province of Zuid-Holland - The first road to be CO_2-negative, with 35 kW 350 V public lighting along the highway
Public lighting by Citytec (Nieuw Reijerwaard business park)	- The largest DC lighting system in Europe with reduced use of resources, improved reliability, and efficiency - Public lighting works on 350 V DC and is connected to the smart DC microgrid with sophisticated control and protection
Demo DC grid Hengelo	- DC users connected to the smart DC microgrid which is directly coupled to solar panels - A 700 V DC modeling and development project on renewable energy in the Netherlands with EV charging, public lighting, batteries for peak shaving, etc.
Energy neutral homes in Stroomversnelling	- A national project with six housing corporations focused to convert around 110000 houses into zero energy homes - Such energy-neutral homes called "Nul-op-de-Meter" homes, termed "Zero-on-the-energy-meter"
DC flexhouse	- To develop a strategy for replacing the conventional AC-based homes with DC technology - The project results in a method for adapting electrical installations to DC installations for homes including new components/products - An industry-institute collaborative project with ABB in the development of components and mutual interconnectivity, and Hague University of Applied Sciences in the bottom-up vision development for DC at the district level
DC and sustainability in the greenhouse	- DC version of the current ballast for the greenhouse market aimed at reducing energy wastage during AC-DC conversion - A highly efficient centralized control-based conversion of AC to DC, instead of local conversion to save maximum energy
Washington DC university DC microgrid	- Gallaudet University, scale microgrid solutions, and urban ingenuity collaborate on a solar plus storage microgrid to power the university and surrounding homes through a community solar plan - Microgrid consisting of 2.5 MW of solar panels spreads across numerous campus rooftops and parking garages, a 1.2 MW/2.5 MWh lithium-ion battery, and a 4.5 MW combined cooling, heat, and power (CCHP) system
McKinleyville wastewater treatment plant	- Expected to complete in 2022 - 580 kW solar array with 500 kW of energy storage backup - Designed to provide power for the wastewater treatment plant
Montgomery County's electric bus depot microgrid	- A 5.6 MW microgrid with battery storage of about 2 MW in Brookville smart energy bus depot - Main vision of the project being a net-zero emission in the system by 2035
Los Angeles transportation electrification	- 7.5 MW EV charging stations coupled with solar and storage
Florida's neighborhood microgrid project	- Including 37 homes in the Medley at Hillsborough - Studies of the capacity of the microgrid to ride through the disturbances in the upstream AC network - Aimed to evaluate the integration of various renewable sources, and reduce peak load
UK microgrid project on residential electrification	- Private microgrid project with 162 houses, to be completed by 2025 - Energy as a service concept implementation - Focusing on de-carbonizing - Aiming for zero carbon-ready, all-electric homes with no gas connection
Ameresco, a microgrid project, California	- Designed to make the 165000-acre training center a net-zero energy center by 2022 - Microgrid developed by Ameresco, with 3.75 MW of PV and 5 MWh of storage for the training requirements - Functions autonomously with various controls and interconnection for new and existing generation and energy storage
New Jersey's town center project	- 10.5 MW of new or existing PV generation and 2.9 MW of new or existing battery storage - Coordinating a minimum of 30 new or existing charging stations - Project aimed to reduce over 24000 tons of carbon dioxide emissions yearly

REFERENCES

[1] Z. Martnek, K. Tom, and H. Jaroslav, "Reliability of the electrical power system," in *Proceedings of 2014 15th International Scientific Conference on Electric Power Engineering*, Brno-Bystrc, Czech, May 2014, pp. 81-84.

[2] C. Davidson, "Thomas Edison vindicated the resurgence of DC in MV and HV power grids," in *Proceedings of 2020 22nd European Conference on Power Electronics and Applications*, Lyon, France, Sept. 2020, pp. 1-6.

[3] M. F. Mansuri, B. K. Saxena, and S. Mishra, "Shifting from fossil fuel vehicles to hydrogen based fuel cell electric vehicles: case study of a smart city," in *Proceedings of 2020 International Conference on Advances in Computing*, *Communication Materials*, Dehradun, India, Aug. 2020, pp. 316-321.

[4] H. A. Loiciga, "Challenges to phasing out fossil fuels as the major source of the world's energy," *Energy & Environment*, vol. 22, no. 6, pp. 659-679, Feb. 2011.

[5] X. Chen, J. Han, Q. Zhang *et al.*, "Economic comparison of AC and DC distribution system," in *Proceedings of 2019 IEEE 8th International Conference on Advanced Power System Automation and Protection*, Xi'an, China, Oct. 2019, pp. 769-774.

[6] Y. Zhang, Q. Zhou, L. Zhao *et al.*, "Dynamic reactive power configuration of high penetration renewable energy grid based on transient stability probability assessment," in *Proceedings of 2020 IEEE 4th Conference on Energy Internet and Energy System Integration*, Wuhan, China, Oct. 2020, pp. 3801-3805.

[7] M. Saeedifard, M. Graovac, R. Dias *et al.*, "DC power systems: challenges and opportunities," in *Proceedings of IEEE PES General Meeting*, Minneapolis, USA, Jul. 2010, pp. 1-7.

[8] Y. Ito and H. Akagi, "DC microgrid based distribution power generation system," in *Proceedings of 2004 4th International Power Electronics and Motion Control Conference*, Xi'an, China, Aug. 2004, pp. 1740-1745.

[9] E. T. Fasina, A. S. Hassan, and L. M. Cipcigan, "Impact of localised energy resources on electric power distribution systems," in *Proceed-*

ings of 2015 50th International Universities Power Engineering Conference, Stoke-on-Trent, United Kingdom, Sept. 2015, pp. 1-5.

[10] A. Zobaa and C. Cecati, "A comprehensive review on distributed power generation," in *Proceedings of International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, Taormania, Italy, May 2006, pp. 514-518.

[11] P. Dondi, D. Bayoumi, C. Haederli *et al.*, "Network integration of distributed power generation," *Journal of Power Sources*, vol. 106, no. 1, pp. 1-9, Jan. 2002.

[12] V. Rajaraman, A. Jhunjhunwala, P. Kaur *et al.*, "Economic analysis of deployment of DC power and appliances along with solar in urban multi- storied buildings," in *Proceedings of 2015 IEEE First International Conference on DC Microgrids*, Atlanta, USA, Jun. 2015, pp. 32-37.

[13] O. P. Rahi, H. K. Thakur, and A. K. Chandel, "Power sector reforms in India: a case study," in *Proceedings of 2008 Joint International Conference on Power System Technology and IEEE Power India Conference*, New Delhi, India, Oct. 2008, pp. 1-4.

[14] N. Anglani and G. Petrecca, "Fossil fuel and biomass fed distributed generation and utility plants: analysis of energy and environmental performance indicators," in *Proceedings of 2nd International Symposium on Power Electronics for Distributed Generation Systems*, Hefei, China, Jun. 2010, pp. 964-969.

[15] I. Arias, R. Ardila, and J. Ruiz, "Distributed generation: regulatory and commercial aspects," in *Proceedings of PES Transmission Distribution Conference and Exposition: Latin America*, Caracas, Venezuela, Aug. 2006, pp. 1-4.

[16] P. Chiradeja, "Benefit of distributed generation: a line loss reduction analysis," in *Proceedings of 2005 IEEE/PES Transmission Distribution Conference Exposition: Asia and Pacific*, Dalian, China, Aug. 2005, pp. 1-5.

[17] S. Mukhopadhyay and B. Singh, "Distributed generation basic policy, perspective planning, and achievement so far in India," in *Proceedings of 2009 IEEE PES General Meeting*, Calgary, Canada, Jul. 2009, pp. 1-7.

[18] S. Puchalapalli, S. K. Tiwari, B. Singh *et al.*, "A microgrid based on wind-driven DFIG, DG, and solar PV array for optimal fuel consumption," *IEEE Transactions on Industry Applications*, vol. 56, no. 5, pp. 4689-4699, Sept. 2020.

[19] H. Wang, J. Tian, J. Yan *et al.*, "Definition and influencing factors of power quality in DC microgrids," in *Proceedings of 2021 IEEE 4th International Electrical and Energy Conference*, Wuhan, China, May 2021, pp. 1-5.

[20] A. Kirakosyan, E. F. Saadany, M. Moursi *et al.*, "Sharing of the loading of asynchronous AC microgrids connected through DC microgrids," in *Proceedings of 2020 IEEE PES General Meeting*, Montreal, Canada, Aug. 2020, pp. 1-5.

[21] G. Ding, S. Zhang, Q. Jian *et al.*, "Coordinate control of distributed generation and active power electronics loads in islanding microgrid," in *Proceedings of 2017 IEEE 3rd International Future Energy Electronics Conference and ECCE*, Kaohsiung, China, Jun. 2017, pp. 1581-1585.

[22] I. Mazhari and B. Parkhideh, "DC-bus voltage regulation for DC distribution system with controllable DC load," in *Proceedings of 2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems*, Florianopolis, Brazil, Apr. 2017, pp. 1-6.

[23] G. Lin, J. Ma, Y. Li *et al.*, "A virtual inertia and damping control to suppress voltage oscillation in islanded DC microgrid," *IEEE Transactions on Energy Conversion*, vol. 36, no. 3, pp. 1711-1721, Jun. 2021.

[24] T. Sato, A. Umemura, R. Takahashi *et al.*, "Cooperative virtual inertia control of PMSG based wind generator and battery for power system stability enhancement," in *Proceedings of 2020 2nd International Conference on Smart Power Internet Energy Systems*, Bangkok, Thailand, Sept. 2020, pp. 144-149.

[25] M. Jami, Q. Shafiee, and H. Bevrani, "Dynamic improvement of DC microgrids with cpls using virtual inertia concept," *International Journal of Industrial Electronics Control and Optimization*, vol. 4, no. 1, pp. 67-76, Apr. 2021.

[26] M. Veerachary and V. K. Tiwari, "Power management in DC-grid through two-input DC-DC converter," in *Proceedings of 2014 Eighteenth National Power Systems Conference*, Guwahati, India, Dec. 2014, pp. 1-6.

[27] A. Korompili and A. Monti, "Analysis of the dynamics of DC voltage droop controller of DC-DC converters in multi-terminal DC grids," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids (ICDCM)*, Nuremburg, Germany, Jun. 2017, pp. 507-514.

[28] I. Yamamoto, K. Matsui, and M. Matsuo, "A comparison of various DC-DC converters and their application to power factor correction," in *Proceedings of Power Conversion Conference*, Osaka, Japan, Apr. 2002, pp. 128-135.

[29] R. Hareesh and C. P. Pramod, "Distributed generation integration with enhanced power system protection," in *Proceedings of 2015 International Conference on Technological Advancements in Power and Energy*, Kollam, India, Jun. 2015, pp. 310-315.

[30] D. Han, J. Fang, J. Yu *et al.*, "Small-signal modeling, stability analysis, and controller design of grid-friendly power converters with virtual inertia and grid-forming capability," in *Proceedings of 2019 IEEE Energy Conversion Congress and Exposition*, Baltimore, USA, Sept. 2019, pp. 27-33.

[31] S. Hashimoto, T. Yamamoto, K. Nara *et al.*, "Capacity determination of the DC-side battery for hybrid batteries in PV generation system," in *Proceedings of 2019 IEEE Innovative Smart Grid Technologies*, Chengdu, China, May 2019, pp. 1745-1750.

[32] X. Wang and Y. Liu, "Analysis of energy storage technology and their application for microgrid," in *Proceedings of 2017 International Conference on Computer Technology, Electronics and Communication*, Dalian, China, Dec. 2017, pp. 972-975.

[33] A. Olabi, C. Onumaegbu, T. Wilberforce *et al.*, "Critical review of energy storage systems," *Energy*, vol. 214, p. 118987, Jan. 2021.

[34] S. Ferahtia, A. Djeroui, H. Rezk *et al.*, "Optimal control and implementation of energy management strategy for a DC microgrid," *Energy*, vol. 238, p. 121777, Jan. 2022.

[35] X. Han, L. Lu, Y. Zheng *et al.*, "A review on the key issues of the lithium-ion battery degradation among the whole life cycle," *eTransportation*, vol. 1, p. 100005, Jul. 2019.

[36] M. Elhadidy and S. Shaahid, "Optimal sizing of battery storage for hybrid (wind+diesel) power systems," *Renewable Energy*, vol. 18, no. 1, pp. 77-86, Sept. 1999.

[37] *IEEE Approved Draft Recommended Practice for Sizing Lead-acid Batteries for Stationary Applications*, IEEE Standard P485/D7, 2020.

[38] S. Konar and A. Ghosh, "Interconnection of islanded DC microgrids," in *Proceedings of 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Brisbane, Australia, Nov. 2015, pp. 1-5.

[39] K. Palaniappan, S. Veerapeneni, R. Cuzner *et al.*, "Assessment of the feasibility of interconnected smart DC homes in a DC microgrid to reduce utility costs of low income households," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids*, Nuremburg, Germany, Jun. 2017, pp. 467-473.

[40] K. Jithin, R. Harikumar, N. Mayadevi *et al.*, "A centralized control algorithm for power management in interconnected DC microgrids," in *Proceedings of Symposium on Power Electronic and Renewable Energy Systems Control*, Bhubaneswar: Springer, 2021.

[41] G. V. Somanath, V. P. Mini, N. Mayadevi *et al.*, "Optimal energy sharing in smart DC microgrid cluster," in *Proceedings of 2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy*, Cochin, India, Jan. 2020, pp. 1-6.

[42] D. Magdefrau, T. Taufik, M. Poshtan *et al.*, "Analysis and review of DC microgrid implementations," in *Proceedings of International Seminar on Application for Technology of Information and Communication*, Semarangin, Indonesia, Sept. 2016, pp. 241-246.

[43] F. Li, Z. Lin, Z. Qian *et al.*, "Active DC bus signaling control method for coordinating multiple energy storage devices in DC microgrid," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids*, Nuremburg, Germany, Jun. 2017, pp. 221-226.

[44] J. Dong, H.-S. Kim, J.-W. Baek *et al.*, "Dual active bridge converter for energy storage system in DC microgrid," in *Proceedings of 2016 IEEE Transportation Electrification Conference and Expo*, Busan, South Korea, Jun. 2016, pp. 152-156.

[45] S. Tomar, S. A. Kumar, and H. Kanak, "Energy storage in DC microgrid system using non-isolated bidirectional soft-switching DC/DC converter," in *Proceedings of 2017 6th International Conference on Computer Applications in Electrical Engineering-Recent Advances*, Roorkee, India, Oct. 2017, pp. 439-444.

[46] U. Manandhar, B. Wang, X. Zhang *et al.*, "Joint control of three-level DC-DC converter interfaced hybrid energy storage system in DC microgrids," *IEEE Transactions on Energy Conversion*, vol. 34, no. 4, pp. 2248-2257, Jun. 2019.

[47] L. Zubieta, "Power management of a DC bus regulated by multiple energy storage resources," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids*, Nuremburg, Germany, Jun. 2017, pp. 571-576.

[48] N. R. Chowdhury, A. Al Hadi, and M. Mann, "Design and analysis of a standalone DC microgrid with battery and fuel cell energy storage penetration for different load characteristic," in *Proceedings of 2018*

International Conference on Power Energy, Environment and Intelligent Control, Greater Noida, India, Apr. 2018, pp. 425-429.

[49] A. Kwasinski and P. T. Krein, "A microgrid-based telecom power system using modular multiple-input DC-DC converters," in *Proceedings of Twenty-Seventh International Telecommunications Conference*, Berlin, Germany, Sept. 2005, pp. 515-520.

[50] J. S. Kumar, S. Petter, and U. Kjetil, "Socio-economic impact of a rural microgrid," in *Proceedings of 2016 4th International Conference on the Development in Renewable Energy Technology*, Dhaka, Bangladesh, Jan. 2016, pp. 1-4.

[51] X. Zhu, S. Premrudeepreechacharn, C. Sorndit *et al.*, "Design and development of a microgrid project at rural area," in *Proceedings of 2019 IEEE PES GTD Grand International Conference and Exposition Asia*, Bangkok, Thailand, Mar. 2019, pp. 877-882.

[52] P. M. Ivry, D. W. P. Thomas, and M. Sumner, "Assessment of power quality in a microgrid with power electronic converters," in *Proceedings of 2016 Asia-Pacific International Symposium on Electromagnetic Compatibility*, Shenzhen, China, May 2016, pp. 825-827.

[53] Z. Fusheng and R. Naayagi, "Power converters for DC microgrids modelling and simulation," in *Proceedings of 2018 IEEE Innovative Smart Grid Technologies*, Singapore, May 2018, pp. 994-999.

[54] N. Grass, M. Grund, B. Gogolka *et al.*, "DC connected modular power converter system for microgrids," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids*, Noida, India, Oct. 2017, pp. 383-386.

[55] R. Dey and S. Nath, "Architecture and power converter for multi-frequency microgrid," in *Proceedings of 2019 National Power Electronics Conference*, Tiruchirappalli, India, Dec. 2019, pp. 1-6.

[56] R. Wang, B. Zhang, S. Zhao *et al.*, "Design of an IGBT-series-based solid-state circuit breaker for battery energy storage system terminal in solid-state transformer," in *Proceedings of 45th Annual Conference of the IEEE Industrial Electronics Society*, Lisbon, Portugal, Oct. 2019, pp. 6677-6682.

[57] A. Hafri, H. Ali, A. Ghias *et al.*, "Transformer-less based solid state transformer for intelligent power management," in *Proceedings of 2016 5th International Conference on Electronic Devices, Systems and Applications*, Ras Al Khaimah, United Arab Emirates, Dec. 2016, pp. 1-4.

[58] A. Elserougi, A. Massoud, and S. Ahmed, "A bi-directional boost converter-based non-isolated DC-DC transformer with modular solid-state switches for medium-/high-voltage DC grids," in *Proceedings of 2017 4th International Conference on Information Technology, Computer, and Electrical Engineering*, Semarang, Indonesia, Oct. 2017, pp. 54-59.

[59] H. R. Mamede, W. M. dos Santos, and D. C. Martins, "A new DC-DC power converter derived from the tab for bipolar DC microgrids," in *Proceedings of 2015 IEEE Energy Conversion Congress and Exposition*, Montreal, Canada, Sept. 2015, pp. 6217-6222.

[60] T. D. Mai, T. Verschelde, and J. Driesen, "Comparative study of current redistributor's topologies for mitigating unbalanced currents in bipolar DC microgrids," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids*, Nuremburg, Germany, Jun. 2017, pp. 242-247.

[61] M. Farhadi and O. Mohammed, "Adaptive energy management in redundant hybrid DC microgrid for pulse load mitigation," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 54-62, Aug. 2015.

[62] C. Ellert, R. Horta, T. Sterren *et al.*, "Modular ICT based energy management system for a LVDC-microgrid with local PV production and integrated electrochemical storage," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids*, Nuremburg, Germany, Jun. 2017, pp. 274-278.

[63] M. Mishra, B. Patnaik, M. Biswal *et al.*, "A systematic review on DC-microgrid protection and grounding techniques: issues, challenges and future perspective," *Applied Energy*, vol. 313, p. 118810, May 2022.

[64] N. L. Diaz, T. Dragievi, J. C. Vasquez *et al.*, "Intelligent distributed generation and storage units for DC microgridsa new concept on cooperative control without communications beyond droop control," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2476-2485, Sept. 2014.

[65] A. A. A. Radwan and Y. A.-R. I. Mohamed, "Linear active stabilization of converter-dominated DC microgrids," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 203-216, Mar. 2012.

[66] J. Mrez, "A modeling and simulation of optimized interconnection between DC microgrids with novel strategies of voltage, power and control," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids*, Nuremburg, Germany, Jun. 2017, pp. 536-541.

[67] L. E. Zubieta and P. W. Lehn, "A high efficiency unidirectional DC/DC converter for integrating distributed resources into DC microgrids," in *Proceedings of 2015 IEEE First International Conference on DC Microgrids*, Atlanta, USA, Jun. 2015, pp. 280-284.

[68] Y. Guo, W. Ma, J. Meng *et al.*, "A virtual inertia control strategy for dual active bridge DC-DC converter," in *Proceedings of 2018 2nd IEEE Conference on Energy Internet and Energy System Integration*, Chengdu, China, May 2018, pp. 1-5.

[69] G. S. Rawat and Sathans, "Survey on DC microgrid architecture, power quality issues and control strategies," in *Proceedings of 2018 2nd International Conference on Inventive Systems and Control*, Coimbatore, India, Jan. 2018, pp. 500-505.

[70] R. S. Balog and P. T. Krein, "Bus selection in multibus DC microgrids," *IEEE Transactions on Power Electronics*, vol. 26, no. 3, pp. 860-867, Mar. 2011.

[71] N. C. Ekneligoda and W. W. Weaver, "A game theoretic bus selection method for loads in multibus DC power systems," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 4, pp. 1669-1678, Apr. 2014.

[72] K. Jithin, N. Mayadevi, R. H. Kumar *et al.*, "The effect of multiple pv and battery penetration on stability of DC microgrid with single bus topology," in *Proceedings of 2021 9th IEEE International Conference on Power Systems (ICPS)*, Kharagpur, India, Dec. 2021, pp. 1-5.

[73] D. Kumar, F. Zare, and A. Ghosh, "DC microgrid technology: system architectures, AC grid interfaces, grounding schemes, power quality, communication networks, applications, and standardizations aspects," *IEEE Access*, vol. 5, pp. 12230-12256, Jul. 2017.

[74] K. Sun, L. Zhang, Y. Xing *et al.*, "A distributed control strategy based on DC bus signaling for modular photovoltaic generation systems with battery energy storage," *IEEE Transactions on Power Electronics*, vol. 26, no. 10, pp. 3032-3045, Oct. 2011.

[75] Z. Luo, H. Geng, and G. Zhu, "Hierarchical cooperative control for islanded DC microgrid cluster," in *Proceedings of 2018 IEEE International Power Electronics and Application Conference and Exposition*, Shenzhen, China, Nov. 2018, pp. 1-5.

[76] H. Kakigano, Y. Miura, and T. Ise, "Low-voltage bipolar-type DC microgrid for super high quality distribution," *IEEE Transactions on Power Electronics*, vol. 25, no. 12, pp. 3066-3075, May 2010.

[77] J.-D. Park, J. Candelaria, L. Ma *et al.*, "DC ring-bus microgrid fault protection and identification of fault location," *IEEE Transactions on Power Delivery*, vol. 28, no. 4, pp. 2574-2584, Sept. 2013.

[78] W. Lu and B. T. Ooi, "Multi-terminal HVDC as enabling technology of premium quality power park," in *Proceedings of 2002 IEEE Power Engineering Society Winter Meeting*, New York, USA, Jan. 2002, pp. 719-724.

[79] R. Ara, U. A. Khan, A. I. Bhatti *et al.*, "A reliable protection scheme for fast DC fault clearance in a VSC-based meshed MTDC grid," *IEEE Access*, vol. 8, pp. 88188-88199, Jun. 2020.

[80] A. T. Elsayed and O. A. Mohammed, "A comparative study on the optimal combination of hybrid energy storage system for ship power systems," in *Proceedings of 2015 IEEE Electric Ship Technologies Symposium*, Old Town Alexandria, USA, Jun. 2015, pp. 1-5.

[81] N. Yadav and N. R. Tummuru, "A real-time resistance based fault detection technique for zonal type low-voltage DC microgrid applications," *IEEE Transactions on Industry Applications*, vol. 56, no. 6, pp. 6815-6824, Dec. 2020.

[82] G. AlLee and W. Tschudi, "Edison redux: 380 VDC brings reliability and efficiency to sustainable data centers," *IEEE Power and Energy Magazine*, vol. 10, no. 6, pp. 50-59, Nov. 2012.

[83] D. Salomonsson and A. Sannino, "Low-voltage DC distribution system for commercial power systems with sensitive electronic loads," *IEEE Transactions on Power Delivery*, vol. 22, no. 3, pp. 1620-1627, Jul. 2007.

[84] P. Sanjeev, N. P. Padhy, and P. Agarwal, "A new architecture for DC microgrids using supercapacitor," in *Proceedings of 2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems*, Charlotte, USA, Jun. 2018, pp. 1-5.

[85] A. A. Sheikh, S. A. Wakode, R. R. Deshmukh *et al.*, "A brief review on DC microgrid protection," in *Proceedings of 2020 IEEE First International Conference on Smart Technologies for Power, Energy and Control*, Nagpur, India, Sept. 2020, pp. 1-6.

[86] Y. Yang, C. Huang, and Q. Xu, "A fault location method suitable for low-voltage DC line," *IEEE Transactions on Power Delivery*, vol. 35, no. 1, pp. 194-204, Feb. 2020.

[87] Y.-J. Kim and H. Kim, "Arc extinguishment for DC circuit breaker by pptc device," in *Proceedings of 2017 IEEE International Conference on Industrial and Information Systems*, Peradeniya, Sri Lanka, Dec. 2017, pp. 1-5.

[88] F. Kurokawa, Y. Furukawa, I. Sugimoto *et al.*, "Suppression of output capacitance of DC-DC converter in HVDC system," in *Proceedings of*

2015 IEEE International Telecommunications Energy Conference, Osaka, Japan, Oct. 2015, pp. 1-4.

[89] G. Zheng, "Study on DC circuit breaker," in *Proceedings of 2014 Fifth International Conference on Intelligent Systems Design and Engineering Applications*, Zhangjiajie, China, Jun. 2014, pp. 942-945.

[90] R. Igual and C. Medrano, "Research challenges in real-time classification of power quality disturbances applicable to microgrids: a systematic review," *Renewable and Sustainable Energy Reviews*, vol. 132, p. 110050, Mar. 2020.

[91] H. Hu, S. Shi, X. Zhan *et al.*, "Feeder fault section identification without DC circuit breaker based on injected traveling wave," in *Proceedings of 2021 IEEE 4th International Conference on Electronics Technology*, Chengdu, China, May 2021, pp. 544-548.

[92] A. A. Sheikh, S. A. Wakode, R. R. Deshmukh *et al.*, "A brief review on DC microgrid protection," in *Proceedings of 2020 IEEE First International Conference on Smart Technologies for Power, Energy and Control*, Nagpur, India, Sept. 2020, pp. 1-6.

[93] X. Wu, B. Niu, L. Cheng *et al.*, "IGBT-based self-powered bidirectional solid state DC circuit breaker," in *Proceedings of 2020 4th International Conference on HVDC*, Xi'an, China, Nov. 2020, pp. 957-960.

[94] C. Li, P. Rakhra, P. J. Norman *et al.*, "Multi-sample differential protection scheme in DC microgrids," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 3, pp. 2560-2573, Jun. 2021.

[95] H. Sun, M. Rong, Z. Chen *et al.*, "Investigation on the arc phenomenon of air DC circuit breaker," *IEEE Transactions on Plasma Science*, vol. 42, no. 10, pp. 2706-2707, Oct. 2014.

[96] S. Mirsaeidi, X. Dong, and D. M. Said, "Towards hybrid AC/DC microgrids: critical analysis and classification of protection strategies," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 97-103, Jun. 2018.

[97] H. Li, W. Li, M. Luo *et al.*, "Design of smart MVDC power grid protection," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 9, pp. 3035-3046, Sept. 2011.

[98] F. Mohan and N. Sasidharan, "DC microgrid and its protection – a review," in *Proceedings of 2020 International Conference on Power, Instrumentation, Control and Computing*, Thrissur, India, Dec. 2020, pp. 1-6.

[99] P. S. Sarker, S. Biswas, A. Mehrizi-Sani *et al.*, "Modeling and analysis of transient interactions in AC/DC interconnected microgrid," in *Proceedings of 2019 IEEE 28th International Symposium on Industrial Electronics*, Vancouver, Canada, Jun. 2019, pp. 141-146.

[100] V. Patel and V. Patel, "A comprehensive review: AC DC microgrid protection," in *Proceedings of 2020 21st National Power Systems Conference*, Gandhinagar, India, Dec. 2020, pp. 1-6.

[101] W. Liu, F. Liu, X. Zha *et al.*, "An improved SSCB combining fault interruption and fault location functions for DC line short-circuit fault protection," *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 858-868, Jun. 2019.

[102] W. Leterme, S. P. Azad, and D. V. Hertem, "A local backup protection algorithm for HVDC grids," *IEEE Transactions on Power Delivery*, vol. 31, no. 4, pp. 1767-1775, Jun. 2016.

[103] H. Yang, X. Liu, Y. Guo *et al.*, "Fault location of active distribution networks based on the golden section method," *Mathematical Problems in Engineering*, vol. 20, pp. 1767-1776, Jan. 2020.

[104] P. Jafarian and M. Sanaye, "A traveling-wave-based protection technique using wavelet/PCA analysis," *IEEE Transactions on Power Delivery*, vol. 25, no. 2, pp. 588-599, Apr. 2010.

[105] R. Mohanty, U. S. M. Balaji, and A. K. Pradhan, "An accurate non-iterative fault location technique for low voltage DC microgrid," *IEEE Transactions on Power Delivery*, vol. 31, no. 2, pp. 475-481, Apr. 2016.

[106] I. Jahn, N. Johannesson, and S. Norrga, "Survey of methods for selective DC fault detection in MTDC grids," in *Proceedings of 13th IET International Conference on AC and DC Power Transmission*, Manchester, UK, Feb. 2017, pp. 1-7.

[107] D. M. Bui, S.-L. Chen, C.-H. Wu *et al.*, "Review on protection coordination strategies and development of an effective protection coordination system for DC microgrid," in *Proceedings of 2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Hong Kong, China, Dec. 2014, pp. 1-10.

[108] A. Chandra, G. K. Singh, and V. Pant, "Protection techniques for DC microgrid – a review," *Electric Power Systems Research*, vol. 187, p. 106439, Oct. 2020.

[109] M. E. Baran and N. R. Mahajan, "Overcurrent protection on voltage-source-converter-based multiterminal DC distribution systems," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 406-412, Feb. 2007.

[110] A. Meghwani, S. C. Srivastava, and S. Chakrabarti, "A new protection scheme for DC microgrid using line current derivative," in *Proceedings of 2015 IEEE PES General Meeting*, Denver, USA, Jul. 2015, pp. 1-5.

[111] S. Fletcher, P. Norman, S. Galloway *et al.*, "Optimizing the roles of unit and non-unit protection methods within DC microgrids," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2079-2087, Dec. 2012.

[112] C. Yuan, M. A. Haj-ahmed, and M. S. Illindala, "Protection strategies for medium-voltage direct-current microgrid at a remote area mine site," *IEEE Transactions on Industry Applications*, vol. 51, no. 4, pp. 2846-2853, Jul. 2015.

[113] X. Feng, Z. Ye, C. Liu *et al.*, "Fault detection in DC distributed power systems based on impedance characteristics of modules," in *Proceedings of Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy*, Rome, Italy, Oct. 2000, pp. 2455-2462.

[114] E. Christopher, M. Sumner, and D. Thomas, "Fault location for a DC zonal electrical distribution systems using active impedance estimation," in *Proceedings of 2011 IEEE Electric Ship Technologies Symposium*, Alexandria, USA, Apr. 2011, pp. 310-314.

[115] M. Zheng, X. Kang, L. Liu *et al.*, "Research on the application of traveling wave protection for DC lines in the hybrid HVDC system," in *Proceedings of 2019 IEEE 8th International Conference on Advanced Power System Automation and Protection*, Xi'an, China, Oct. 2019, pp. 1701-1705.

[116] K. A. Saleh, A. Hooshyar, and E. F. El-Saadany, "Ultra-high-speed traveling-wave-based protection scheme for medium-voltage DC microrids," *IEEE Transactions on Smart Grid*, vol. 10, no. 2, pp. 1440-1451, Jul. 2019.

[117] D. Soto, M. Sloderbeck, H. Ravindra *et al.*, "Advances to megawatt scale demonstrations of high speed fault clearing and power restoration in breakerless MVDC shipboard power systems," in *Proceedings of 2017 IEEE Electric Ship Technologies Symposium*, Arlington, USA, Aug. 2017, pp. 312-315.

[118] L. Tang and B.-T. Ooi, "Locating and isolating DC faults in multi- terminal DC systems," *IEEE Transactions on Power Delivery*, vol. 22, no. 3, pp. 1877-1884, Oct. 2007.

[119] R. Cuzner and A. Jeutter, "DC zonal electrical system fault isolation and reconfiguration," in *Proceedings of 2009 IEEE Electric Ship Technologies Symposium*, Baltimore, USA, Apr. 2009, pp. 227-234.

[120] S. Cui, J. Hu, and R. de Doncker, "Fault-tolerant operation of a tlc-mmc hybrid DC-DC converter for interconnection of MVDC and HVDC grids," *IEEE Transactions on Power Electronics*, vol. 35, no. 1, pp. 83-93, Jan. 2020.

[121] V. Nougain, V. Nougain, and S. Mishra, "Low-voltage DC ring-bus microgrid protection with rolling mean technique," in *Proceedings of 2018 IEEMA Engineer Infinite Conference*, New Delhi, India, Mar. 2018, pp. 1-6.

[122] N. Xi, F. Lin, and T. Ye, "A low injection spur injection-locked lcqvco with self-injection technique," in *Proceedings of 2018 IEEE International Conference on Integrated Circuits, Technologies and Applications*, Beijing, China, Nov. 2018, pp. 30-31.

[123] D. Groot Boerle, "EMC and functional safety, impact of IEC 61000-1-2," in *Proceedings of 2002 IEEE International Symposium on Electromagnetic Compatibility*, Minneapolis, USA, Aug. 2002, pp. 353-358.

[124] S. Song, M. Yoon, and G. Jang, "Analysis of six active power control strategies of interconnected grids with VSC-HVDC," *Applied Sciences*, vol. 9, no. 1, p. 183, Mar. 2019.

[125] M.-H. Wang, S. Yan, S.-C. Tan *et al.*, "Hybrid-DC electric springs for DC voltage regulation and harmonic cancellation in DC microgrids," *IEEE Transactions on Power Electronics*, vol. 33, no. 2, pp. 1167-1177, Feb. 2018.

[126] G. van den Broeck, J. Stuyts, and J. Driesen, "A critical review of power quality standards and definitions applied to DC microgrids," *Applied Energy*, vol. 229, pp. 281-288, Nov. 2018.

[127] D. L. Gerber, V. Vossos, W. Feng *et al.*, "A simulation based comparison of AC and DC power distribution networks in buildings," in *Proceedings of 2017 IEEE Second International Conference on DC Microgrids*, Nuremburg, Germany, Jun. 2017, pp. 588-595.

[128] E. Taylor, M. Korytowski, and G. Reed, "Voltage transient propagation in ac and DC datacenter distribution architectures," in *Proceedings of 2012 IEEE Energy Conversion Congress and Exposition*, Raleigh, USA, Sept. 2012, pp. 1998-2004.

[129] B. Davies, "Analysis of inrush currents for DC powered IT equipment," in *Proceedings of 2011 IEEE 33rd International Telecommunications Energy Conference*, Amsterdam, Netherlands, Oct. 2011, pp.

1-4.
[130] M. Farhadi and O. Mohammed, "Realtime operation and harmonic analysis of isolated and non-isolated hybrid DC microgrid," in *Proceedings of 2013 IEEE Industry Applications Society Annual Meeting*, Lake Buena Vista, USA, Oct. 2013, pp. 1-6.
[131] *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Standard 1159-2019, 2019.
[132] A. J. Roscoe, S. J. Finney, and G. M. Burt, "Tradeoffs between AC power quality and DC bus ripple for 3-phase 3-wire inverter-connected devices within microgrids," *IEEE Transactions on Power Electronics*, vol. 26, no. 3, pp. 674-688, Jul. 2011.
[133] S. I. Rai and R. A. Ravishankar, "Review of DC microgrid system with various power quality issues in real time operation of DC microgrid connected system," *Majlesi Journal of Mechatronic Systems*, vol. 8, no. 3, pp. 35-44, Jan. 2019.
[134] A. Emadi, A. Khaligh, C. Rivetta *et al*., "Constant power loads and negative impedance instability in automotive systems: definition, modeling, stability, and control of power electronic converters and motor drives," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 4, pp. 1112-1125, Jul. 2006.
[135] T. J. Browne and N. R. Browne, "Power quality considerations for utilities supplying residential DC installations," in *Proceedings of 2008 13th International Conference on Harmonics and Quality of Power*, Wollongong, Australia, Sept. 2008, pp. 1-5.
[136] K. Asakimori, K. Murai, T. Tanaka *et al.*, "Effect of inrush current flowing into EMI filter on the operation of ICT equipment in HVDC system," in *Proceedings of 2014 IEEE 36th International Telecommunications Energy Conference*, Vancouver, Canada, Sept. 2014, pp. 1-5.
[137] B. Davies, "Analysis of inrush currents for DC powered IT equipment," in *Proceedings of 2011 IEEE 33rd International Telecommunications Energy Conference*, Amsterdam, Netherlands, Oct. 2011, pp. 1-4.
[138] B. Kwak, M. Kim, and J. Kim, "Inrush current reduction technology of dab converter for low-voltage battery systems and DC bus connections in DC microgrids," *IET Power Electronics*, vol. 13, no. 8, pp. 1528-1536, Jun. 2020.
[139] H. Zhu, L. Tian, D. Qi *et al*., "Voltage harmonic and interharmonic detection method for DC microgrid based on hanning window interpolation," *Journal of Physics Conference Series*, vol. 1346, pp. 12-20, Nov. 2019.
[140] J. Wang, F. Yang, and X. Du, "Microgrid harmonic and interharmonic analysis algorithm based on cubic spline interpolation signal reconstruction," in *Proceedings of IEEE PES Innovative Smart Grid Technologies*, Tianjin, China, May 2012, pp. 1-5.
[141] A. Sangwongwanich, Y. Yang, D. Sera *et al*., "Analysis and modeling of interharmonics from grid-connected photovoltaic systems," *IEEE Transactions on Power Electronics*, vol. 33, pp. 8353-8364, Nov. 2018.
[142] D. Li, L. Kong, C. Nie *et al*., "Grid stability enhancement by a high voltage SiC MOSFET-based asynchronous microgrid power conditioning system," in *Proceedings of 2021 IEEE Applied Power Electronics Conference and Exposition*, Phoenix, USA, Jun. 2021, pp. 111- 118.
[143] K.-T. Mok, M.-H. Wang, S.-C. Tan *et al*., "DC electric springs – a technology for stabilizing DC power distribution systems," *IEEE Transactions on Power Electronics*, vol. 32, no. 2, pp. 1088-1105, Jul. 2016.
[144] Q. Wang, M. Cheng, Y. Jiang *et al*., "DC electric springs with DC/DC converters," in *Proceedings of the 2016 IEEE 8th International Power Electronics and Motion Control Conference*, Hefei, China, May 2016, pp. 3268-3273.
[145] S. Whaite, B. Grainger, and A. Kwasinski, "Power quality in DC power distribution systems and microgrids," *Energies*, vol. 8, pp. 4378-4399, May 2015.
[146] R. M. Cuzner and G. Venkataramanan, "The status of DC micro-grid protection," in *Proceedings of 2008 IEEE Industry Applications Society Annual Meeting*, Edmonton, Canada, Oct. 2008, pp. 1-8.
[147] T. Pieter and D. V. Hertem, "The relevance of inertia in power systems," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 999-1009, Oct. 2016.
[148] X. Zhu, Z. Xie, S. Jing *et al*., "Distributed virtual inertia control and stability analysis of DC microgrid," *IET Generation, Transmission & Distribution*, vol. 12, no. 14, pp. 3477-3486, Feb. 2018.
[149] X. Lyu, Z. Xu, J. Zhao *et al*., "Advanced frequency support strategy of photovoltaic system considering changing working conditions," *IET Generation, Transmission & Distribution*, vol. 12, no. 2, pp. 363-370, Jan. 2018.
[150] B. Liu, F. Zhuo, Y. Zhu *et al.*, "System operation and energy management of a renewable energy-based DC micro-grid for high penetration depth application," *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1147-1155, May 2014.
[151] B. Liu, F. Zhuo, and X. Bao, "Control method of the transient compensation process of a hybrid energy storage system based on battery and ultra-capacitor in micro-grid," in *Proceedings of 2012 IEEE International Symposium on Industrial Electronics*, Hangzhou, China, May 2012, pp. 1325-1329.
[152] A. Hosseinipour and H. Hojabri, "Virtual inertia control of PV systems for dynamic performance and damping enhancement of DC microgrids with constant power loads," *IET Renewable Power Generation*, vol. 12, no. 4, pp. 430-438, Jun. 2018.
[153] M. Song, S. Fan, Y. Wang *et al.*, "A flexible virtual capacitance control strategy for DC micro-grid," in *Proceedings of 2018 2nd IEEE Conference on Energy Internet and Energy System Integration*, Beijing, China, Oct. 2018, pp. 1-4.
[154] J. Meng, Y. Zhang, Y. Wang *et al.*, "Flexible virtual capacitance control strategy for a DC microgrid with multiple constraints," *IET Renewable Power Generation*, vol. 14, no. 17, pp. 3469-3478, May 2020.
[155] G. Melath and V. Agarwal, "A novel virtual inertia implementation scheme using model predictive control for enhancing the voltage stiffness of a grid tied DC microgrid," in *Proceedings of 2019 IEEE Transportation Electrification Conference*, Bengaluru, India, Dec. 2019, pp. 1-5.
[156] Y. Guo, J. Meng, Y. Wang *et al*., "A virtual DC machine control strategy for dual active bridge DC-DC converter," in *Proceedings of 2019 IEEE Innovative Smart Grid Technologies-Asia*, Chengdu, China, May 2019, pp. 2384-2388.
[157] Z. Yi, X. Zhao, D. Shi *et al*., "Accurate power sharing and synthetic inertia control for DC building microgrids with guaranteed performance," *IEEE Access*, vol. 7, pp. 63 698-63 708, Jul. 2019.
[158] Z. Jin, L. Meng, R. Han *et al*., "Admittance-type RC-mode droop control to introduce virtual inertia in DC microgrids," in *Proceedings of 2017 IEEE Energy Conversion Congress and Exposition*, Cincinnati, USA, Oct. 2017, pp. 4107-4112.
[159] X. Zhu, F. Meng, Z. Xie *et al.*, "An inertia and damping control method of DC-DC converter in DC microgrids," *IEEE Transactions on Energy Conversion*, vol. 35, no. 2, pp. 799-807, Jun. 2019.
[160] N. Zhi, K. Ding, L. Du *et al.*, "An SoC-based virtual DC machine control for distributed storage systems in DC microgrids," *IEEE Transactions on Energy Conversion*, vol. 35, no. 3, pp. 1411-1420, Jun. 2020.
[161] M. Arani, M. Fakhari, and E. F. Saadany, "Implementing virtual inertia in DFIG-based wind power generation," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1373-1384, May 2012.
[162] J. Morren, J. Pierik, and S. W. H. de Haan, "Inertial response of variable speed wind turbines," *Electric Power Systems Research*, vol. 76, no. 11, pp. 980-987, July 2006.
[163] N. P. Yengijeh, H. M. CheshmehBeigi, and A. Hajizadeh, "Inertia emulation with the concept of virtual supercapacitor for islanded DC microgrid," in *Proceedings of 7th Iran Wind Energy Conference*, Shahrood, Iran, May 2021, pp. 1-4.
[164] X. Zhang, H. Li, and Y. Fu, "Optimized virtual DC machine control for voltage inertia and damping support in DC microgrid," in *Proceedings of 2021 IEEE Applied Power Electronics Conference and Exposition*, Phoenix, USA, Jun. 2021, pp. 2727-2732.
[165] T. Shucheng, D. Ge, Z. Hui *et al.*, "Virtual DC machine control strategy of energy storage converter in DC microgrid," in *Proceedings of 2016 IEEE Electrical Power and Energy Conference*, Ottawa, Canada, Oct. 2016, pp. 1-5.
[166] A. K. Niran, A. Kumar, and R. Sharma, "Photovoltaic and battery storage energy system connected to AC micro-grid to maintain constant DC voltage," in *Proceedings of 2019 2nd International Conference on Signal Processing and Communication*, Coimbtore, India, Mar. 2019, pp. 59-63.
[167] Y. Fu, X. Shao, and X. Zhang, "Research on virtual inertia control of the DC microgrid," in *Proceedings of 16th IET International Conference on AC and DC Power Transmission*, vol. 2020, pp. 350-355, Jul. 2020.
[168] D. Kumar, F. Zare, and A. Ghosh, "DC microgrid technology: system architectures, AC grid interfaces, grounding schemes, power quality, communication networks, applications and standardizations aspects," *IEEE Access*, vol. 5, pp. 12230-12256, Jun. 2017.
[169] M. Lonkar and S. Ponnaluri, "An overview of DC microgrid operation and control," in *Proceedings of 2015 the Sixth International Renewable Energy Congress*, Sousse, Tunisia, Mar. 2015, pp. 1-6.
[170] M. A. Moonem, X. Feng, S. Strank *et al.*, "Secure data communication through power electronic converters in a DC microgrid," in *Pro-*

ceedings of 2021 IEEE Fourth International Conference on DC Microgrids, Arlington, USA, Jul. 2021, pp. 1-7.
[171] X. Yang, F. Tang, X. Wu *et al.*, "Hierarchical control strategy of grid-connected DC microgrids," in *Proceedings of 2016 IEEE 8th International Power Electronics and Motion Control Conference*, Hefei, China, May 2016, pp. 3723-3727.
[172] M. Mehdi, C.-H. Kim, and M. Saad, "Robust centralized control for DC islanded microgrid considering communication network delay," *IEEE Access*, vol. 8, pp. 77765-77778, May 2020.
[173] J. Hu, J. Duan, H. Ma *et al.*, "Distributed adaptive droop control for optimal power dispatch in DC microgrid," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 778-789, Jan. 2017.
[174] F. Guo, L. Wang, C. Wen *et al.*, "Distributed voltage restoration and current sharing control in islanded DC microgrid systems without continuous communication," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 4, pp. 3043-3053, Apr. 2019.
[175] A. Asheibi, A. Khalil, A. M. Elbreki *et al.*, "Stability analysis of PV-based DC microgrid with communication delay," in *Proceedings of 2018 9th International Renewable Energy Congress*, Hammamet, Tunisia, Mar. 2018, pp. 1-6.
[176] H. Wu, K. Tsakalis, and G. Heydt, "Evaluation of time delay effects to wide-area power system stabilizer design," *IEEE Transactions on Power Systems*, vol. 19, no. 4, pp. 1935-1941, Nov. 2004.
[177] A. Khalil, S. Elkawafi, and A. I. A. Elgaiyar, "Delay-dependent stability of DC microgrid with time-varying delay," in *Proceedings of 2016 22nd International Conference on Automation and Computing*, Cholchestor, UK, Sept. 2016, pp. 360-365.
[178] M. Saleh, Y. Esa, and A. Mohamed, "Effect of wireless communication delay on DC microgrids performance," in *Proceedings of 2018 IEEE Energy Conversion Congress and Exposition*, Portland, USA, Sept. 2018, pp. 5164-5168.
[179] A. B. Shyam, S. Anand, and S. R. Sahoo, "Effect of communication delay on consensus-based secondary controllers in DC microgrid," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 4, pp. 3202-3212, Apr. 2021.
[180] F. Bouhafs, M. Mackay, and M. Merabti, "Links to the future: communication requirements and challenges in the smart grid," *IEEE Power and Energy Magazine*, vol. 10, no. 1, pp. 24-32, Apr. 2012.
[181] Z. Wang, F. Liu, Y. Chen *et al.*, "Unified distributed control of standalone DC microgrids," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 1013-1024, Jan. 2019.
[182] A. Shapoury, V. Venkataramanan, and A. A. Mallikeswaran, "Study of stability of an islanded microgrid in the presence of communication delays," in *Proceedings of 40th Annual Conference of the IEEE Industrial Electronics Society*, Dallas, USA, Oct. 2014, pp. 5666-5671.
[183] Song, J. Qian, D. Wu *et al.*, "Impact of wireless communication delay on load sharing among distributed generation systems through smart microgrids," *IEEE Wireless Communications*, vol. 19, no. 3, pp. 24-29, Jun. 2012.
[184] Q. Zhong and G. Weiss, "A unified smith predictor based on the spectral decomposition of the plant," *International Journal of Control*, vol. 77, no. 15, pp. 1362-1371, Sept. 2004.
[185] M. Saleh, Y. Esa, M. E. Hariri *et al.*, "Impact of information and communication technology limitations on microgrid operation," *Energies*, vol. 12, no. 15, p. 2926, Jul. 2019.
[186] S. Liu, X. Wang, and P. Liu, "Impact of communication delays on secondary frequency control in an islanded microgrid," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2021-2031, Apr. 2015.
[187] B. Tavassoli, A. Fereidunian, and S. Mehdi, "Communication system effects on the secondary control performance in microgrids," *IET Renewable Power Generation*, vol. 14, no. 12, pp. 2047-2057, Sept. 2020.
[188] B. Zhang, T. S. E. Ng, A. Nandi *et al.*, "Measurement-based analysis, modeling, and synthesis of the internet delay space," *IEEE/ACM Transactions on Networking*, vol. 18, no. 1, pp. 229-242, Feb. 2010.
[189] M. Saleh, Y. Esa, and A. Mohamed, "Impact of communication latency on the bus voltage of centrally controlled DC microgrids during islanding," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 4, pp. 1844-1856, Oct. 2019.
[190] I. Rubin, "Communication networks: message path delays," *IEEE Transactions on Information Theory*, vol. 20, no. 6, pp. 738-745, Oct. 1974.
[191] Z. Wang, W. Wu, and B. Zhang, "A distributed control method with minimum generation cost for DC microgrids," *IEEE Transactions on Energy Conversion*, vol. 31, no. 4, pp. 1462-1470, Dec. 2016.
[192] J. Lai, X. Lu, X. Yu *et al.*, "Distributed voltage regulation for cyber-physical microgrids with coupling delays and slow switching topologies," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 50, no. 1, pp. 100-110, Jan. 2020.
[193] C. Dou, D. Yue, Z. Zhang *et al.*, "Analysis and modeling of inter- harmonics from grid-connected photovoltaic systems," *IEEE Systems Journal*, vol. 13, no. 1, pp. 615-624, Nov. 2017.
[194] X. Fang, S. Misra, G. Xue *et al.*, "Smart grid – the new and improved power grid: a survey," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 4, pp. 944-980, Jun. 2011.
[195] W. Wang and Z. Lu, "Cyber security in the smart grid: survey and challenges," *Computer Networks*, vol. 57, no. 5, pp. 1344-1371, May 2013.
[196] S. Sahoo, J. C.-H. Peng, S. Mishra *et al.*, "Distributed screening of hijacking attacks in DC microgrids," *IEEE Transactions on Power Electronics*, vol. 35, no. 7, pp. 7574-7582, Jul. 2020.
[197] S. Sahoo, T. Dragievi, and F. Blaabjerg, "Multilayer resilience paradigm against cyber-attacks in DC microgrids," *IEEE Transactions on Power Electronics*, vol. 36, no. 3, pp. 2522-2532, Aug. 2020.
[198] Y. Guo, "Economic operation of typical microgrids," M.Sc. Dissertation, University of Kentuchy, Lexington, USA, 2018.
[199] L. Che and M. Shahidehpour, "DC microgrids: economic operation and enhancement of resilience by hierarchical control," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2517-2526, Sept. 2014.
[200] F. A. Mohamed and H. N. Koivo, "Microgrid online management and balancing using multiobjective optimization," in *Proceedings of 2007 IEEE Lausanne PowerTech Conference*, Lausanne, Switzerland, Jul. 2007, pp. 639-644.
[201] M. Gulin, J. Matuko, and M. Vaak, "Stochastic model predictive control for optimal economic operation of a residential DC microgrid," in *Proceedings of 2015 IEEE International Conference on Industrial Technology*, Seville, Spain, Mar. 2015, pp. 505-510.
[202] M. Zaery, E. M. Ahmed, and M. Orabi, "Consensus algorithm based distributed control for economic operation of islanded DC microgrids," in *Proceedings of 2016 Eighteenth International Middle East Power Systems Conference*, Cairo, Egypt, Dec. 2016, pp. 854-859.
[203] W. G. Gonzlez, O. M. Giraldo, E. Holgun *et al.*, "Economic dispatch of energy storage systems in DC microgrids employing a semidefinite programming model," *The Journal of Energy Storage*, vol. 21, pp. 1-8, Feb. 2019.
[204] D. Deng and G. Li, "Research on economic operation of grid-connected DC microgrid," in *Proceedings of International Conference on Renewable Power Generation*, Beijing, China, Oct. 2015, pp. 1-6.
[205] R. Babazadeh-Dizaji and M. Hamzeh, "Distributed hierarchical control for optimal power dispatch in multiple DC microgrids," *IEEE Systems Journal*, vol. 14, no. 1, pp. 1015-1023, Mar. 2020.
[206] R. de Leone, A. Giovannelli, and M. Pietrini, "Optimization of power production and costs in microgrids," *Optimization Letters*, vol. 11, pp. 497-520, Apr. 2017.
[207] I. U. Nutkani, W. Peng, P. C. Loh *et al.*, "Autonomous economic operation of grid connected DC microgrid," in *Proceedings of 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems*, Galway, Ireland, Jun. 2014, pp. 1-5.
[208] C. Li, F. de Bosio, S. K. Chaudhary *et al.*, "Operation cost minimization of droop-controlled DC microgrids based on real-time pricing and optimal power flow," in *Proceedings of 41st Annual Conference of the IEEE Industrial Electronics Society*, Yokohama, Japan, Nov. 2015, pp. 3905-3909.
[209] J. Chen, X. Yang, L. Zhu *et al.*, "Genetic algorithm based economic operation optimization of a combined heat and power microgrid," *Power System Protection and Control*, vol. 41, pp. 7-15, Apr. 2013.
[210] H. G. Tran, N. G. M. Thao *et al.*, "Energy management and optimization method based on Lagrange multiplier for microgrid with considerations of electricity price and vehicle," in *Proceedings of 2021 IEEE 10th Global Conference on Consumer Electronics (GCCE)*, Kyoto, Japan, 2021, pp. 898-899.
[211] J. Johnston, J. Counsell, G. Banks *et al.*, "Beyond power over ethernet: the development of digital energy networks for buildings," in *Proceedings of CIBSE Technical Symposium 2012*, London, UK, Apr. 2012, pp. 1-7.
[212] D. J. Becker and B. Sonnenberg, "DC microgrids in buildings and data centers," in *Proceedings of 2011 IEEE 33rd International Telecommunications Energy Conference*, Amsterdam, Netherlands, Oct. 2011, pp. 1-7.
[213] T. Dragievi, X. Lu, J. C. Vasquez *et al.*, "DC micro grids part II: a review of power architectures, applications, and standardization issues," *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3528-3549, Apr. 2016.

[214] Y. Lim, M. J. Hossain, S. Javaid *et al.*, "Study of home energy management system for DC-based nanogrid," in *Proceedings of 2020 IEEE International Conference on Consumer Electronics*, Taoyuan, China, Sept. 2020, pp. 1-2.

[215] Y. K. Paarveandan, S. Krishnan, S. S. Vishwesh *et al.*, "Solar powered DC home with MPPT and integrating voltage control," in *Proceedings of 2021 International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation*, Coimbatore, India, Oct. 2021, pp. 1-6.

[216] A. Mishra, K. Rajeev, and V. Garg, "Assessment of 48 volts DC for homes," in *Proceedings of 2018 IEEMA Engineer Infinite Conference*, New Delhi, India, Oct. 2018, pp. 1-6.

[217] G. B. A. Kumar, Shivashankar, N. Sujay *et al.*, "Design and implementation of wireless sensor network based smart DC grid for smart cities," in *Proceedings of 2019 4th International Conference on Recent Trends on Electronics, Information, Communication Technology*, Bangalore, India, May 2019, pp. 1453-1458.

[218] Q. Shafiee, T. Dragievi, J. C. Vasquez *et al.*, "Hierarchical control for multiple DC-microgrids clusters," *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp. 922-933, Dec. 2014.

[219] H. R. Rajaram and G. Balamurugan, "A study on green house gas mitigation from solar parks in India," in *Proceedings of 2020 International Conference and Utility Exhibition on Energy, Environment and Climate Change*, Pattaya, Thailand, Oct. 2020, pp. 1-8.

[220] H. Joshi. (2021, Mar.). Top 10 largest solar parks in the world. [Online]. Available: https://solarfunda.com/largest-solar-parks-in-the-world

[221] A. Pradhan. (2021, Sept.). Top 10 largest wind farms in the world. [Online]. Available: https://earthandhuman.org/world-largest-wind-farms

[222] P. Pourang, M. Masnavi, M. Bavili *et al.*, "Designing the renewable energy parks in order to reduce the environmental crisis in the framework of ecological design, case of renewable energy park of Manjil-Iran," in *Design for Innovative Value Towards a Sustainable Society*, Dordrecht: Springer, 2012, pp. 43-48.

[223] I. Crciun, T. Kerekes, D. Sra *et al.*, "Overview of recent grid codes for PV power integration," in *Proceedings of 2012 13th International Conference on Optimization of Electrical and Electronic Equipment*, Brasov, Romania, May 2012, pp. 959-965.

[224] H. T. Mokui, M. A. S. Masoum, and M. Mohseni, "Review on Australian grid codes for wind power integration in comparison with international standards," in *Proceedings of 2014 Australasian Universities Power Engineering Conference*, Perth, Australia, Sept. 2014, pp. 1-6.

[225] A. Mohamed and O. Mohammed, "Real-time energy management scheme for hybrid renewable energy systems in smart grid applications," *Electric Power Systems Research*, vol. 96, pp. 133-143, Mar. 2013.

[226] C. Chen, S. Duan, T. Cai *et al*., "Optimal allocation and economic analysis of energy storage system in microgrids," *IEEE Transactions on Power Electronics*, vol. 26, no. 10, pp. 2762-2773, Jul. 2011.

[227] Y. Song, Y. Zheng, and D. J. Hill, "Optimal scheduling for EV charging stations in distribution networks: a convexified model," *IEEE Transactions on Power Systems*, vol. 32, no. 2, pp. 1574-1575, Mar. 2017.

[228] M. F. Shaaban, S. Mohamed, M. Ismail *et al.*, "Joint planning of smart EV charging stations and DGS in eco-friendly remote hybrid microgrids," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 5819-5830, Sept. 2019.

[229] R. O. Oliyide, C. Marmaras, E. Xydas *et al.*, "Estimating the true GHG emissions reduction due to electric vehicles integration," in *Proceedings of 2015 50th International Universities Power Engineering Conference*, Stoke-on-Trent, UK, Sept. 2015, pp. 1-5.

[230] V. M. Iyer, S. Gulur, G. Gohil *et al.*, "Extreme fast charging station architecture for electric vehicles with partial power processing," in *Proceedings of 2018 IEEE Applied Power Electronics Conference and Exposition*, San Antonio, USA, Mar. 2018, pp. 659-665.

[231] Y.-C. Hsu, S.-C. Kao, C.-Y. Ho *et al.*, "On an electric scooter with G2V/V2H/V2G and energy harvesting functions," *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6910-6925, Aug. 2018.

[232] M. A. H. Rafi and J. Bauman, "A comprehensive review of DC fast-charging stations with energy storage: architectures, power converters, and analysis," *IEEE Transactions on Transportation Electrification*, vol. 7, no. 2, pp. 345-368, Jun. 2021.

[233] C. Xu, K. Wang, P. Li *et al.*, "Renewable energy-aware big data analytics in geo-distributed data centers with reinforcement learning," *IEEE Transactions on Network Science and Engineering*, vol. 7, no. 1, pp. 205-215, Mar. 2020.

[234] H. Dou, Y. Qi, W. Wei *et al.*, "Carbon-aware electricity cost minimization for sustainable data centers," *IEEE Transactions on Sustainable Computing*, vol. 2, no. 2, pp. 211-223, Jun. 2017.

[235] D. Salomonsson, L. Soder, and A. Sannino, "An adaptive control system for a DC microgrid for data centers," *IEEE Transactions on Industry Applications*, vol. 44, no. 6, pp. 1910-1917, Dec. 2008.

[236] P. Brijesh, K. Jiju, P. Dhanesh *et al.*, "Microgrid for sustainable development of remote villages," in *Proceedings of TENCON 2019 - 2019 IEEE Region 10 Conference*, Kochi, India, Oct. 2019, pp. 2433-2438.

[237] P. E. Battaiotto, M. G. Cendoya, G. M. Toccaceli *et al.*, "Stand-alone hybrid microgrid for remote areas. topology and operation strategy," in *proceedings of 2017 IEEE URUCON*, Montevideo, Uruguay, Oct. 2017, pp. 1-4.

[238] F. Shahnia, "Stability of a sustainable remote area microgrid," in *Proceedings of 2016 IEEE Region 10 Conference*, Singapore, Nov. 2016, pp. 1220-1223.

[239] R. O. Kene, T. O. Olwal, and D. S. P. Chowdhury, "Distributed generation with photovoltaic power prediction in remote microgrid application," in *Proceedings of 2019 IEEE PES/IAS PowerAfrica*, Abuja, Nigeria, Aug. 2019, pp. 711-716.

[240] N. Ninad, D. Turcotte, and Y. Poissant, "Analysis of PV-diesel hybrid microgrids for small Canadian arctic communities," *Canadian Journal of Electrical and Computer Engineering*, vol. 43, no. 4, pp. 315-325, May 2020.

[241] S. Chalise and R. Tonkoski, "Day ahead schedule of remote microgrids with renewable energy sources considering battery lifetime," in *Proceedings of 2014 11th IEEE/IAS International Conference on Industry Applications*, Juizcle Fora, Brazil, Dec. 2014, pp. 1-5.

[242] B. Sahoo, S. K. Routray, and P. K. Rout, "AC, DC, and hybrid control strategies for smart microgrid application: a review," *International Transactions on Electrical Energy Systems*, vol. 31, no. 1, pp. 63-72, Jun. 2021.

[243] E. Unamuno and J. A. Barrena, "Hybrid AC/DC microgrids part i: review and classification of topologies," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1251-1259, Dec. 2015.

[244] S. K. Sahoo, A. K. Sinha, and N. K. Kishore, "Control techniques in AC, DC, and hybrid ACDC microgrid: a review," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 2, pp. 738-759, Dec. 2018.

[245] D. Fregosi, S. Ravula, D. Brhlik *et al*., "A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles," in *Proceedings of 2015 IEEE First International Conference on DC Microgrids*, Atlanta, USA, Jun. 2015, pp. 159-164.

[246] R. K. Behera and S. K. Parida, "DC microgrid management using power electronics converters," in *Proceedings of 2014 Eighteenth National Power Systems Conference*, Guwahati, India, Dec. 2014, pp. 1-6.

[247] Z. Chen, K. Wang, Z. Li *et al*., "A review on control strategies of ac/DC microgrid," in *Proceedings of 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe*, Milan, Italy, Jun. 2017, pp. 1-6.

[248] T. Ardriani, P. A. Dahono, A. Rizqiawan *et al*., "A DC microgrid system for powering remote areas," *Energies*, vol. 14, no. 2, Jan. 2021.

[249] S. Mirsaeidi and S. Shi, "AC and DC microgrids: a review on protection issues and approaches," *Journal of Electrical Engineering and Technology*, vol. 12, Nov. 2017.

[250] L. Che, M. Shahidehpour, A. Alabdulwahab *et al.*, "Hierarchical coordination of a community microgrid with AC and DC microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 3042-3051, Nov. 2015.

[251] R. Sirsi, S. Prasad, A. Sonawane *et al.*, "Efficiency comparison of AC distribution system and DC distribution system in microgrid," in *Proceedings of the 2016 International Conference on Energy Efficient Technologies for Sustainability*, Nagercoil, India, Apr. 2016, pp. 325-329.

[252] DC Systems by Schneider Electric. (2022, Jul.). Applications. [Online]. Available: https://www.dc.systems/applications/projects

Kolampurath Jithin received the B.Tech. degree in electrical and electronics engineering and the M.Tech. degree in power system from College of Engineering Trivandrum, Thiruvananthapuram, India, in 2015 and 2018, respectively, under APJ Abdul Kalam Technological University (APJKTU), Thiruvananthapuram, India. He is currently a Research Scholar under APJKTU. His research interests include DC microgrid, renewable power generation, and interconnected DC microgrid.

Puthan Purayil Haridev received the B.Tech. degree in electrical and elec-

tronics engineering from College of Engineering Trivandrum, Thiruvananthapuram, India, in 2021, under APJ Abdul Kalam Technological University (APJKTU), Thiruvananthapuram, India. He is currently working as a Systems Engineer at Tata Consultancy Services (TCS), Kochi, Thiruvananthapuram, India. His research interests include DC and AC microgrids, renewable energy systems, hybrid energy storage, and electric vehicles.

Nanappan Mayadevi received the B.Tech. degree in electrical and electronics engineering from Rajiv Gandhi Institute of Technology, Kottayam, India, the M.Tech. degree in computer and information sciences from Cochin University of Science and Technology, Cochin, India, and the Ph. D. degree from the University of Kerala, Thiruvananthapuram, India. She is currently working as Professor, at the Department of Electrical Engineering, College of Engineering Trivandrum, Thiruvananthapuram, India. Her research interests include machine learning, supervisory control and data acquisition (SCADA), and database systems.

Raveendran Pillai Harikumar received the B. E. degree in electrical and electronics engineering from the Manipal Institute of Technology, Manipal, India, in 1995, the M.Tech. degree in power systems from the National Institute of Engineering, India, in 2006, and the Ph.D. degree in electrical engineering from Kerala University, Trivandrum, India in 2018. Since 2008, he has been with the Department of Electrical Engineering, College of Engineering Trivandrum, Thiruvananthapuram, India, where he is currently working as an Associate Professor. His current research interests include control and protection of microgrids, smart grids, and electric drives.

Valiyakulam Prabhakaran Mini received the B. Tech. degree in electrical and electronics engineering from MA College of Engineering, Kottayam, India, in 1991, the M. Tech. degree in 2006 from NIT Trichy, and the Ph. D. degree in 2015 from University of Kerala, Trivandrum, India. She is currently working as Professor at the Department of Electrical Engineering, College of Engineering Trivandrum, Thiruvananthapuram, India. Her research interests include electric vehicles, electric drives, and fuzzy logic.