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DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects

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ABSTRACT To meet the fast-growing energy demand and, at the same time, tackle environmental concerns resulting from conventional energy sources, renewable energy sources are getting integrated in power networks to ensure reliable and affordable energy for the public and industrial sectors. However, the integration of renewable energy in the ageing electrical grids can result in new risks/challenges, such as security of supply, base load energy capacity, seasonal effects, and so on. Recent research and development in microgrids have proved that microgrids, which are fueled by renewable energy sources and managed by smart grids (use of smart sensors and smart energy management system), can offer higher reliability and more efficient energy systems in a cost-effective manner. Further improvement in the reliability and efficiency of electrical grids can be achieved by utilizing dc distribution in microgrid systems. DC microgrid is an attractive technology in the modern electrical grid system because of its natural interface with renewable energy sources, electric loads, and energy storage systems. In the recent past, an increase in research work has been observed in the area of dc microgrid, which brings this technology closer to practical implementation. This paper presents the state-of-the-art dc microgrid technology that covers ac interfaces, architectures, possible grounding schemes, power quality issues, and communication systems. The advantages of dc grids can be harvested in many applications to improve their reliability and efficiency. This paper also discusses benefits and challenges of using dc grid systems in several applications. This paper highlights the urgent need of standardizations for dc microgrid technology and presents recent updates in this area.

INDEX TERMS DC microgrid, architectures, power quality, grounding, communication network, smart grid and standardization.

I. INTRODUCTION

The era of 20th century had begun with a very crucial debate on the electricity delivery type and its fundamental aspects, basically how it is generated, transmitted and utilized. This debate is known as the ‘‘war of currents,’’ where George Westinghouse and Nikola Tesla supported Alternating Current (AC) and their opponent Thomas Edison advocated Direct Current (DC). It was clear that the DC power generation was limited to a relatively low voltage and the drop in the voltage level was a critical issue. Therefore, Edison’s power plants had to be utilized locally, i.e. loads had to be close to the generating stations [1]. In contrary, the AC voltage could easily be stepped up to facilitate the power transfer over long distances and then stepped down to deliver to the end users. Furthermore, Tesla invented AC Induction Motor (IM), which proved to be the game changer in this war. Due to these factors AC won ‘‘war of currents’’ as the prominent form of electricity generation and delivery [2], [3]. The achievement of this foundational milestone in the electricity history remarkably led the era of centralized power generation (power plant) and expansion of the AC power transmission and distribution worldwide. Also, fossil fuel (coal and natural gas) based power plants became the prominent means of electricity generation.

In the recent years, environmental issues of conventional energy sources have become the main concerns due to greenhouse gas emission and depletion on energy sources. Coupled with these, the ageing of current transmission and distribution infrastructure and ever-growing demand of electrical energy have stressed the power delivery systems. As a consequence, many researchers and politicians have considered that innovation in sustainable energy supply is essential in order to provide reliable and clean energy sources and to improve the quality of life on this planet. Although recent developments in distributed generations such as grid connected Renewable Energy Sources (RES) have already shown promise, increasing penetration of distributed generations into utility AC grids can cause voltage rise and protection issues. These will increase the challenge for the utility grid security, reliability and quality. In order to solve these problems, new concepts, known as ''Microgrid'' and ''Smart grids'', for future electrical power systems have been proposed. A microgrid is a low voltage (LV) power network containing distributed energy sources such as photovoltaic (PV) arrays, micro-wind turbines, fuel cell and energy storage devices (e.g. batteries, super capacitor and flywheel). The idea of microgrid began as a solution to meet the local energy demand by connecting distributed power sources to distribution networks such as local substations without further expansion of costly centralized utility grids. Microgrids are normally interconnected to low or medium voltage (MV) distribution networks via a direct connection or an interfacing power converter, which gives an opportunity to get power from the utility grid and also feeds power back to utility grid during surplus power generation. In the event of a fault, the microgrid disconnects from the utility network as fast as possible and controls its load using different control methods such as a droop control. In this condition, the microgrid operates in an islanding mode. The special characteristics of microgrid (as defined smart grid requirements) improve the power security, reliability and quality of the grid as well as local customers.

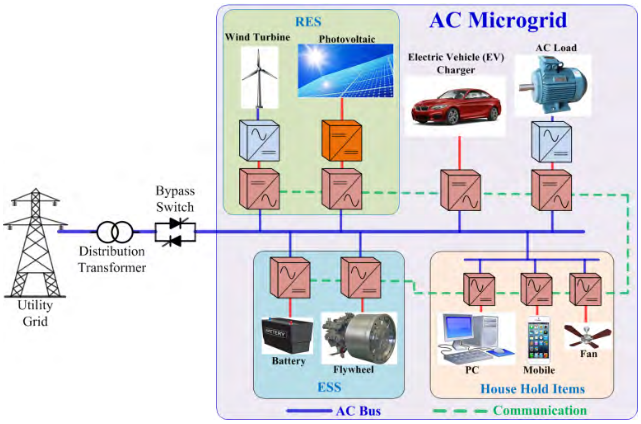


FIGURE 1. Building block of an AC microgrid system.

Presently, most of the microgrids adopt conventional AC grid systems (Fig. 1). Since a large number of renewable sources generate DC voltages, power converters are required to transfer power from these energy sources to the AC grid system. For example, wind turbines require back-to-back power converters to synchronize and adjust the output frequency and voltage level with the AC grid system.

With the recent trend in the Electric Vehicles (EV) development, the impact of their connections to the low voltage distribution systems is significantly increased. Similarly, in industrial environments, a number of adjustable speed AC drives are used, which also require AC-DC and DC-AC conversion stages. In residential and commercial segments, grid connected equipment such as computers, high efficient lighting systems and battery chargers use DC power. Thus, these devices require an AC-DC conversion stage for AC grid connection. These multiple conversion stages reduce the overall efficiency and reliability of the systems. Some of these conversion stages can be reduced or replaced by a high efficient DC-DC converter if these devices are directly connected to a DC grid. It seems ''Microgrid'' concept and modern power electronics based renewable power systems can lead to a rebirth the Edison's original vision for a power system.

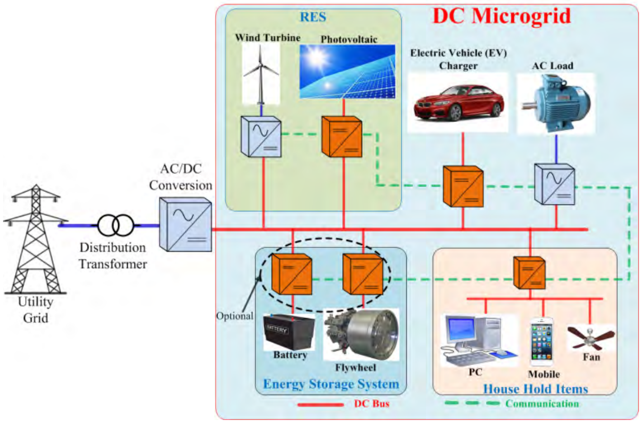


FIGURE 2. Building block of a DC microgrid system.

In a DC grid system, the energy sources and power electronic loads can be supplied more effectively and efficiently by choosing a suitable voltage level and thereby avoiding a few conversion stages as shown in Fig. 2. Furthermore, the Energy Storage System (ESS) can be directly connected to the main DC bus or connected via a DC-DC converter. Each approach has some pros and cons that depend on the applications and their requirements. For example, a battery system has no constant output voltage and the variation in the output voltage depends on the battery chemistry, current, ambient temperature and state of charge (SoC). The direct connections of a battery to DC bus can result fluctuation in the bus voltage and inrush current, thereby shortening the lifetime of the battery [4]. Fluctuating DC voltage can create stability and protection problems in the DC grid system. Therefore, DC-DC converters are normally recommended for interfacing battery systems to the DC bus. A DC-DC converter can ensure a controllable current and output voltage level, providing opportunities to integrate a number of batteries despite their completely different SoC characteristics. Overall, DC distribution systems can offer a number of advantages in different applications, such as:

- Recently environmental agencies posed strong requirements on electricity production, which is largely responsible for carbon dioxide (CO_2) and other harmful emissions. An increase in the use of renewable energy sources to produce electricity will help in reducing the CO_2 emissions in the environment. Further reduction in CO_2 emissions can be achieved by improving the efficiency of power generation and transmission systems. This can be done in DC grid systems with less number of power converters [5].
- There is no skin effect in a DC system which allows the current to flow through the entire cable and not just the outer edges. This reduces losses and also provides a possibility to use a smaller cable for the same amount of the current [6].
- There is no need for any synchronization of grid connected renewable energy systems with the grid and also reactive power control. This can further reduce the operational complexity of the system.
- DC microgrid increases stability, reliability, controllability and power quality of the system during power blackout or grid disturbances (e.g., voltage sag or swell).

However, there are some obstacles in the practical implementation of the DC microgrid, which need more attention from the research community. Some of these are:

- Protection of the DC grid system is more difficult compared to the AC distribution system as there is no natural zero crossing of the current.
- Transition from AC to DC system in low voltage distribution networks requires several stages such as new standards for products and voltage levels.
- Grounding and corrosion issues in DC systems.

With increasing demand for smart and efficient loads and rapid growth in renewable energy sources, Low Voltage DC (LVDC) power distribution can be suitable power grids for many applications. However, there are number of applications where DC grid already in use for many years such as traction, telecom and vehicular technology. In order to accommodate the new technologies such as RES, modifications in the existing DC architectures are required to further enhance their flexibility and controllability. Electric power in DC system can be transmitted over two-wire (unipolar) or three-wire (bipolar) system configuration. The new architectures in DC system depend on the voltage polarity requirement in those specific applications. Recently a number of researchers from both industry and academia have proposed various possible architectures for DC microgrid systems. In this paper, DC architectures have been reviewed and discussed with their pros and cons.

An interface between a DC microgrid (LVDC) and an AC utility grid is very important in terms of how electrical power flows between AC and DC networks. Increasing penetration of RES such as PV and wind turbine can offer possibility of transferring surplus power back to the AC grids from the DC side. There are various AC-DC converter topologies, which can be used in AC and DC grid interfaces. Even in some applications, multi-parallel AC-DC converters are frequently used by sharing a common DC bus. These arrangements offer numerous advantages such as high power to DC bus, flexible and more reliable system. However the elimination of the circulating current through the parallel converters is a challenge problem. Very limited literature is available that discusses these challenges in the context of DC microgrid systems. Therefore, in this paper, possible AC-DC conversion topologies have been reviewed – their challenges and needs for future investigations are discussed.

For the safe operation of any power system, grounding (earthing) of its supply network and grid connected electrical equipment are important. An effective grounding scheme can minimize risks of electric shock hazards. The DC microgrid system is more complex than traditional AC utility grid due to integration of new power electronic technologies and the interface with the AC network. Therefore, a detail assessment is required for a suitable grounding scheme in the DC microgrid. This paper shows how the AC grid grounding scheme is important for selection of a DC microgrid grounding configuration.

Advantages of DC microgrid/distribution system are widely debated in recent years. However very few articles have discussed about the power quality issues in the DC grids. Some of the power quality disturbances may come from AC utility interface, nevertheless the DC microgrid is a complex system and includes many power electronics converters, which may cause different power quality issues similar to the traditional AC grids. Therefore, this paper highlights the major power quality concerns in DC microgrid systems.

Future modern electrical grid (smart grid) will include several Intelligent Electronic Devices (IED). Integration of DC microgrid with smart grid might require a reliable communication infrastructure that will allow a utility to manage these devices from a central station. Communication network should meet specific requirements based on grid applications. This paper discusses a need of reliable communication infrastructure in DC microgrid system and reviews various available communication technologies that are suitable for DC microgrid applications.

Recent development in LVDC systems has attracted a number of applications where the DC grid can be used for improved performance, efficiency, reliability and cost optimization. Although in some of the applications such as Telecom sector where -48V DC system is used for many years, recent learning from Data Center pilot studies [7]–[10] with 380V DC has shown that this sector can further improve their system performance by increasing the voltage level. Therefore, in this paper, not only the existing DC power applications (such as Telecom) has been reviewed, but also the use of DC in future applications such as Net-Zero-Energy (NZE) buildings (both residential and commercial), data centers, commercial electrical vehicle charging stations, industrial and ship networks are discussed.

One of the biggest issues to visualize the Edison's dream (DC power) to a reality is a suitable standardization for the DC grids, especially voltage level and safety regulations. Various national and international standardization organizations have already started working in this area. To update the LVDC research community, recent LVDC related activities within these standardization organizations are reviewed and reported in this paper.

The rest of the paper is organized as follows: In Section-II, the interface of DC microgrid with AC grid is analyzed with a few possible AC-DC converter topologies. In Section-III, the classification of DC microgrid based on DC bus voltage polarity has been discussed. Section-IV summarizes the different architecture of DC microgrid systems. Importance of AC grid grounding scheme for the selection of DC microgrid grounding scheme discussed in Section-V. Various power quality challenges in DC microgrid system are discussed in Section-VI. Communication system is an integral part of DC microgrid, Section-VII briefly describes the need of communication system and commonly available communication technologies. Section-VIII highlights the future market application of DC grid system. Section-IX discusses the need of standardization in low voltage DC grid and also reports the recent update carried out in this regards. Finally, Section-X concludes the paper and also presented the future trends.

II. AC INTERFACE OF DC MICROGRID

In a DC micro grid system, it is very important to analyze how electrical power flows between AC and DC networks. In fact, smart DC grid systems should be designed based on bidirectional power flow in which electrical energy generated by some RES such as PV panel or fuel cells can be transferred back to the AC grid to support the AC grid. In order to analyze the interface issues between the AC and the DC grids, different AC-DC topologies are considered in this section. Circulating current issues in multi-parallel rectifiers of DC grid systems are also discussed in details.

A. GRID-INTERFACE AC-DC CONVERTER TOPOLOGIES FOR DC MICROGRID

The AC-DC conversion for DC microgrid system can be classified into the following categories:

- Diode and controlled rectifiers
- Active Front End (AFE)
- Special Topologies

1) DIODE AND CONTROLLED RECTIFIERS

Diode and controlled rectifiers are unidirectional power flow topologies and their line currents are distorted by significant low order harmonics, mainly below 2 kHz. There are several solutions to improve the quality of the line current such as passive filters in the DC link and/or in the front end of the rectifier [11]. These rectifiers can be either single-phase or three-phase as shown in Fig. 3.

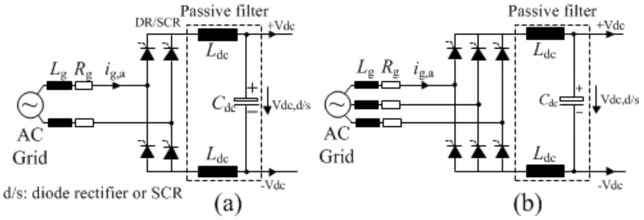


FIGURE 3. **Diode or controlled rectifier (a) single phase and (b) three-phase.**

2) ACTIVE FRONT END (AFE)

This is a bidirectional power flow converter that provides a high quality sinusoidal line current waveform. The system has a six active power switches such as IGBTs or MOSFETs and are controlled based on a suitable Pulse Width Modulation (PWM) technique. In order to control the switching frequency ripple, a front side filter is required, which can be of L, LC or LCL type. The LCL filter is a very common as it can remove high frequency current and clean the line current at the grid side, where this filter is connected (see Fig. 4). However due to a stability issue of the converter, a proper damping method is required. Possible control methods are:

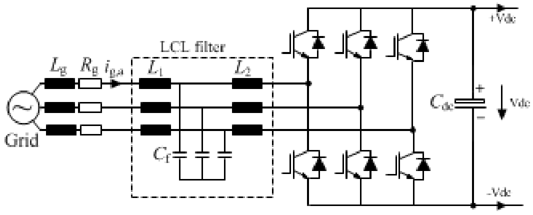


FIGURE 4. **Active Front End (AFE) with integrated LCL filter.**

(a) Passive damping, by adding a resistor in series with the capacitor, which can affect the efficiency of the system.

(b) Active damping by adding one of the state variables in the control method such as capacitor current in order to develop a virtual resistor. Although the active method can improve the efficiency but additional sensor is required for the measurement.

(c) A proper control design around the filter, which is very challenging due to close locations of the system poles to the origin.

3) SPECIAL TECHNOLOGIES

There are some other AC-DC topologies which are shown in Fig. 5. The most common one is a single phase system, based on a diode rectifier with a boost converter at the DC link side (Fig. 5 (a)). The main advantages of this topology are the improved line current quality and power factor of the system based on the active circuit in the DC link system. This topology is named as a single phase with Power Factor Correction (PFC) circuit.

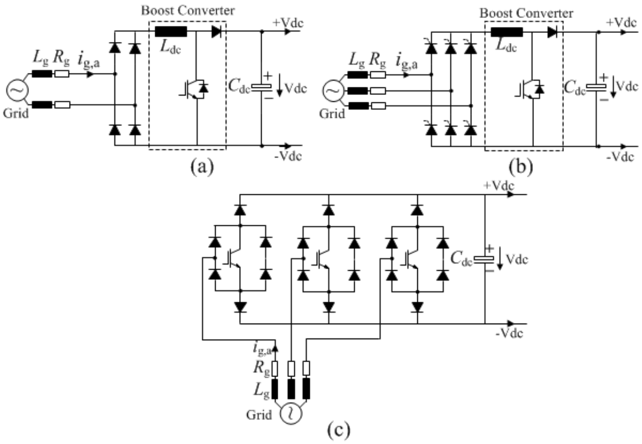


FIGURE 5. **Different AC-DC topologies: (a) single-phase PFC, (b) three-phase EI, and (c) three-phase Vienna rectifier.**

A similar concept has been utilized in a three-phase diode or controlled rectifier and the topology is named Electronic Inductor (EI) as shown in Fig. 5(b). A main advantage of this topology is the ability to control the DC link current and voltage under different load profiles. The DC link current can be either flat or modulated waveform [12], [13]. In this three-phase system, each diode conducts for 120 degrees, therefore the line current can be a square wave with or without modulated waveform to improve line current harmonics.

The Vienna rectifier (Fig 5(c)) facilitates only a unidirectional power flow, but its line current is almost sinusoidal. The number of switches is reduced compared to an AFE topology and this has a big impact on the reliability and the cost of the system.

B. PARALLEL CONNECTIONS OF AC-DC CONVERTERS TO DC MICROGRID

One of the major issues of multi-parallel rectifiers with a common DC link capacitor (for example, in a DC micro grid) is a circulating current, which should be reduced as low as possible. The circulating current depends on the topology of the rectifiers and the configuration of the whole system. In the following, the circulating currents of several cases with different topologies have been considered.

Case 1: Diode rectifiers are cheap and simple contraptions that are used in many products and systems. However, to reduce the line current harmonics below a limit - defined by a regulation such as IEC 61000-3-2 & 12 [14], [15] or IEEE 519 [16] - a proper passive filter is connected either in the DC link and/or in the AC side of the rectifier. As shown in Fig. 6 (a), when two or more parallel rectifiers are connected to a DC network, the filter configuration can affect the circulating current due to different filter types or power rating. For example, in Fig. 6 (a), two diode rectifiers with a same DC link filter are considered. Even though the topologies are the same, the power rating can be different. The inductance values of the filters are determined according to the base impedances in Per Unit (∼x% PU). Therefore the inductance values are changed with respect to the power level as well. As shown in Fig. 6 (b and c), two parallel legs (*the positive or the negative DC link legs: rectifier 1 and 2*) are connected to the same terminals ($V_{phase}(t)$ and V_{dc}). A major issue in this topology is that the DC current depends on the resistance of the DC link legs (mainly diode and DC link choke), while the ripple current (the main frequency at 300 Hz) depends on the inductance value. Therefore, the current sharing significantly depends on the quality and the tolerance of the components.

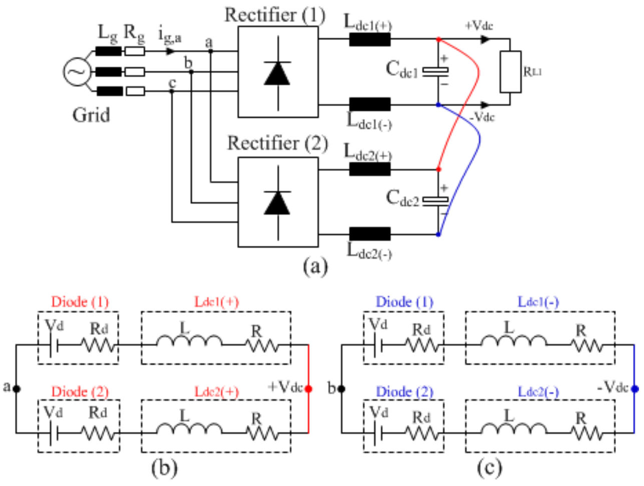


FIGURE 6. **(a) Parallel connection of two three-phase rectifiers of different power rating, (b) equivalent impedance loops in the positive DC bus leg and (c) the negative DC bus leg.**

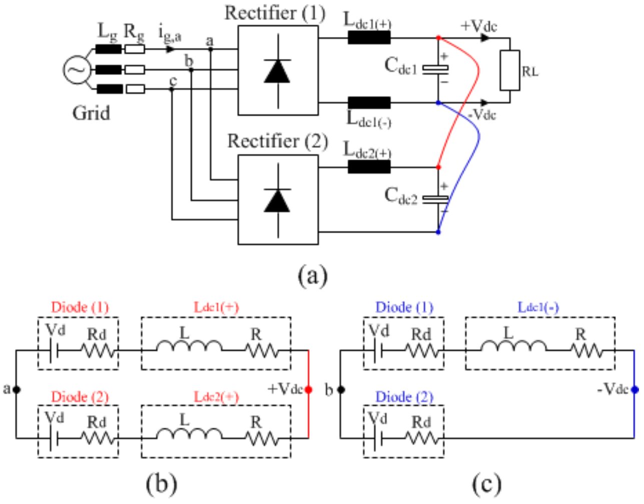


FIGURE 7. **(a) Parallel connection of two three-phase rectifiers with different DC-link filter configurations (b) equivalent impedance loop in the positive DC bus legs and (c) the negative DC bus legs.**

Fig. 7 (a) shows two rectifiers with different DC link filters. The voltage across two parallel legs (*the positive DC link legs: unit 1 and unit 2*) is the same, and therefore, the DC and AC current sharing depends on the resistive and the inductive values and the voltage drop across the diodes. The situation is much worse for the other two parallel legs (*the negative DC link legs: rectifier 1 and 2*). As the rectifier 2 has only one inductor at the positive DC link side, the negative leg impedance is very low and most of current passes through this leg. A possible solution is to add an AC inductor to share the current through the negative DC link legs.

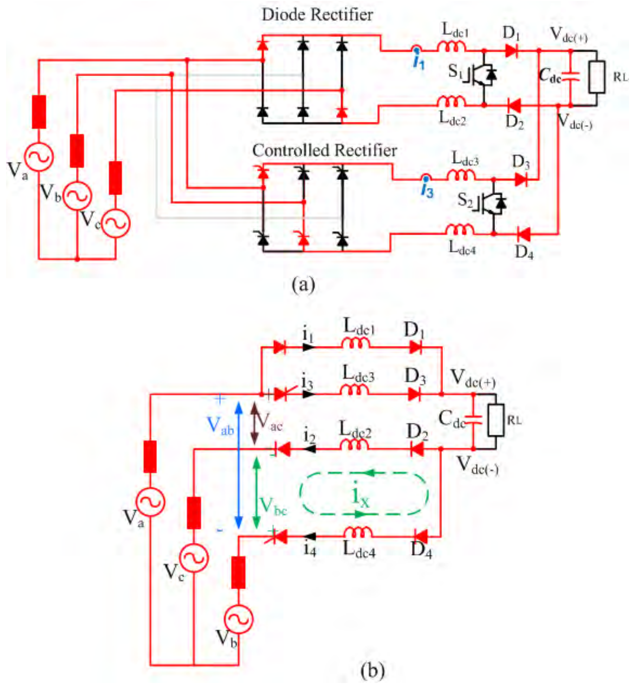


FIGURE 8. **(a) MMR topology when S1 and S2 are turned off. (b) Voltage across the negative DC link legs of the rectifiers.**

Case 2: Parallel connection of rectifiers has almost no circulating current as the diode rectifiers are turned on and off at the same time with no firing angle delay. When control rectifiers are utilized in a system, the line current quality can be improved based on multi-level current waveform. This topology is named Modular Multi Rectifier (MMR) [17], [18]. When the firing angle of the controlled rectifier is not zero, the circulating current is generated. This is due to the fact that the voltages across two negative legs of the rectifier are connected to two different phases (in Fig. 8 (a)) and can generate a circulating current (Fig. 8 (b)). However, this current can be controlled based on active current control method [18].

Case 3: The last case is about parallel connection of AFE converters with a common DC bus system as shown in Fig. 9. This issue is related to the PWM method applied to paralleled converters. The input sides of all AFE converters are connected to the same voltage sources and the DC link capacitors are connected to a common DC link for all converters. Therefore circulating current can be generated during switching states when the switching devices are turned on and off. One of the approaches to reduce the circulating current is to control the PWM patterns [19] and/or increased the switching frequency [20].

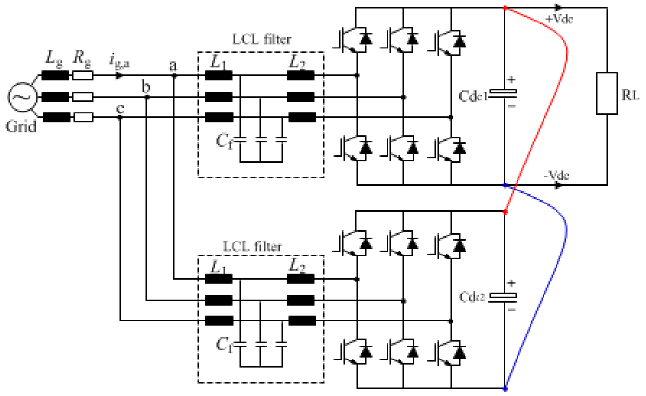


FIGURE 9. **Parallel connection of two three-phase Active Front End (AFE) rectifiers.**

C. GRID-INTERFACE ELECTRONIC TRANSFORMER FOR DC MICROGRID

The Electronic Transformer or Solid State Transformer (SST) is considered as a key enabling technology for implementation in future electric power distribution architecture such as smart grid [21]–[23]. The application of SST has been already visualized in microgrid, traction and data center [24]–[29]. There are several different configurations of SST which have been reported over the last two decade [30], [31]. Dual active bridge (DAB) based SST topology shows its application in DC microgrid system [24], [25], [30], [32]–[34], in which it can replace the existing passive distribution transformer operated at the line frequency of 50Hz/60Hz, while providing a direct connection to the LVDC system.

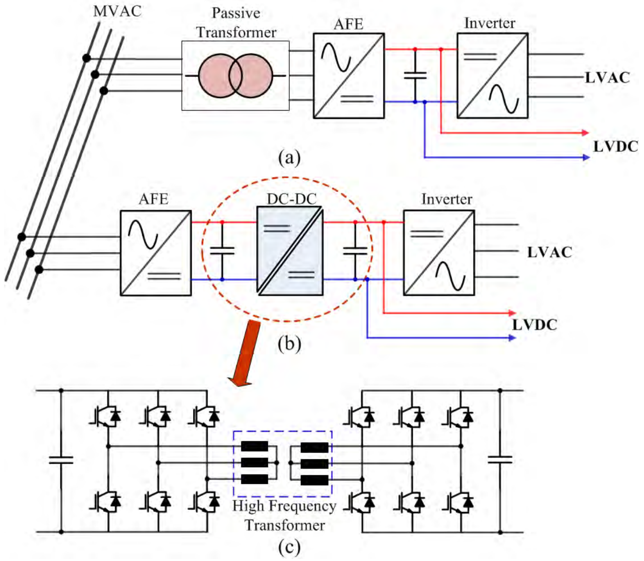


FIGURE 10. **(a) Active Front End (AFE) with passive distribution transformer, (b) SST topology, and (c) Dual active bridge DC-DC converter.**

The SST concept enables equal functionality feature as that of an AFE with passive distribution transformer (shown in Fig. 10 (a)). Moreover, SST topology integrates with

DC-DC conversion stages (dual active bridge topology shown in Fig. 10 (c)), which provides galvanic isolation and voltage adaption as shown in Fig. 10 (b). The DC-DC converter can operate at higher frequency range (few 100 Hz to kHz), and thus a considerable reduction in reactive component size can also be achieved [35], [36].

An SST typically includes a high voltage AC to DC power conversion to generate a high DC link voltage, and then a high frequency DC-DC converter stage is required to regulate the DC bus voltage. Therefore, the SST is basically a three-energy port system: where one port is interfaced with high AC voltage and other two ports are DC port (LVDC) and low voltage AC port (LVAC). The three-port characteristic of SST makes it very suitable for DC microgrid application, where the input side is connected to an AC grid and/or a distributed energy source and the DC side to PV, Fuel cell and battery systems as shown in Fig. 10 (b).

The SST based AC-DC conversion has a better power factor regulation, VAR compensation capability and also can provide galvanic isolation to the DC bus system. Overall, the SST based DC microgrid will be more compact with better functionality in which an AC grid interface is required.

Although, it is widely assumed that SST will bring the revolution to future DC microgrid systems, but its practical implementation is long awaited.

III. DC MICROGRID VOLTAGE POLARITY

In AC grid systems, the power from utility side can be transmitted using two wires (single-phase) and four wires (three-phase). The power in DC grids can also be transmitted using similar configuration: two-wire (unipolar) and three-wire (bipolar) systems [37]–[40]. The difference between these two DC grid configurations is the number of available voltage levels.

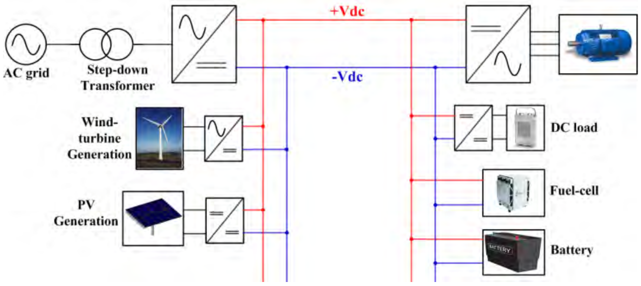


FIGURE 11. **Unipolar DC microgrid configuration.**

A. UNIPOLAR DC MICROGRID SYSTEM

In a unipolar DC system, sources and loads are connected between the positive and the negative pole of the DC bus as illustrated in Fig. 11. The energy is transmitted over the DC bus at one voltage level; therefore selection of DC bus voltage level is a key factor in this system. Higher voltage level increases power transmission capability of the system, but it demands more DC-DC converters in order to match the end user voltage level. Furthermore, higher voltage level can possibly increase safety risks.

With low voltage level, the transmission capability of the system is limited to a short distance. However the proper selection of low voltage level can avoid the deployment of a large number of DC-DC converters in low power grid connected equipment. The unipolar system is viable for off-grid houses in remote rural areas, where no utility grid infrastructure exists. Recently 48V DC unipolar systems have been implemented with the integration of PV panel in microgrids for off-grid houses in rural areas of India [41].

Overall, the unipolar system is simple to implement and there is no chance of having any asymmetry between the DC poles. However this system does not provide any redundancy, and therefore even a single fault can lead to a shutdown of the complete system [42]. Moreover, this system does not offer different voltage level options to the customers.

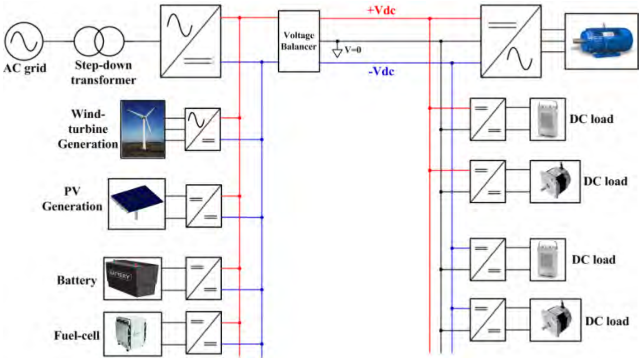


FIGURE 12. **Bipolar DC microgrid configuration.**

B. BIPOLAR DC MICROGRID SYSTEM

A bipolar system can overcome aforementioned limitations associated with a unipolar system. The bipolar system also known as three-wire DC bus system, which consists of $+V_{dc}$, $-V_{dc}$ and a neutral line as illustrated in Fig. 12. In this configuration customers have option to choose three different voltage levels: $+V_{dc}$, $-V_{dc}$ and $2V_{dc}$. Furthermore, under a fault situation in one of the DC poles, the power can still be supplied by the other two wires (bipolar) and an auxiliary converter. Therefore, the reliability, availability and power quality of the system are increased during fault conditions. Different voltage levels offer more flexibility to the customers in order to connect different loads, but at same time this can result unbalance in the system due to unequal distribution of loads. Therefore, a voltage balancer circuit or a suitable control system for the power converters at the source side is highly recommended in this type of systems [43].

The unipolar and bipolar topologies are the basis for the future system architecture and grounding scheme in DC microgrid systems.

IV. DC MICROGRID ARCHITECTURE

Some of the RES (such as PV panel) and ESS are increasingly getting integrated to distribution power systems. Since they generate power at DC voltage, their integration in DC microgrids is gaining tracking in the research community. However, power capacity of any DES is very variable and uncertain due to its dependency on weather condition. Therefore, an interface with the AC grid is very important in order to improve the reliability and availability of power in a DC microgrid system. There are a few options to interface a DC microgrid with an AC grid such as:

- Radial configuration
- Ring or loop configuration
- Interconnected configuration

Each connection scheme has its pros and cons. Based on these connection schemes, different DC microgrid architectures are possible. There are number of such architectures that have been already reported in the recent years. This section reviews each connection scheme in details including their applications, advantages and disadvantages.

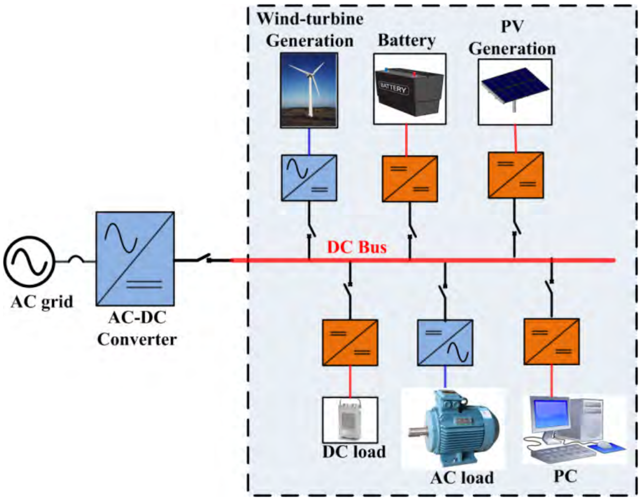
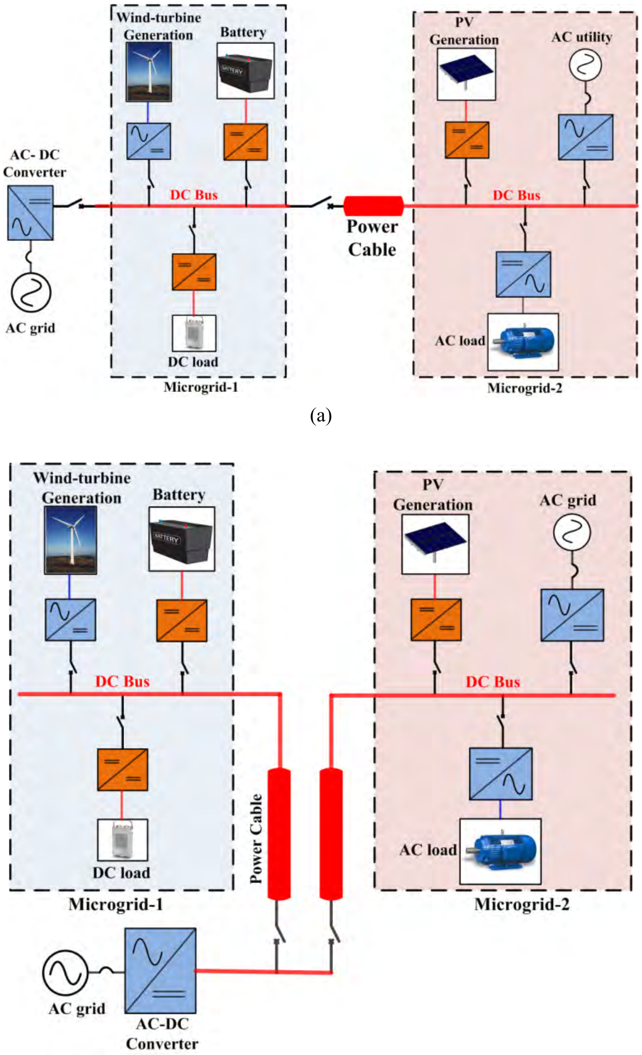


FIGURE 13. Radial architecture of DC microgrid system.

A. RADIAL CONFIGURATION

In this configuration, the DC bus is interfaced with an AC grid at one end and power flows along a single path towards the loads. Therefore, only one path is available between each load to the AC grid interface. A single line diagram of the radial DC microgrid system is shown in Fig. 13, where a number of RES, ESS and loads (both AC and DC) are connected to the DC bus. This bus can be unipolar or bipolar depending on applications and requirements. This architecture can be used in residential buildings, where low voltage DC bus is preferred to match the voltage level of many appliances and to avoid extra DC-DC conversion stages. Also in such systems, loads and AC grid interface can be located close to each other in order to reduce the distribution losses.

The same concept can be extend to a multi DC microgrid system such as a multi-story building or a local community, where each microgrid can have RES and ESS together with different loads. In such systems, the DC bus of each microgrid can be interconnected in series or in parallel depending on the physical layout of the buildings or communities. In this way, every building acts as a cluster of the microgrid and is able to consume or inject power to the neighboring microgrids. The parallel radial architecture can increase the reliability of the system by isolating only faulty buses in case of faults, thereby allowing the healthy buses continue their normal operation. The series radial architecture may have some stability issues during islanding modes. These two configurations are shown in Fig. 14.



(a)

(b)

FIGURE 14. Radial architecture of a multi DC microgrid system, (a) series configuration [44] and (b) parallel configuration.

The radial DC microgrid configurations can offer a number of advantages such as simplicity, multi voltage level (in bipolar) and ability to share the power from neighboring buses (in multi-bus architecture). However, the series radial architecture is not flexible during fault conditions. For example, a single fault can affect all customer connected to single bus system. In case of series radial multi-bus system, when a faulty bus is isolated by circuit breakers, the buses after and before the faulty bus will not have a possibility to share their power with the entire system.

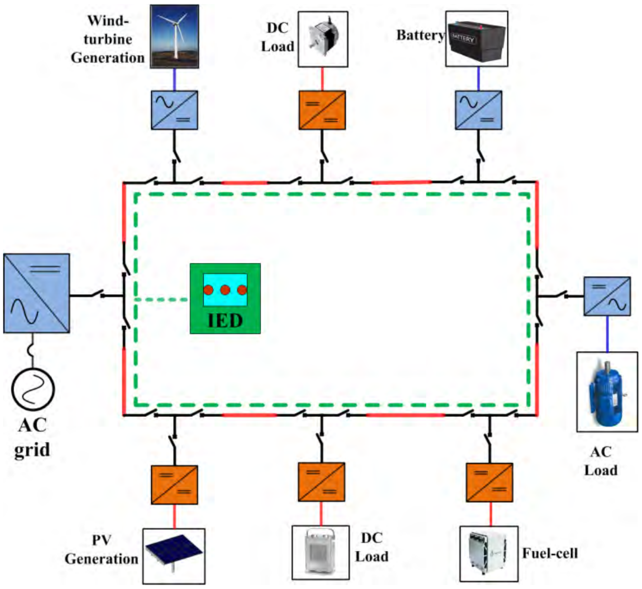


FIGURE 15. **Ring bus architecture of DC microgrid.**

B. RING OR LOOP CONFIGURATION

In order to overcome the aforementioned limitation of radial configuration, a ring or loop type distribution system can be used. This configuration consists of two or more paths between the AC grid interface and the customers as shown in Fig. 15. Fast DC switches are placed at both ends of each DC bus, which offer the flexibility to isolate the faulty bus from the system. An Intelligent Electronic Device (IED) is used to control each bus and their interface with other neighboring buses [6]. When a fault is encountered in any bus, the IED first detects and isolates the faulty bus from the system and then provides an alternative path to supply the power to the customers. This type of distribution system can be used in urban and industrial environments.

The ring type distribution system is more reliable compared to radial system, but both these microgrid systems depend on the AC grid supply. If any fault occurs in the AC feeder, the DC microgrid system does not have any possibility to get the required supply from the AC grid.

C. INTERCONNECTED CONFIGURATION

The reliability of DC microgrid system can be improved by ensuring an alternative AC grid supply to the customers in the event of failure of one or more feeders. This can be done by interconnecting the DC bus with more than one supply from the AC grid. Two different architectures are possible:

i) Mesh Type DC Microgrid System
ii) Zonal Type DC Microgrid System

1) MESH TYPE DC (MTDC) MICROGRIDS

In a mesh type DC microgrid, also known as a multi-terminal grid, more than one AC grid interfaces are connected to the DC grids, each through an AC-DC converter. Different DC microgrid architectures are possible based on this configuration where several DC and AC power supplies are connected to the DC feeders. Fig. 16 shows one such architecture. The MTDC is more reliable compared to the radial or the ring DC grids due to the availability of other feeders to supply power to various parts of the system. Similar architectures are utilized in High Voltage Direct Current (HVDC) system such as off-shore wind farms and underground urban sub-transmission and distribution system [45]–[47].

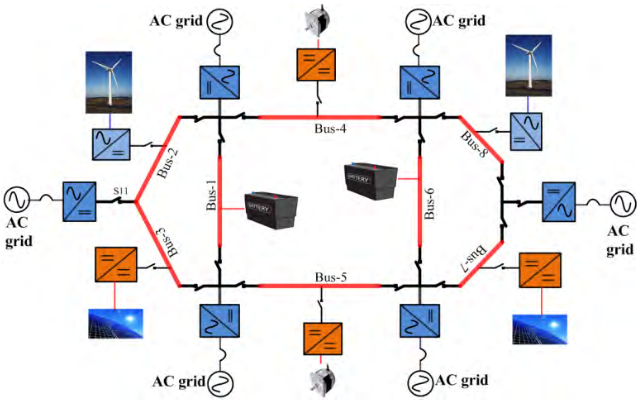


FIGURE 16. **Mesh type DC microgrid architecture.**

A ‘‘handshaking’’ method has been proposed to locate and isolates the faulty DC bus and restore the MTDC system without any internal communication within AC-DC converters in the system [48], [49].

2) ZONAL TYPE DC (ZTDC) MICROGRID SYSTEM

To further improve the reliability of the system, a zonal electrical distribution system have been proposed in [50]–[52], where distribution system is sub-divided into number of zones and each zone have two redundant DC buses as shown in Fig. 17. In fact, this DC grid architecture consists of cascaded DC microgrid systems with a symmetrical configuration.

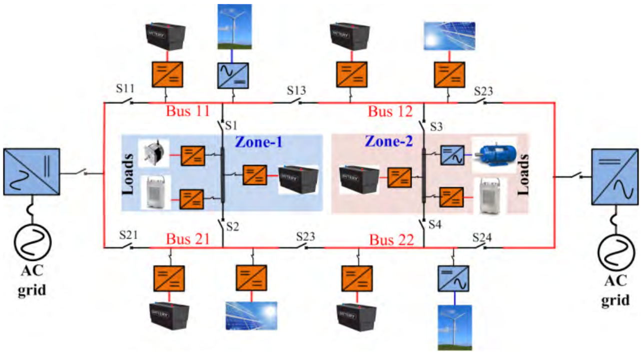


FIGURE 17. **Zonal type DC microgrid architecture.**

The ZTDC microgrid system contains several power system elements, such as power converters, energy storage systems, generations and switchgears with the aim of supplying a group of loads. Each zone is connected with two redundant DC buses powered by the AC grid and distributed DC and AC energy sources. This type of architecture provides a better reliability and availability for the loads that can be supplied through one of the feeders. Assuming that a fault happens in the upper bus (Bus 11) of Zone-1, the switches at the upper side (S_{11} and S_{13}) will be turned off while the switches at the lower side (S_2) are kept on such that the power is transferred to the loads through other feeders. Furthermore, since each zone is also connected with its own power supply (DC and/or AC sources), multiple faults in both upper and lower feeders of each zone can divide the DC grid system into few sections. This configuration is more flexible and modular due to higher number of switches and is suitable for distribution planning.

The ZTDC grid provides multiple options to supply power to loads. Power can be supplied from multiple buses simultaneously, sequentially or only from one bus exclusively. However power drawn from multiple buses can complicate the design and operation of the distribution system [53]–[56]. For this reason, a bus selection strategy has been proposed in [57]. Based on this strategy, a load draws power from the bus with highest voltage level (only one bus at a time). However the load can switch to another bus depending on required conditions. This type of configuration is commonly used in shipboard power supplies [58]–[61].

V. GROUNDING SCHEME IN DC MICROGRID

Even though the DC microgrid concepts are very well discussed in various literatures, but some issues such as DC microgrid safety is still unresolved and needs more focused attention to take the DC microgrid technology to an advanced stage of maturity. System grounding is a very crucial issue. A low voltage DC microgrid is normally designed to be interfaced with an AC grid and/or other renewable energy sources in order to improve the availability of power in the microgrid. The selection of a proper grounding configuration for a DC microgrid system is much more complicated than its AC counterpart. A number of articles [62]–[64] have discussed about the possible grounding strategies for DC grid systems. However, most of them have just focused on the DC system grounding without considering the AC grid system type and characteristics. A few articles actually have highlight the importance of AC grid grounding configuration on DC microgrid system [65], [66]. In [65], it has been pointed out that a TN network in the AC grid side and an isolated grounding configuration in the DC bus side can cause a high neutral voltage fluctuation due a common mode voltage generated by PWM active front end converters. The situation even worsens when the fluctuation penetrates through all downstream converters connected to the same DC bus in the DC grid system. The high voltage fluctuations create loop/circulating current within the converters connected to the same DC bus and can also affect the grounding of the system. The high circulating current becomes a challenging issue in the design of a DC grid system as discussed in Section-II of this paper. In [66], this issue has been further analyzed with the suggestion of using High Resistance Grounding (HRG) instead of isolated grounding scheme in the DC grid system. However, both of these papers considered only the TN networks at the AC grid side.

This section gives an in-depth overview of different AC grid grounding configurations and then their effects on the DC grounding scheme in both isolated and non-isolated microgrid systems. Finally, fault current paths in commonly used AC-DC converter topologies are addressed in the DC grids interfaced with the AC grid systems.

A. SYSTEM DESCRIPTION

The DC microgrid system is normally interfaced with AC grid through AC-DC power converters. On the AC side of the system, there is a step-down distribution transformer connecting the system to a medium voltage (MV) AC network. The selection of AC-DC power converter topology depends on the application requirement, e.g., unidirectional (diode rectifier based topology) or bidirectional (active front end) power flow. These power converter topologies need to fulfil the EMC and harmonics requirements. Therefore these converter systems are equipped with low and high frequency filters on the AC line side and/or DC bus side. The DC-link capacitor is utilized to smooth and regulate the DC-link voltage in these topologies. The number of distributed generation sources and loads are connected on the DC bus as shown in Fig. 18. The AC grid can have different grounding/earthing configurations such as TN, TT and IT depending on application requirements and specific regulations [67]. The AC earthing configurations are briefly described in the following sub-sections.

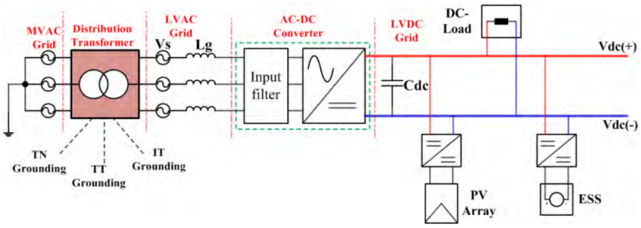


FIGURE 18. Line diagram of DC microgrid interface with AC grid system.

B. AC GRID GROUNDING ARRANGEMENTS

According to IEC 60364 standard [68], there are three families of grounding arrangements in low voltage AC grid system. High Resistance Grounding (HRG) is also known as a viable option and will be discussed below. The grounding arrangements are:

i) TN grounding system
ii) TT grounding system
iii) IT grounding system
iv) High resistance grounding system (HRG)

1) TN GROUNDING SYSTEM

In TN grounding system, the generator or transformer star point in a 3-phase system is directly connected to earth and all

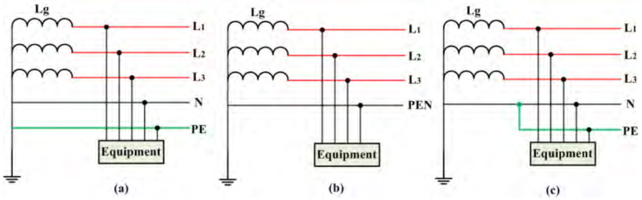


FIGURE 19. **TN grounding system: (a) TN-S, (b) TN-C, and (c) TN-S-C.**

the exposed metallic (conductive) parts of an installation are connected to earth via this earth connection at the transformer side.

The conductor which connects the star point of the transformer to the earth is called *Neutral (N)* and this is used as a return current path for single-phase loads. The conductor that connects the exposed conductive parts of consumer's electrical equipment to earth is called *Protective Earth (PE)*.

The *N* and *PE* can have different configuration in TN network such as:

- **TN-S:** the *N* and *PE* conductors are ***separated*** throughout the system, as shown in Fig. 19 (a).
- **TN-C:** The *N* and *PE* functions are ***combined*** in a single conductor throughout the system, as shown in Fig. 19 (b).
- **TN-C-S:** part of system uses TN-C arrangement (mainly from substation to building) and then TN-S arrangement in downstream installation, as shown in Fig. 19 (c).

Each TN configuration has its pros and cons. For example, a TN-C system is cost effective due to the use of a single conductor for both *N* and *PE terminals*, but it has a degraded EMC performance as compared to that of a TN-S system.

2) TT GROUNDING SYSTEM

In this system, the supply source or transformer has a direct connection to the earth and the conductive parts of the equipment are connected to *PE* which is provided by a local earth electrode and is electrically independent of the transformer's earth, as illustrated in Fig. 20 (a).

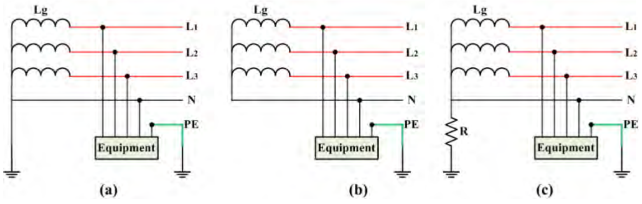


FIGURE 20. **AC grid grounding system: (a) TT, (b) IT, and (c) High Resistance Grounding (HRG).**

The TT grounding arrangement is very effective for EMC performance of the system. It reduces the conductive path of the interference generated by other equipment in the installation.

3) IT GROUNDING SYSTEM

In this system, the supply source or transformer is isolated from the earth and all exposed conductive parts of the equipment are connected to *PE* that is provided by a local earth electrode, as shown in Fig. 20 (b).

Main advantage with IT grounding arrangement is the increased availability of the installation under fault conditions. During the first earth fault, unlike to "Solid Grounded" system such as TN and TT network, the IT system will not provide low impedance path for the fault current loop via the transformer's neutral. The fault current remains very low, so that the protective devices will not trip and process will continue. However, a large transient voltage may occur during the ground fault - which can lead to a significant safety concern of the system [69]. Although an IT network is a floating system, it is still referenced to the ground based on the stray and/or the filter capacitors. When there is no fault, these stray capacitors are charged by the respective to the phase voltages. If fault occur in any one of the phases, the charged capacitors in the faulty phase get discharged through the fault path, i.e., between the phase and the ground. However, the capacitors in the healthy phases may be charged in the opposite direction due to the fault current – they discharge later. This repeated charging and discharging of capacitors can produce severe voltage oscillation such as 3-4 times of normal voltage [70]. Such a high voltage stress can easily deteriorate the insulation in the healthy phases and might lead to a second ground fault or a possible phase-phase fault. The second ground fault will generate large fault current that will require instantaneous tripping of the circuit breakers.

4) HIGH RESISTANCE GROUNDING SYSTEM (HRG)

A possible solution to reduce overvoltage stress without losing advantage of IT network is to connect the transformer neutral to the earth through a high resistance (*R*), as shown in Fig. 20 (c). In practice, the value of *R* is selected in such a way that the earth fault current is limited to eliminate flash hazards, but it is still sufficient to permit the operation of earth fault protection system [71], [72].

C. IMPORTANCE OF AC UTILITY GROUNDING FOR SELECTION OF DC MICROGRID GROUNDING ARRANGEMENT

As per the European Low Voltage Directive, LVD 2006/95/EC [73], the DC grid systems should be grounded on either positive or negative DC bus to ensure the safety of the personnel. The DC grid system is normally interfaced with AC grids, which have different grounding arrangements (e.g., TN, TT and IT discussed above). Consider that a DC grid system, where a DC bus (either positive or negative) connected to the ground, is interfaced with a solid grounded (TN or TT) AC utility network. This will create a permanent short-circuit fault through ground (shown in Fig. 21 (a)), which will prevent normal operation of the system until the

DC grid is electrically isolated using a low or a high frequency transformer from the AC system as shown in Fig. 21 (b and c).

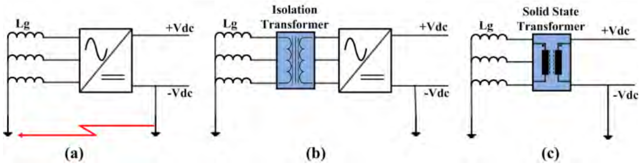


FIGURE 21. Solid grounding (TN or TT) at the AC side and (a) non-isolated DC grid, (b) isolated DC grid based on a low frequency transformer, (c) isolated DC grid based on a high frequency transformer.

The above discussion highlights the importance of the AC grid grounding system which should be considered for a proper selection of grounding arrangement in the non-isolated DC grid system [74], [75]. Even in an isolated DC grid system, the severity level of current shock in the event of a fault depends on the type of grounding arrangement in the DC grid system. Therefore, it is important to analyze the performance of different grounding schemes under fault condition for both isolated and non-isolated DC grid systems.

A DC microgrid system comprises of various power converters such as AC-DC converter (for example in AC grid interface) and DC-DC power converters (in RES, DC loads and ESS). These power converters consist of high frequency common mode capacitors (C_{cm}) and differential mode capacitor (C_{dm}) in their EMI filters. The common mode capacitors can provide a current path for fault currents which can affect the normal operation of the system even in an isolated DC grid system. In order to analyze different DC grounding schemes, it is important to first address the possible common mode ground path in these power converters.

D. FAULT CURRENT PATHS IN AC-DC CONVERTER TOPOLOGY

As discussed in Section-II, there are various possible AC-DC converter topologies that can be used to interface the DC grid system with the AC grid based on specific application requirements. Most of these power converter topologies need an EMI filter to fulfil the required regulations. Moreover, these EMI filters comprise of common mode capacitors, which provide a current path for the fault current to be circulated through the ground and thereby to the entire system. Therefore, it is important to address the fault current path via the EMI filters. The discussion in this sub-section is limited to only two most popular converter topologies – diode rectifier and active front end. However, there are a number of topologies, which can also be considered in a similar fasion. A diode rectifier topology requires common mode coupling capacitors on the AC line side and on the DC-link side, as shown in Fig. 22 (a). Similarly in the active front end topology, the EMI filter requires a coupling capacitor on the line side and/or on the DC side depending on the applications (shown in Fig. 22 (b)). However the placement of the coupling capacitor depends on the design of EMI filter. In the event of line-to-ground fault, these coupling capacitors provide a low impedance path for the fault current through which the current can be circulated through the capacitor and the grounding system.

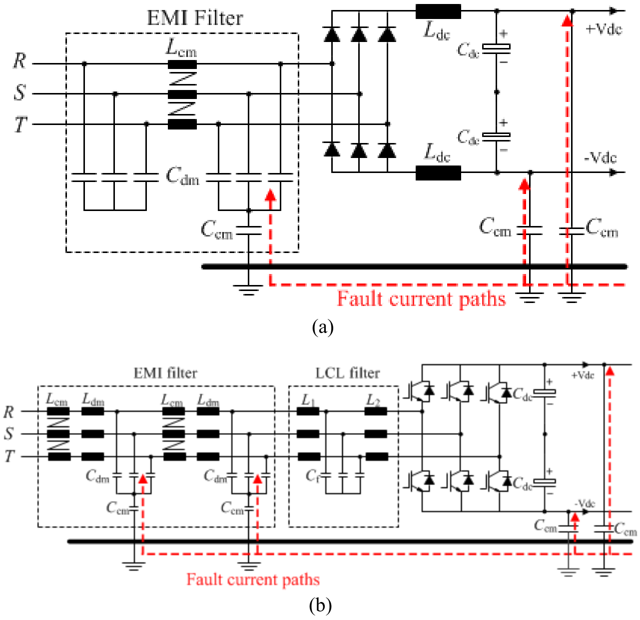


FIGURE 22. Fault current paths in (a) the three-phase diode rectifier and (b) active front end topology.

E. POSSIBLE GROUNDING ARRANGEMENTS IN DC MICROGRID

In this section, the three most popular AC grid grounding arrangements (TT, TN and IT) have been considered to investigate the possible grounding schemes in the DC grid system in term of safety and protection points of views.

1) AC GRID: TT NETWORK

In order to analyze the grounding scheme in the DC microgrid system, a simplified three-phase system has been considered without losing overall generality. In the simplified system, an AFE converter topology has been used and only one DC load assumed to be connected to the DC grid, as shown in Fig. 23. Moreover, in the AFE topology, only the common mode coupling capacitors are of interest to analyze the system behavior under line-to-ground fault conditions. It is important to note that the AFE topology is based on PWM technique, which often produces common mode voltage in the system. However, in the system of Fig. 23, it has been assumed that the AFE topology comprises with a common mode filter. Thus, the common mode filter can provide a low impedance path for the ground and fault currents.

In a TT network, the distribution transformer has a direct connection to the earth, which prevents the possibility of the solid grounding in the DC grid system (as shown in Fig. 20). Based on this fact and configuration, a possible grounding scheme in DC grid system isolates the DC bus. If a human body comes in direct contact with the DC bus live terminals,

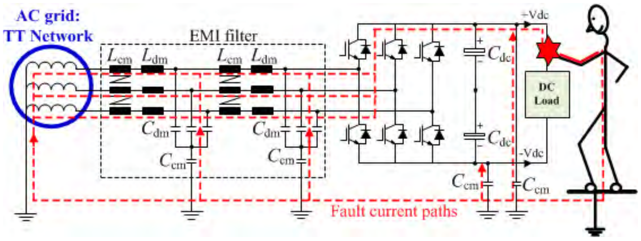


FIGURE 23. Fault current path in TT-AC grid network and isolated DC bus grounding arrangement.

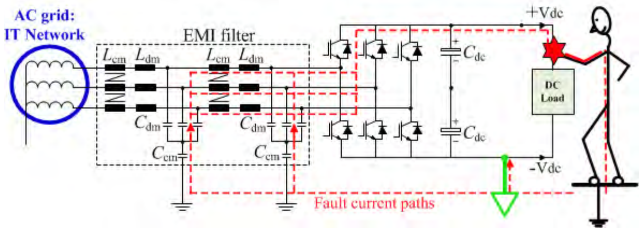


FIGURE 24. Fault current path in IT-AC grid network and non-isolated DC bus grounding arrangement.

the current flowing through the human body will be determined based on the loop impedance including the human body impedance and the transient current, as shown in Fig. 23. This current value can be significantly higher than the maximum permissible level of 35 mA considered in IEC 60479-1 [76]. If the duration of electrical discharge exceeds more than 200 ms, the human body receives a severe shock that can result in cardiac and breathing arrests [76]. Moreover, this high current may not be detected and interrupted by a protective device on the AC side of the converter. This is due to the fact that the major current can be circulated through the circuit that is downstream from the protection system at the AC side. Therefore, by isolating the DC bus alone, it is not possible to handle the hazards of faults and electric shocks. This will require implementation of appropriate protection devices in the DC side of the system.

Thus, if grounding at the DC side is required, then either a low or a high frequency transformer should be utilized in the AC to DC interface, as shown in Fig. 21 (b and c).

2) AC GRID: TN NETWORK

Similar to the TT network, in a TN-AC grid network, the distribution transformer has a direct connection to the earth and this precludes the possibility of solid grounding in the DC grid system. However in the TN-AC network, the *N* and *PE* conductors are connected to the conductive parts of loads. Based on this fact, similar approach to that is recommended for the TT network can also be adopted in this case.

3) AC GRID: IT NETWORK

In an IT-AC grid network, the distribution transformer (low frequency or high frequency transformer (SST)) is isolated from the earth and does not provide any path for fault current loop, unlike TN or TT networks. This gives more flexibility of choice for grounding option in the DC grid system. Therefore, the following possible grounding options are proposed in the DC microgrid system:

- Non-isolated DC bus grounding
- Non-isolated DC bus mid-point grounding
- Isolated DC bus grounding

a: NON-ISOLATED DC BUS GROUNDING

In this grounding scheme, one of the DC buses is directly connected to the earth, as shown in Fig. 24, where the negative DC bus is directly connected to the ground (shown in green). With this grounding scheme, if a human body comes in a direct contact with the live terminal of the positive DC bus system, the body current will be determined based on the loop impedance including the human body impedance and the transient current. The solid grounding of negative DC bus will provide low impedance path for the fault current. This current value can be significantly higher than the permissible level of 35 mA considered in IEC 60479-1 [76] if the DC link voltage is high.

b: NON-ISOLATED DC BUS MID-POINT GROUNDING

The DC mid-point grounding is another possible grounding scheme commonly used in a bipolar DC bus system. During a fault condition, the current flowing through a human body can be reduced due to half of DC bus voltage is exposed to the body. The fault current path in DC bus mid-point grounding scheme is illustrated in Fig. 25.

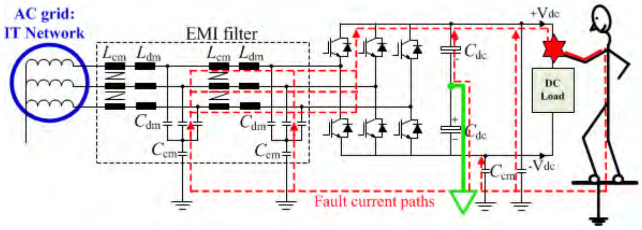


FIGURE 25. Fault current path in IT-AC grid network and non-isolated DC bus mid-point grounding arrangement.

c: ISOLATED DC BUS GROUNDING

One possible solution to interrupt the fault current loop is to isolate the DC bus system, as shown in Fig. 26. However the fault current can still enter in the converter system through EMI filter capacitors and other stray capacitors in the DC and AC side of the converter. Thus, the isolated IT system has no mechanism to detect fault current accurately.

From the above discussions, it is clear that the selection of the grounding arrangement in the DC microgrid system depends on many factors such as the type of the AC grid network, the DC bus voltage level and the power electronic converter configurations. Therefore a system assessment is required to decide which DC microgrid grounding arrangement is suitable along with the proper protection devices.

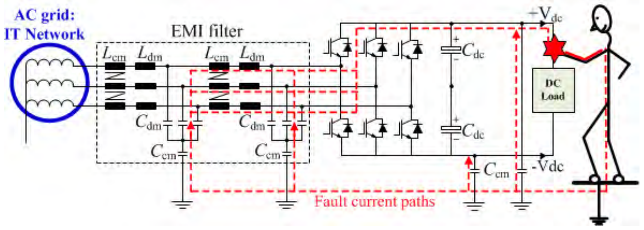


FIGURE 26. **Fault current path in IT-AC grid network and isolated DC bus grounding arrangement.**

VI. POWER QUALITY ISSUES IN DC MICROGRID

It is well known that AC grid systems suffer a number of power quality issues such as harmonics, voltage sag and swell, line frequency variation and distorted voltages/currents. It is often overlooked in DC grid systems, especially the harmonics issue. As a DC microgrid is one of the prominent emerging technologies, a number of researcher groups all over the world have been working in this area. In order to take this technology from the research stage to a practical implementation stage, it is important to give harmonics and power quality issues careful considerations. Most of the recent published articles in the literature demonstrate the advantage of the DC grids compared to the conventional AC grids. Very few articles discussed about the power quality issues in the DC grid system. In order to highlight the concern of power quality issues in the DC grid system, this section lists the most common concerns. The DC grid can operate in an islanded mode, but it may also have an interface with an AC grid system in order to absorb or deliver power during normal operation. Therefore, the power quality issue in the DC microgrid can arise either internally or from the AC grid side.

The most common power quality issues in DC microgrid system are:

- Voltage transient from AC grid
- Harmonics due to resonances and power electronics based converters
- Electromagnetic Interference Compatibility (EMC) issue
- Communication failures
- Inrush currents
- DC bus faults
- Voltage unbalance in bipolar DC bus
- Circulating currents

Voltage transients are frequently encountered in an AC grid system mainly due to capacitor bank switching, load changes and power fluctuations in grid connected renewable energy systems. A recent study in data center applications has showed that the voltage transient could be vulnerable for the DC grid system [77]. It has been found that if a transient occurs in a DC grid system, the transient overvoltage not only reaches 194% of the operating voltage but also stabilized at new voltage level of 111%. This could be very dangerous for other equipment sharing the same DC bus [77].

Together with the voltage standardization, the standard limits of voltage tolerance and transient voltage disturbances will be very important for components manufacturers such as sockets, plug and cable. Most of DC applications based products/systems (such as USB, desktop computer, LED lightning, traction and marine) already have their own standard limits for voltage tolerance and transient disturbances. Again most of these DC application standards are based on traditional use of DC power, however future public DC networks will be more complex due to the penetration of distributed energy sources and ESS. Therefore a more harmonized approach is required to develop the power quality standards that ensure the compatibility within different types of energy sources and loads.

Due to the absence of AC-DC power converter, there will be no issue for low frequency harmonics in the DC microgrid system. However the increasing use of DC-DC converters, which are commonly operated at higher switching frequency, could cause electromagnetic interference (EMI) in the system.

In a DC microgrid system, multiple PWM based converters are employed with DC capacitors at both sides of the converter. These DC side capacitors and the impedance of the DC bus cable or feeder can cause multiple resonance frequencies [78]. If one of the resonant frequencies is tuned at any frequency range in which harmonics are generated by the converter, there will be serious power quality problems and over voltages. This can affect the stability of the DC link. The frequency range for which a DC microgrid should comply can vary from very low frequency (below 9 kHz) to very high frequency ranges such conducted emission within the bands of 9-150 kHz and 150 kHz-30 MHz. Power Line Communication (PLC) is utilized in Smart Grid applications for signaling purposes [79], [80]. PLC systems are commonly used in power cable infrastructures for data transmission between a central control systems and loads [81]. In a DC microgrid, a number of power electronics converters are used that operate at high switching frequency. These converters generate low and high frequency harmonics and noise, which may interrupt the data transmission capability of PLC system and finally can affect the microgrid control operation. Therefore, a detail noise analysis is required to ensure the correct operation of PLC system in the future design of DC microgrid systems.

Power electronic converters have EMI filters to fulfil EMC regulations. When these converters are connected to the DC bus system, inrush current will flow through the EMI filters. This inrush current may cause voltage oscillations in the DC bus, which can affect the operation of other equipment connected to the same DC bus [82]. This inrush current could also cause voltage sag in the DC bus system.

In a DC grid system, a fault at the DC bus can directly force the fault current to flow through the converters, energy sources or capacitance. Therefore, the fault current limit depends on power rating of these converters, energy resources and the charge stored in the ESS and DC bus capacitors. A low energy fault current may not affect the protection circuits in the DC grid system, but it may create voltage disturbances on the other parts of the system [83]. Also the protection setting may not be able to distinguish between fault and heavy load conditions if the fault current magnitude is low [84]. Moreover, due to unavailability of periodic voltage and natural zero crossing points in the DC grid system, series of faults could develop a self-sustained arc which will be difficult to detect [85].

The frequent on and off connection of loads can generate significant transient in the DC bus [86]. However in most of the DC microgrid systems, a number of energy storage devices (e.g. battery) are connected to compensate these transient, but still some oscillations can be seen on the DC bus.

Voltage unbalance could occur due to unbalance in AC grid side or may be due to unequal distribution of single-phase loads or DG sources in bipolar DC distribution system [87], [88].

Circulating current can be problematic when a high number of converters are connected to a common DC bus. The circulating current may flow among the units when there is a common grounding point at the converter sides [89], [90].

VII. COMMUNICATION SYSTEM

Microgrid systems (both AC and DC) consist of local power generations, ESS and loads to meet the internal power demand or to exchange power with utility AC grid, if it is connected. Energy sources such as solar, wind and fuel cells generate power at low voltages. In order to provide bi-directional power flow, a microgrid is normally interfaced with an AC grid through a direct connection or through a back-to-back converter. In the event of a fault in the AC grid, the microgrid system can be disconnected from the AC grid and can function autonomously. This is usually called an *islanded* or autonomous operation, in which distributed energy sources continue to power the connecting load in the microgrid system. Although, microgrids do not get power from AC grid in the islanded mode, they may still exchange some information with utility grid such as the status of the AC grid to decide whether it should be reconnected with the AC grid in order to exchange power. This exchange of information mechanism between the utility grid and the microgrid requires a reliable *communication infrastructure*.

The DC microgrid becomes attractive in modern smart grid concept to encourage penetration of RES and ESS with better efficiency (due to reduced losses in conversion and distribution). Smart grid delivers electricity between suppliers and consumers using two-way digital technologies. It controls intelligent appliances at consumers' premises to save energy, reduce cost, increase reliability, efficiency and transparency [91]. This requires deployment of a) smart meters in the customers' premises and b) smart monitoring and measurement devices such as sensors and energy management units in the transmission and/or distribution networks. With a reliable communication infrastructure, intelligent electronic devices such as smart meters can monitor real time energy consumption from the utility grid and send consumers' surplus power (from rooftop PV) back to the grid. The network operators can receive consumers' power usage data and on-line market pricing from data centers to optimize their electricity generation and distribution. The National Institute of Standard and Technology (NIST) provides a conceptual model to show the importance of communication infrastructure in the future smart grid system. This is shown in Fig. 27 [92].

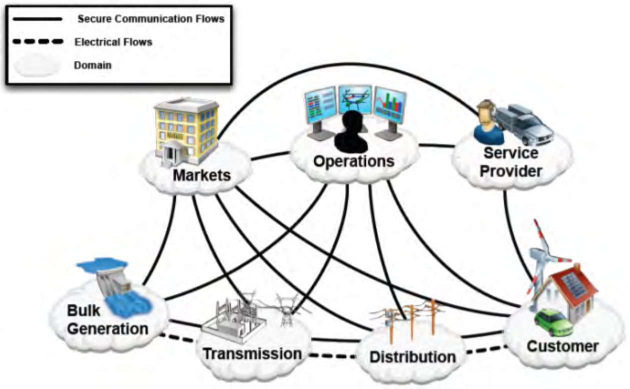


FIGURE 27. NIST conceptual model of smart grid [92].

Communication systems in DC microgrid and smart grid systems should meet some specific requirements based on grid applications such as reliability, latency, bandwidth and security [92]. However, the selection of proper communication network is a big challenge in smart grid and DC microgrids due to many variables and different component requirements, which depend on applications and utility expectations.

There are some articles already available which describe the need of communication infrastructures, their required characteristics and traffic requirements [93]–[95]. Authors in [96] have covered various available wire and wireless communication technologies with their possible use in smart grid applications.

In DC microgrid systems, the information subsystem (e.g. smart meter and sensors) will be different than traditional AC system, but same communication infrastructure can be used in both AC and DC systems. The selection of particular communication technology depends on the required data rate and coverage range of any specific application.

A. DC MICROGRID COMMUNICATION NETWORKS

Communication networks in DC microgrid systems can be classified into the following categories based on their application requirements (as shown in Fig. 28):

- Consumers' Premises Area Networks: Home Area Networks (HAN), Building Area Networks (BAN) and Industrial Area Networks (IAN)
- Neighborhood Area Networks (NAN)
- Wide Area Networks (WAN)

Data rate, coverage range and relevant communication technologies for each category are shown in Fig. 29 [96].

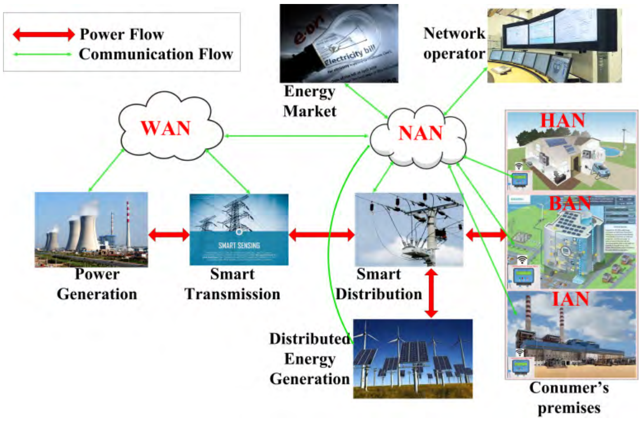


FIGURE 28. **DC microgrid communication infrastructure.**

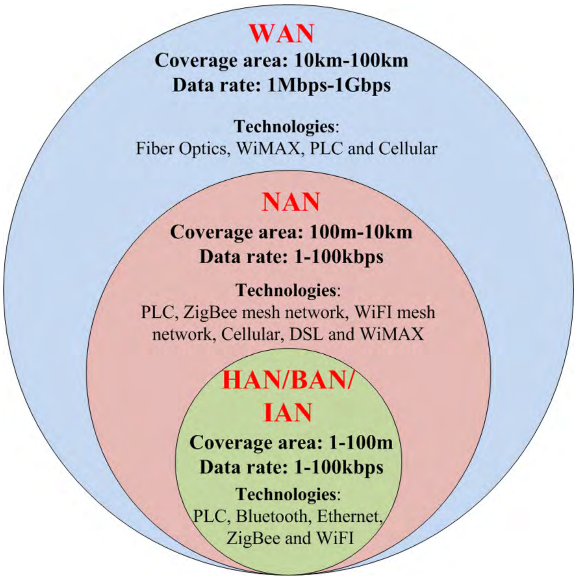


FIGURE 29. **Different communication networks and technologies in a DC microgrid system.**

1) CONSUMER'S PREMISES AREA NETWORKS

At consumers' premises (in residential, commercial and industrial areas), there are a number of appliances and equipment which send signals to and receive signals from a smart energy meter and/or an energy management system. As these appliances reside in the same premises, it is not required to have very high frequency data transmission system. Therefore any communication technology which can offer 100 kbps data rate up to 100 m coverage range is normally sufficient for HAN, BAN and IAN applications.

There are a number of available communication technologies which can fulfill aforementioned requirements. Some of these are power line communication (PLC), Bluetooth, Ethernet, ZigBee and WiFi [97]–[103].

2) NEIGHBORHOOD AREA NETWORKS (HAN)

In order to communicate and send/receive data to/from grid connected equipment in the consumer premises such as electricity consumption information to energy service provider via smart energy meter, it is required that communication technologies could support higher data rate (100 kbps-10 Mbps) up to 10 km coverage area.

Suitable available communication technologies for HAN applications are PLC, ZigBee mesh network, WiFi mesh network, Cellular, Digital Subscriber Line (DSL) and WiMAX [97]–[108].

3) WIDE AREA NETWORKS (WAN)

Future DC microgrid systems require deployment of many monitoring and measurement devices (such as sensors and power management controllers) in wide areas to exchange information with modern smart grid systems and to improve power system planning, stability and protection.

These wide area monitoring and measurement applications require higher data resolution and faster response time compared to traditional Supervisory Control and Data Acquisition (SCADA) systems. The required data rate for WAN applications is in the range 100 Mbps-1 Gbps, with a coverage area are up to 100 km.

Available communication technologies that can be suitable for WAN applications are Fiber Optics, WiMAX, PLC and Cellular [97]–[99], [106], [108], [109].

B. CHALLENGES IN DC MICROGRID COMMUNICATION INFRASTRUCTURES

For the full deployment of reliable communication infrastructures in DC microgrids and smart grid systems, the following challenges exist:

- There might be many communication protocols and technologies which can be used in DC microgrid systems. Each of them will have their own protocols and working principles. Integration and interoperation of these different technologies will require common protocols and standardizations [110].
- Communication networks in the existing power grids support mainly SCADA systems, which are very old and were designed without considering a large data exchange capability to support huge number of Intelligent Electronic Devices. The currentchallenge is how to upgrade the protocols of the existing networks to cope with the future grid requirements.
- Above challenges are equally applicable for selection of new communication technologies for DC microgrids and smart grids. It is important to address what is the optimum data rate and bandwidth that should be planned and considered for these communication networks with respect to the future demands and expansions.
- The deployment of communication infrastructure can offer many benefits such as higher reliability, energy efficiency and improve transparency in the system. However, at the same time, it can raise issues of cyber security and data privacy problems [111], [112].

VIII. APPLICATIONS OF DC MICROGRIDS

DC microgrid systems is an attractive solution for power networks due to the fast growing of RES and electronic loads based on modern power converters. Such systems can reduce a number of conversion stages and operational complexity as no frequency synchronization required.

Recently, several pilot studies have further validated these advantages and successfully implemented different DC microgrid systems such as in data centers and residential applications [7]–[9], [41]. DC microgrid systems can be used to improve the performance of existing systems in terms of efficiency, reliability and cost optimization. In this section some of these applications have been discussed and the benefits and challenges using DC grids system are analyzed.

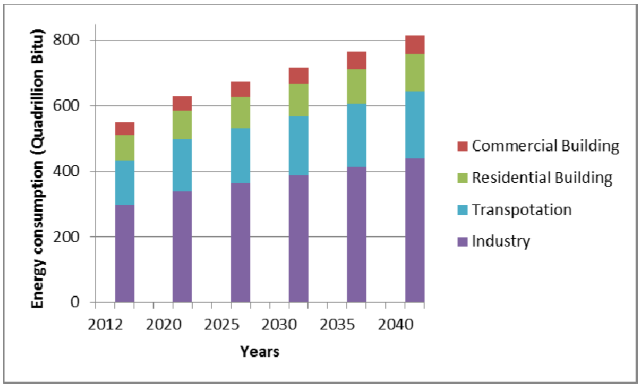


FIGURE 30. Total energy consumption by different sectors in wordwide.

A. COMMERCIAL AND RESIDENTIAL BUILDING

The electricity consumption in commercial and residential building is increasing worldwide and is expected to increase around 50% from the current consumption level by 2040, as illustrated in Fig. 30 [113]. This increasing electricity demand, and at the same time, significant increase in the emission of greenhouse gases have become matters of grave concerns in the recent years. Many countries, including the European Union (EU) and the USA, have already started reviewing their climate and energy policies. For example, the EU has already set very ambitious target "20-20-20" in order to reduce the greenhouse gas emission and improving the efficiency of all systems. The phrase "20-20-20" defines a cut in greenhouse gas emissions of at least 20% below 1990 levels, a 20% share of energy consumption from renewable resources and a 20% improvement in energy efficiency. In this target, building plays a major role as they consume around 40% of total EU energy consumption. To achieve this target, EU commission has mandated that after 2020, only net-zero-energy (NZE) buildings shall be constructed within the EU [114]. The NZE concept is a building where energy needs are greatly reduced by improving efficiency such that the balance of energy needs can be supplied by renewable energy resources [115].

In order to achieve NZE goals, the penetration of distributed renewable energy resources has increased significantly in recent years. For example, California has set target that renewable generation (which does not include large-scale hydro generation) should be 33% of all generating sources by 2030 [116], [117].

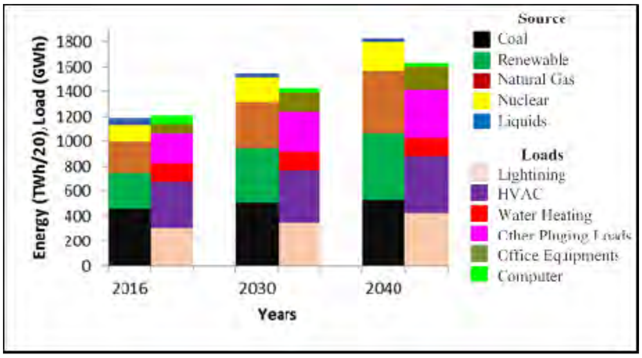


FIGURE 31. Most common loads in commercial buildings.

Fig. 31 shows the most common loads used in commercial buildings and their future projections [113]. Most of these loads are inherently based on electronics, which use low-voltage DC. However, they are connected to AC grids through AC-DC power conversion systems [118], [119]. Similarly, the deployments of PV to building scale system are encouraged by a number of governments' subsidies worldwide. The PV and other building scale generation and storage systems (batteries and fuel cells) produce power at DC voltages, but they require another power conversion (DC-AC) stage so as to be connected to the AC grids. Therefore, a common DC bus system can reduce the number of AC-DC or DC-AC conversion systems, which can make the overall system more efficient and reliable. It is estimated that commercial office buildings waste about 13% of their electricity every years in the form of distribution and converting power from the AC grids. Furthermore, the power conversion components add to cost, space, and also the physical waste generated by short-lived consumer products [120].

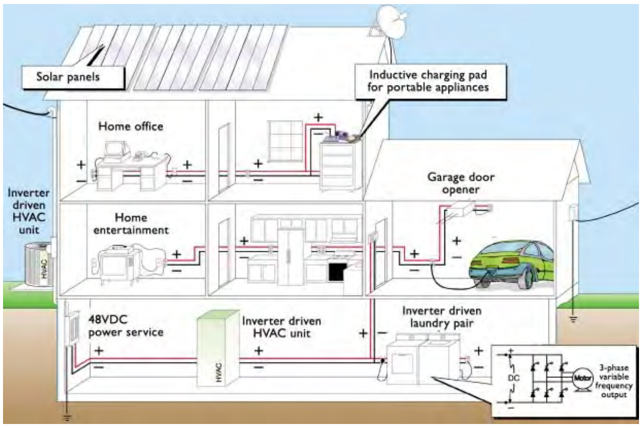


FIGURE 32. DC distribution system based future smart house [1].

From aforementioned discussions, it is clear that, in order to achieve ZEB goal, one of the possible alternative solutions is to use DC microgrids for commercial and residential buildings. Fig. 32 shows an imaginary diagram of a future smart house where DC distribution system can be used to integrate PV panel and many domestic loads. However there is still a number of challenges that need clarifications before practical implementation, such as:

- Voltage standardization: can DC-DC converters operate in a broad range of DC link voltage? What are the most optimum voltage levels?
- Existing system: all existing building use AC wiring system and also the existing appliances have AC-DC conversion stage. How DC can be implemented with minimum changes?

B. INDUSTRIAL SUCH AS MOTOR DRIVES WITH A COMMON DC SYSTEMS

Electric motor drive systems consume more than 40% of the global electricity, which made them to be major source of electricity user [121]. Due to rapid industrialization in different parts of the world, the electricity demand is continuously growing. Therefore, industry, as a major electricity consumer, has been pushed towards an era of developing more energy-efficient motor drive systems.

In many industrial applications such as steal, paper, metal and mining, marine and production lines, a large number of motor drive systems are used [122], [123]. In these applications, some of the motor drives may be operating in motoring mode, while, at the same time, some others are operating in the generating mode. Thus, it is possible to utilize the regenerative (braking) power if all converters share a common DC bus [124]. This will reduce power drawn from a front-end unit such as a generator or an AC grid [125], [126]. Therefore, the common DC bus configuration can be a cost effective and energy efficient solution for many industrial applications. A common front-end unit can supply power to all DC-AC converters (see Fig. 33.) instead of individual front-end units in a standalone AC drives.

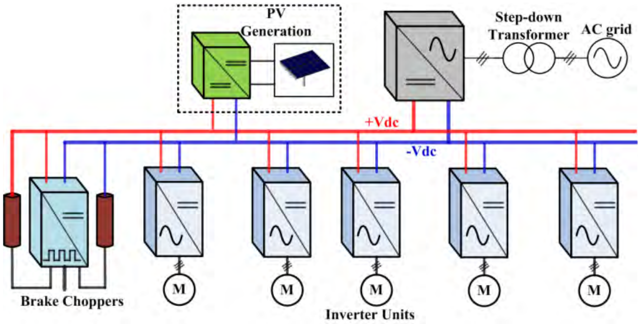


FIGURE 33. A non-regenerative common DC bus system (dotted part is optional).

The common DC-bus configuration can be classified into two main categories:

- Regenerative system
- Non-regenerative system

In the regenerative DC bus system, the front-end unit capable of sending power back to the main grid to save energy usage. This fits very well with the future smart grid concept. For this case, an active front end topology is required for enabling a bidirectional power flow.

In non-regenerative DC bus system, the braking power is redirected to other inverters in the system via the common DC bus and the remaining excess power can be dissipated as heat by using braking registers or different loads that are in a stand-by mode. For example, an energy saving can be made by connecting ESS such as battery that can absorb excess energy, which can be utilized in the DC grid system when needed. This can help in improving the system performance against the main grid disturbances such as voltage sag and interruption.

Due to the DC nature of this configuration, it offers better "plug and play" opportunities, where distributed energy systems can be connected or withdrawn in future without any significant change in the operation of the existing systems.

C. DATA CENTERS

Internet has been one of the major innovations of the 20^{th} century and digital information systems have become an important part of everyday life. This has led to a rapid growth in number and size of data centers across the world. It has been estimated that data center power consumption around the world has been between 1.1% and 1.5% of the total power consumption in 2010 [127], resulting in around 2% of the global CO_2 emission. Due to the fast expansion of internet infrastructure in the fast developing countries such as India and China in the recent years, it is expected that the power consumption of data center will increase from 10 MW to 50 MW. In a typical data center, only 50% of the total power consumption is delivered to the Information Technology loads, such as microprocessors, memory and disk drives. The rest of the power is lost in the form of distribution, power conversion and air-conditioning system [128]. Due to continuing demand for efficient electrical power in data centers, researchers from both industry and academia have considered to develop an energy efficient system based on DC microgrid systems.

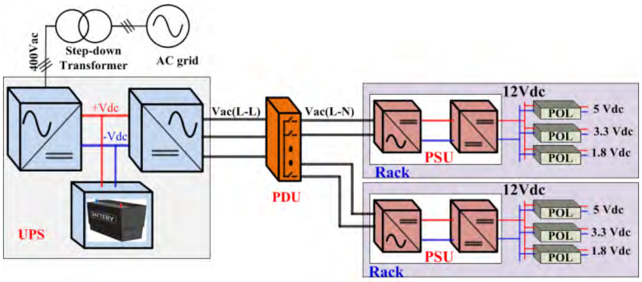


FIGURE 34. AC-based traditional power distribution in data center.

A general block diagram of an electrical power distribution in a conventional AC based data center is shown in Fig. 34.

The front end of the system is connected to the AC grid through a back-to-back converter, where a Uninterruptible Power Supply (UPS) is connected to the DC bus connecting the two converters. In this configuration, the AC input voltage is first converted into DC. The UPSC is essentially an energy storage system (such as battery and or fuel cell). The DC voltage is inverted into AC to supply power to a Power Distribution Unit (PDU). Although different configurations may exist for data centers, the UPS is the key element to support the center during outages. Every rack has a Power Supply Unit (PSU), which converters the AC voltage into DC voltage levels suitable for different loads. 12 V DC voltage is commonly used in server electronics board, and this is further stepped-down by Point-of-Load (PoL) DC-DC converter to 1-1.3 V at the chip level. Typically, three to five different voltage levels are required from the distribution network to the chip-level, placed in a server electronic board. Only about 75% to 77% of the electrical energy is delivered to the chipsets [128]. Therefore, about 23% to 25% of energy is lost in the energy conversions and this is dissipated in the form of heat. To control the temperature of the center, the dissipated heat is removed by air-conditioning systems, which, in turn, requires extra energy. The main challenge is to improve the efficiency of the system in order to reduce the energy consumption significantly.

There are two basic ways to improve the efficiency of the system. They are:

- Reduce the number of conversion stages such that less energy dissipated as heat, thereby reducing capacity requirement of the cooling system.
- Increase system voltage level such that the distribution losses can be reduced.

The above objectives can be achieved in a DC microgrid system where the AC voltage is converted to a DC, while the PSU system and all DC-DC converters are connected to the same DC bus. This is shown in Fig. 35. There are currently 23 facilities worldwide using DC grid systems [10].

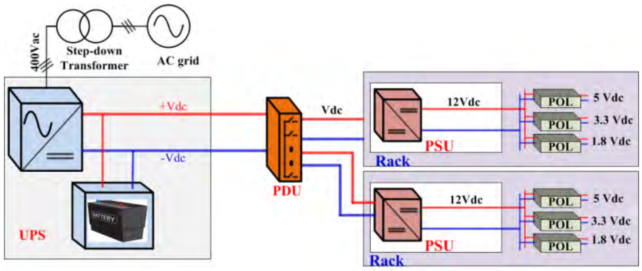


FIGURE 35. **DC-based traditional power distribution in data center.**

Lawrence Berkley National Laboratory (LBNL) reported the advantage of 380V DC distribution system for data center application [7]. They have estimated that, compared to 415 V AC system, the DC system 7% more efficient, can have 15% less capital cost, 33% less space requirement and 36% lower cost over the full lifetime. Besides efficiency, cost and space requirement, other benefits with DC grid system are higher reliability (due to less conversion stage) and high power quality (no harmonics).

This technology can give additional benefits in future to implement Net-Zero Energy (NZE) concept by utilizing distributed renewable energy sources on site. However, DC cannot be-all and end-all solutions for all data centers. A detail feasibility study is required to analyze all pros and cons of a practical DC microgrid for different applications [129].

D. TELECOMMUNICATION SYSTEMS

Telecommunication (Telecom) sector has emerged as one of the fastest growing sectors in the recent years, especially due to widespread expansion of wireless and broadband technologies. As results of this rapid growth, telecom has become a significant power consumer and CO_2 emission contributor. According to International Telecommunication Union estimation, the Information and Telecom technologies generate about 2-2.5% of the global CO_2 emission [130] and it is expected to grow in future.

Due to significant technology advancement in the telecom sectors, the amount of information and data traffic has become much higher than traditional voice exchanges. This results in a larger number of Datacom equipment such as servers and computers. Today, the load density of these low power electronics telecom equipments is much higher than the traditional switching system used in telecom equipment. The existing telecom facilities were not designed to handle such a high power density load. Presently -48V DC is the common distribution system used in telecom facility worldwide [131]–[133]. In order to meet the growing demand in the information and data traffic, an expansion of the present telecom infrastructure is highly desirable. The expansion with the existing -48 V DC system needs longer cables, which can result in low efficiency, extra space and higher installation cost. Therefore, more efficient and optimized distribution system is the need of today's telecom industry.

In the recent years 380 V, DC grids gained more popularity in data centers and many residential and commercial buildings [7]–[10]. With a 380V DC system, the cross-section area of cable conductors can be significantly decreased without sacrificing the system efficiency. It will also be feasible to use long cables to optimize the overall space requirement in a telecom installation. For example, with a long cable, a centralized battery system can be placed far away from the loads. This will help to improve the overall cooling system in the facility at reduced utility bills [134].

E. ELECTRIC VEHICLE FAST CHARGING STATIONS

Currently around 50% of the liquid crude oil production is mainly used in the transportation sector. It is needless to mention that this high consumption of crude oil increases air pollution, greenhouse gas emission and acts as a catalyst for global warming. Plug-in Electric Vehicle (PEV) has gained much attention in the recent years as these cars do not pollute the atmosphere directly. Together with many research groups, many automotive industries have started to consider PEV as an alternative to the traditional diesel/gas based vehicles. Furthermore, PEV is well-fitted in the future smart grid roadmap, where integration of renewable energy sources such as wind and solar power generation is on the rise. In a smart grid, PEV can play an important part as an energy storage system to improve the availability of a distribution system by sending power back to grid during the fluctuations in the power production from RESs [135].

The PEVs can be broadly classified into two main categories: Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). The BEV includes a large battery as the only energy source to supply the traction motors. The requirement of high efficient battery and deployment of fast charging infrastructure are crucial for BEVs.

In a PHEV, an Internal Combustion (IC) Engine is placed in parallel with a battery energy storage. These vehicles operate in ‘‘mixed’’ mode to significantly reduce the diesel/gas consumption and to increase the operating range of PEVs [136].

At this moment, there are three main types of EV charging: Level 1, Level 2 and DC fast charge. Level 1 and Level 2 convert AC to DC using an on-board converter in the EV. Each vehicle on-board converter has specific limit on how fast it can charge [137].

Residential charging infrastructure and home charger are considered under Level 1 category, where typically single-phase AC main of 110 V (or 220/230 V) at 60 Hz (or 50 Hz) is used to charge the EV battery. Even though, Level 1 charging is convenient for home use, the charging process is very slow. For example, 16 hours are required to change a 130 km range battery. Most of the public charging stations are Level 2, where typically three-phase AC main of 400 V at 50 Hz (or 60 Hz) is used. Since this can charge a battery within few hours, it can be classified as semi-fast charging configuration. For example, 3.5 hours are required to change a 130 km range battery [138].

The main problem with Level 1 and 2 charging infrastructure is the limitation in the power extraction in the range of 10 kW from the conventional AC plugs., This makes the recharging process very slow and hence unattractive to end users. In order to make the EV technology a commercial success, reducing recharging time is probably the prime requirement for the customers. Due to natural integration of RES, ESS and EV into a DC grid system, it is possible to provide high charging current (power) for shorter duration that can adequately charge EVs. Thus, a DC microgrid system can be a game changer to support EVs in the era of smart grids. However, the proper design of the charging architecture has to take into account the DC current must be fed into a battery at variable DC voltage level in the range of 50-600 V DC to satisfy the requirement of different vehicle and their battery range. Together with latest battery technology, the DC charging configuration can allow to recharge a car battery within few minutes which is comparable to the refueling time of the traditional gasoline based vehicles.

Since fast DC charging infrastructure requires high power extraction, there are reasonable concerns about the adverse effects of large penetration of EV fast charging stations on distribution networks [139]. Therefore, it will be essential to use some kind of ESS and smart energy management strategy for DC distribution systems for the integration of PEVs [140], [141].

F. SHIP NETWORKS

Presently AC based diesel-electric propulsion is a preferred choice for varying velocity and dynamic positioning operation in marine applications. Due to depleting levels of fossil fuel and increasing environmental concerns, improvements in the existing propulsion system for increasing power density and vessel power requirement are becoming difficult [142], [143].

Recently on-board DC grid system has been considered as an emerging technology in the marine applications [144]–[146]. This can overcome most of the limitations of the existing propulsion systems and can offer several benefits such as:

- The main AC switchboards and transformers are no longer needed. This will result in optimized and more flexible power and propulsion system. Also with DC on-board system, efficiency and reliability of the system will increased due to less installed components.
- Power network is no longer fixed at 50/60 Hz. Therefore, variable speed diesel generators can operate at wider fuel-efficient loading ranges compared to the conventional fixed speed diesel generators [147].
- Even though the variable speed diesel generators can offer better fuel-efficiency, these generators can be more vulnerable during frequent load variations. With the integration of ESS in DC grid systems, the power variations during significant load variations can easily be compensated. This will improve the dynamic performance of the propulsion system, albeit with less fuel consumption [148].
- A DC on-board system will be ‘‘plug and play,’’ which offers easy integration of future energy source and ESS without any significant change in the system.

IX. STANDARDIZATION OF DC MICROGRID SYSTEM

In order to challenge the predominance of AC in low voltage distribution network, the biggest obstacle for DC microgrids is the requirement to standardize the voltage level, new safety regulations and suitable protection solutions as illustrated in Fig. 36.

A. DC MICROGRID VOLTAGE

One of the main challenges for voltage standardization in DC microgrid system is the use of different voltage levels in distributed generation with residential, commercial and industrial loads. Table I summarizes the preferred voltage levels in major applications. In November 2014, International Electrotechnical Commission (IEC) formed a new

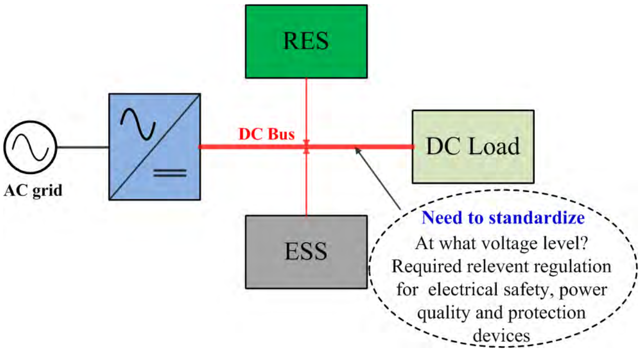


FIGURE 36. DC distribution system with requirement of standardization [149].

TABLE 1. DC power application with their preferred voltage level.

	Applications	Voltage (Vdc)
1	USB and other small electronic equipmets	≤ 5V
2	Cars, desktop computer	12V
3	LED lights, trucks, fans	24V
4	Future PV installation	48V
5	Telecom	− 48 V
6	Power over Ethernet	50 V
7	Energy Storage System (Batteries)	110V/220V
8	Data center	380V
9	EV charging	400V
10	Future residential and commercial building distribution	350-450V
11	Industry and transpotation (metro, light rail transit)	600-900V
12	Traction system, marine and aircraft system	1000-1500V

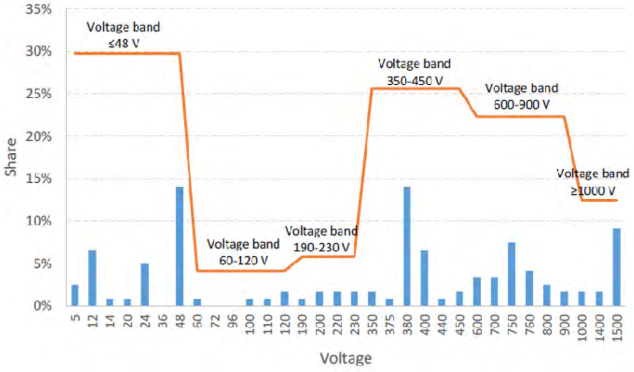


FIGURE 37. IEC SEG4 survey results for nominal voltage and voltage bands based on used case description [149].

System Evaluation Group (SEG4) mainly focus on LVDC applications, distribution and safety regulations [149]. The IEC SEG4 organized an online survey to know more about LVDC market related application experiences and possible stakeholders worldwide. In this survey, one question was about the DC voltage level and the survey results (illustrated in Fig. 37) confirm that no standard voltage level is used at the present moment. Furthermore, in recent years, numbers of articles have reported about DC voltage levels [5], [150]–[153]. However there has been no agreement for one specific voltage level within the research community so far.

The non-standardized voltage level is one of the biggest obstacles in the DC microgrid systems. For example without voltage standardization, it is impossible to standardize appliances, devices and equipment connected directly to DC grids. It is often inconvenient for industry and manufacturers to design products to handle different voltage levels and standards. In order to speed up the adoption of DC microgrid technology and its related products, voltage standardization is the highest priority, which will attract other stakeholders (including sellers, buyers and users) to take this technology to higher readiness level.

B. DC MICROGRID SAFETY

With the fast development of DC microgrid technology, both islanding and grid connected systems require additional safety requirements. The DC grid technology is different from the conventional AC grid system such as the type and the use of energy storage systems, corrosion effects due to DC stray currents and DC arcing mechanism [154]. This subsection highlights the gaps that need to be considered for future DC electrical safety standards:

- In the recent years, a number of pilot studies have shown the advantages of DC over AC. It is expected that during the transition phase, DC cables with different voltage ratings will be alongside with the AC cables. Therefore, future standards should make recommendation on electrical safety for AC and DC cables including their insulation levels.
- DC grid connected equipment have energy storage capacitors. These must either be isolated or de-energized before any maintenance work. Therefore, future electrical safety as well as fire safety standard should recommend safest time and approach to isolate and de-energize the DC microgrid systems.
- Different grounding schemes are possible in DC microgrid systems as discussed in Section-V of this paper. Each grounding scheme offers different advantages to DC microgrid systems. The European Telecom Standards Institute (ETSI) standard ETSI EN 301 605 [155] has discussed the relevant grounding scheme for 400V DC telecom and data center and has concluded that IT and TN AC grid networks are suitable to interface with low voltage DC microgrid systems. On the other hand, British standard BS 7671 [156] recommends against the use of DC in IT networks due to lack of practical experience with DC microgrid systems. Therefore, future standard should resolve these contradictory recommendations to come up with the optimum grounding scheme for DC grid systems.
- Requirement of operational and warning signs for DC microgrid installations.

In addition to the above recommendations, most of the DC applications are based on old standards or conventional DC systems. Therefore, many of these standards are also required to be updates based on recent developments in the low voltage DC grid systems.

C. DC MICROGRID PROTECTION

Despite many advantages of DC over AC system, the most challenging aspect of the DC technology is its protection design. This is due to absence of natural zero crossing-point and low inductance in the system [157]–[159].

Currents in the AC systems, on the other hand, are (more or less) sinusoidal in nature even during faults. . Hence, the fault interrupting devices can easily break the currents at the point of zero crossing. Since this natural zero crossing is not available in DC system fault current, most of the AC circuit breakers cannot be deployed in these systems. To complicate the problem further, the fault impedance of DC system is mainly resistive in nature and this leads to high peak in the fault current with a very fast rate of change compared to AC system fault currents. Conventional AC protective devices cannot handle such fast rate of rise in DC fault current.

Due to a number of existing DC applications, protection device such as fuses and circuit breakers (CB) are commercially available for DC system [160], [161]. Some of these devices are specifically designed for DC systems, but many of them can be used for both AC and DC protection applications. However, the ratings of AC and DC systems are different. Therefore the designers need to be very careful in the selection of protection devices. Moreover, most of these devices introduce a large time constant and a time delay before activation, which may not be compatible with the future types of DC microgrid systems.

Recent research shows that aforementioned limitations in DC protective devices can be overcome by utilizing power electronics switches [162]–[166]. Even though these fast solid-state circuit breakers can offer a promising solution for DC microgrid systems, this technology is still at the research stage. To support new developments of this technology, it is important to set new standards and guidelines sooner than later.

Most of the available protection standards for emerging technologies such as solar PV inverters are mainly focused on connecting solar PV systems directly to the AC grids. Very limited information is available regarding the connection of the solar PVs directly to DC grids. Therefore, new sets of standards with full details on protection requirements for the future DC grid systems are on high demand for all power electronics and power engineering stakeholders.

D. STANDARDS DEVELOPMENT UPDATE

Above discussions highlight the growing need of new standard developments for all the aspects of DC microgrid systems. These include voltage standardization, protection, safety and power quality. These are required to improve the readiness level of this technology for practical implementation in wider industrial and commercial applications. The recent interest in DC microgrid system attracts several national and international standard organizations and some of them have already started working in this area. This subsection reviews these activities with the recent update in the DC standard developments:

1) INTERNATIONAL ELECTROTECHNICAL COMMISSION (IEC)

IEC has published many standards for DC systems such as IEC 62040-5-3, IEC 61643-3 and IEC 61643-311 for existing DC applications. Recently a number of activities in the area of low voltage DC applications in Information and Communication Technologies (ICT), residential and commercial buildings etc. have led IEC to establish a new Strategic Group (SG) to study the standardization of DC distribution, in which SG4 has been approved for Low Voltage DC (LVDC) distribution system up to 1500V DC in relation to energy efficiency [149].

2) THE INSTITUTE OF ELECTRICAL AND ELECTRONIC ENGINEERING STANDARD ASSOCIATION (IEEE-SA)

In IEEE standard association, there are a number of ongoing activities on the utilization of DC power distributions in many applications. Some of them are listed below:

WG 946: This standard provides recommended practice for design of lead acid batteries based DC auxiliary power supply system. This standard covers the guidelines for selection of number of batteries, their capacity, voltage level and duty cycle. It also provides brief description about the effect of grounding on the operation of DC auxiliary systems [167].

P2030.10: This ongoing work is mainly looking for the possibility to utilize DC microgrid concept to provide safe and economic electricity in remote areas where centralized utility system do not exist. This standard covers the design, operations, and maintenance of a DC microgrid for rural or remote applications. This standard further provides requirements for providing low voltage DC and AC power to off-grid loads [168].

IEEE DC@Home: is an IEEE approved and sponsored activity to investigate the standard roadmap for the use of LVDC in residential buildings [169].

3) EMERGE ALLIANCE

EMerge Alliance is a group of companies, universities and research labs working together to promote DC distribution systems in residential and commercial applications. This group also involved in developing new DC standards and recently released following two standard:

EMerge Alliance Occupied Space Standard: This standard mainly focuses on 24 V DC distribution system in occupied space such as residential and commercial buildings [170]. The latest version (version 1.1) of this standard is released in 2012 with several updates on voltage limits, cable size and other requirements for related product manufacturing industries.

EMerge Alliance Data/Telecom Center Standard: This standard recommends 380 V DC power distribution for data and telecom centers to reduce energy loss and improve reliability of the system [171]. First version (version 1.0) of this standard has been released in 2012.

4) EUROPEAN TELECOM STANDARD INSTITUTE (ETSI)

ETSI is a standardization organization for the telecommunication industry in Europe. The group has developed standards for ICT including mobile, radio and internet technologies. Due to the recent growing interest of telecom industries to replace existing AC power solution or low voltage -48V DC to high voltage DC infrastructure, ETSI has decided to update the relevant standard ETSI EN 300 132-3-1 to cope with high DC voltage.

ETSI EN 300 132-3-1: This standard is extended by adding new part (part-3) mainly dedicated to new voltage limits from 260 DC to 400V DC. The scope of this standard includes limits and measurement methods for voltage tolerance, power quality, grounding arrangements and protection requirements [172]. The latest version of this standard has been released in 2011.

5) THE INTERNATIONAL TELECOMMUNICATION UNION (ITU)

The ITU has recently published a series of standards for DC distribution in telecom and ICT sectors. A brief update on these standards is given below:

ITU L.1201: This standard makes recommendations on DC power distribution for a voltage level up to 400 V for ICT equipment in telecom center, data center and customer premise [173]. This includes detail description about the possible structure of DC power distribution with redundancy and monitoring options. This standard has been published in 2014.

ITU L.1202: This standard is complements the recommendations made by ITU L.1201. In this, the performance of 400V DC distribution system has been analyzed in terms of system efficiency, reliability/availability and environmental impacts [174]. The performance of 400 V DC systems has been compared with existing -48 V DC and AC power distribution system. This standard has been published in 2015.

ITU L.1203: This standard defines requirements and guidelines for 400V DC power distribution, especially identification by color and marking in telecom/data center installation such as wire, cable and distribution board [175].

6) CHINESE COMMUNICATION STANDARDS ASSOCIATION (CCSA)

The CCSA published few standards for the use of DC power distribution in telecom centers. Some of these standards are listed below

YD/T2378-2011: This standard describes the technical requirements, test methods, inspection rules and marking methods for 240 V DC power distribution system in telecom centers [176].

YD/T 3091-2016: This standard describes the terminology definitions, evaluation requirements and methods for post-operational evaluation of 240 V/336 V DC power distribution systems in telecom centers [177].

There are few other standards such as YD/T 2089-2016 and YD/T 2556-2016, which mainly complement the above standards.

X. CONCLUSION

This paper presents different aspects of DC microgrids such as interface with AC grid, power quality, architecture, grounding, applications and standardization. Each section describes recent developments of DC microgrids from practical view point. Although, a DC microgrid has not been fully utilized in residential or in commercial sectors, the existing applications show it as a promising solution for the future smart grids. Protection, power quality and safety should be analyzed in details for different systems. In this paper, major technical issues for all of these have been discussed in details.

Without a proper standardization, it is not possible to bring the DC microgrid technology as a common and a generic power system solution for the future of micro or nanogrids in residential and commercial systems. Therefore, the latest activities in the area of standardization have been addressed in the last section of the paper.

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