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A review on overall control of DC microgrids

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ABSTRACT

Due to inherent advantages of DC system over AC system such as compatibility with renewable energy sources, storage devices and modern loads, Direct Current Microgrid (DCMG) has been one of the key research areas from last few years. The power and energy management in the DCMG system has been a challenge for the researchers. MG structure and control strategies are the integrated part of the power and energy management system. This paper covers all the aspects of the control of DCMG, whether it is DC bus voltage, power or energy related. Different MG Structures with their comparative analysis has been given in this paper. Various control schemes: Basic control schemes like centralized, decentralized and distributed control and multilevel control scheme such as hierarchal control has been discussed. The Power management in grid-connected, Islanded mode and transition mode has been presented. Different energy management strategies have been presented as energy management plays very important role in optimizing the size and rating of energy storage system and their maximum utilization. The energy management of a battery and super capacitor based HESS in all configurations has also been discussed and finally, future trends in further research are presented.

1. Introduction

Microgrid is not a new development in power distribution network; in fact the earliest power distribution system could be considered MGs due to their small and Islanded distribution system. But from the last few decades, when large conventional power units (coal, hydro and nuclear) installed, concept of high voltage power system (regional and national grid) came into the picture. Environmental concern and limited reserve of conventional fuel (coal, petroleum, etc.) forced to think about their alternatives. MG concept reintroduced in 2002 by R.H. Lasseter as a future low voltage distribution system to integrate distribution generation [1–3]. MGs can work in grid connected or Islanded operation mode. They are an effective, reliable and environmental friendly solution to integrate distributed generation to the main grid [4,5]. Previous research is mainly focused on AC MG, because of the familiarity with the AC Power system [6–9]. Continuous advancement in power electronics and improvements in computational power of real time controllers has made DC systems capability to achieve much broader functions than simple voltage regulation. Modern loads: e.g. computers, laptops, tablets, phones, printers, TVs, microwave ovens and energy storage Devices: e.g. battery, super capacitors are DC in nature [10–14]. So, DC systems are becoming a popular solution for many types of residential and industrial applications such as data centers [15,16], telecom stations [17,18], fast Electrical Vehicles (EV) charging [19–24], DC powered homes [25–29], renewable energy park [30–34], zero net electricity energy buildings [35–40], Railways [41–44], electric ships [45,46] and hybrid energy storage systems [47–53]. A genetic microgrid structure is shown in Fig. 1(a). Very small distributed generation also introduces the concept of "Nanogrid". It introduces another hierarchy in power system and further enhances the reliability of the system. A DCMG made up of multiple Nanogrids is shown in Fig. 1(b) [54]. The issues such as reactive power management and frequency synchronization become irrelevant in DC systems. Absence of frequency makes DC system free from skin effect, proximity effect, harmonics, and inrush current problem. DC systems are also considered safer because of reduction of electromagnetic field compared to its corresponding AC systems [55–59]. According to A. W. Cirino, et al. [60], the relationship between AC and DC cable resistance is as given by (1).

$$R_{ac} = \frac{\pi.r^2}{\pi.r^2\text{-}\ \pi.(r\text{-}\delta)^2}.R_{dc} \tag{1}$$

Where, R_{ac} and R_{dc} are resistance of AC and DC cables respectively, r is the Conductor radius and δ is the Conductor Skin Depth. From (1), it can be observed that the cable AC resistance will be always higher than its corresponding DC resistance. So, the losses in AC system would be

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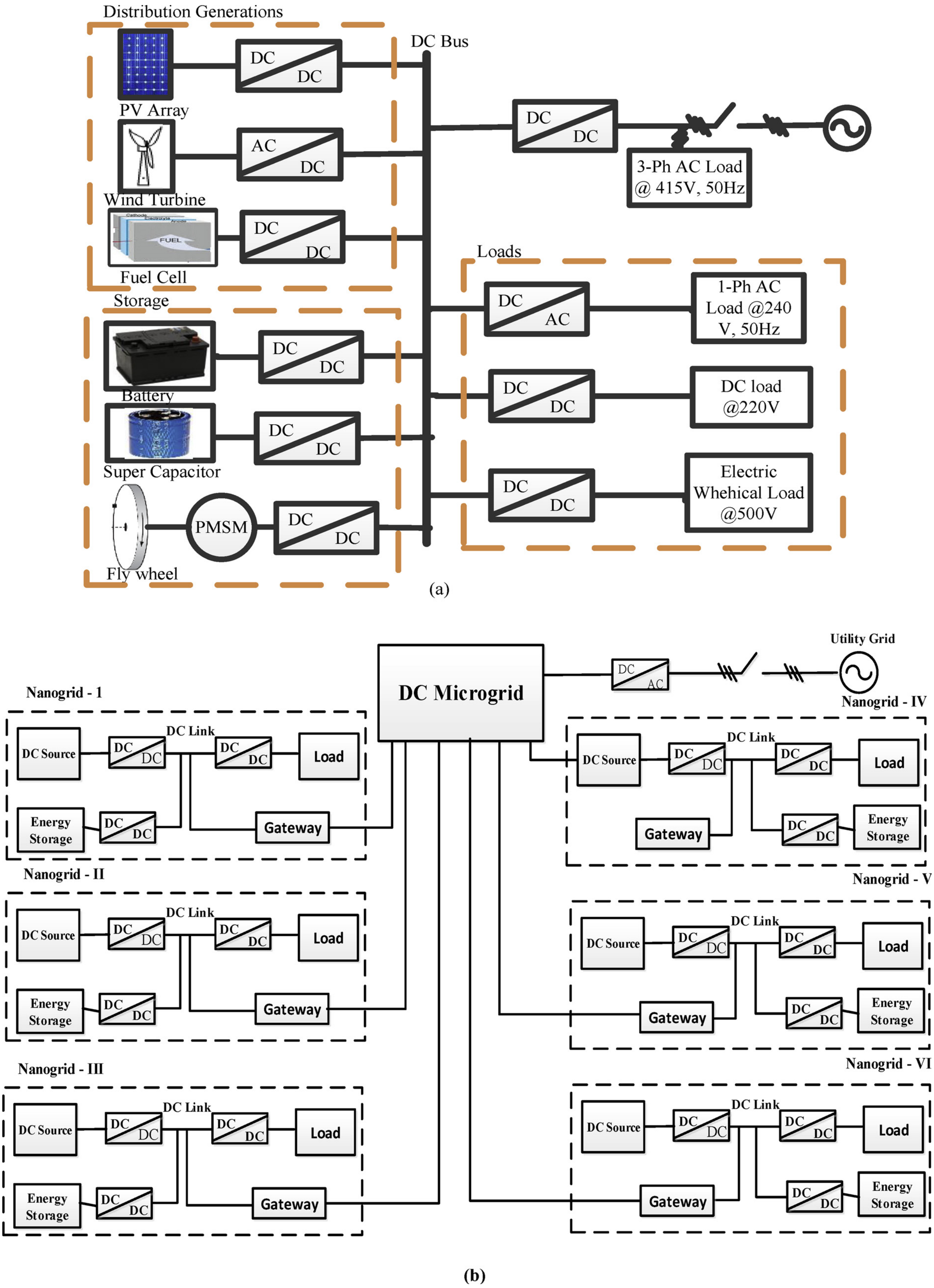


Fig. 1. DCMG (a) Genetic Structure (b) Made up of multiple Nanogrids.

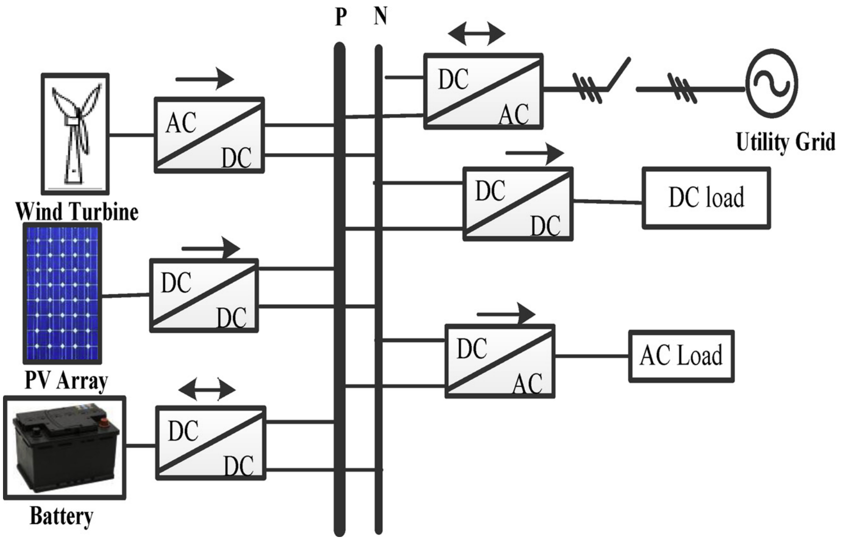


Fig. 2. Typical Single-bus DCMG Structure.

more and current carrying capacity would be less compared to its corresponding DC system. Sources such as fuel cell and solar are easy to integrate with DC system because their output is DC and sources such as wind, wave power generation and gas turbines are more efficient by using only one converter in place of two back to back converters (AC to DC and DC to AC). So, by avoiding unnecessary conversion stages the system complexity can be improved and conversion losses would reduce too [61,62]. Besides, so much of advantages, DC system has some challenges such as technology is not mature enough e.g. Standardization Issues, design of protection system because of absence of the zero crossing point in voltage and current, instability due to mismatch of impedance between lightly damped filters on the source side and tightly regulated power converter, investigation of proper grounding for the systems [63,64].

Although DCMG appears to be a novel technology, but the DCMG concept came with parallel to AC MG. Claiming for simpler control with better efficiency and reliability Y. Ito, et al. [65] reported one of the first DCMG experimental prototypes of 10 kW in 2004. Because the conventional technology was based on AC, so research on AC MG dominates over DCMG. However, with the evolution of IT industry, development of power electronics *devices*, simultaneously increase in DC loads and economic merits of DC systems made it attractive for researchers [66–68]. Most of the Renewable Energy sources (RES) are intermittent in nature. So, the role of other sources such as diesel, fuel cells and storage devices become critical in enabling the Islanded operation of MG or to smoothen the MG power during grid connected mode [48]. On the basis of operative nature of Energy Storage Devices (ESDs), they can be classified into two category i.e. Access oriented ESDs and capacity oriented ESDs. Access oriented devices have fast response time and they are liable for short time disturbances. They can absorb or supply the higher power transients with high power density. Super-capacitors (SCs), flywheel and superconductors come under this category. Capacity oriented devices do not have a fast response and they are used long term energy balancing. Batteries, compressed air energy storage devices, pumped hydroelectric systems and hydrogen storage devices come under this category [51,69–71].

One basic part of the operation of a DCMG is the power and energy management, which, are fundamental for giving sound operation in both grid connected and Islanded operation modes [72,73]. In MG, the expressions "energy management" and "power management" are distinct in terms of control tasks and time scale. In energy management strategies, main factors are capital costs, fuel costs, maintenance costs and the lifetime of the systems, etc. while in power management strategies, key parameters are current, voltage and power, which affect the instantaneous operational conditioning. The power management strategies include voltage regulation and real-time power dispatching among different power sources in MG. Power management is more relevant to the interface and control of power converters in the MG. Hence, energy management is mainly associated with the economics of the systems and power management is mainly associated with the technicality of the systems [53,74]. The purpose of this paper is to provide an overview of power management methods and energy management schemes used in DCMGs. Because system structures and control strategies are integrated part of these schemes, hence they are also discussed. The paper is organized into six sections. The importance of DCMG is stated in the introductory part in Section I while in section II, different DCMG structures are discussed with their pros and cons. Section III covers different control strategies and in section IV available DCMG power management methods are provided and discussed. Section V analyses energy management schemes for DCMGs. Finally, section VI presented the discussions and future research trends with concluding remarks.

2. DCMG structures

Power system structures influence many factor such as the cost of the project, robustness, resiliency, controllability and hierarchy of the system, reliability, availability, resource utilization, and flexibility to consumers [75–77].Various basic factors should be considered to decide the system structure, i.e. impact on the landscape, power available at different points, maximum utilization of resources and scalability in the future [78,79]. A number of topologies have been reported in literatures and it is found that almost all the structures can be covered by six types of structures [55,67,80–84].

2.1. Single-bus DCMG structure

This structure is also called radial or feeder structure. It has a single DC bus in which energy resources, energy storage devices, and loads are connected directly or through interfacing converter. In this structure, the loads get power only if the interfaces at the load are all working. A failure in a source interface would not necessary result in black out of power because of the presence of other sources and ESDs in the system. Fig. 2 shows a single-bus DCMG structure [55,81]. In some structure, battery is directly connected to the common DC bus. It reduces the number of converters, but imposes a limitation on the voltage control of the common DC bus, which mainly depends on the State Of Charge (SoC) of the battery, limits its application. Introducing an interfacing

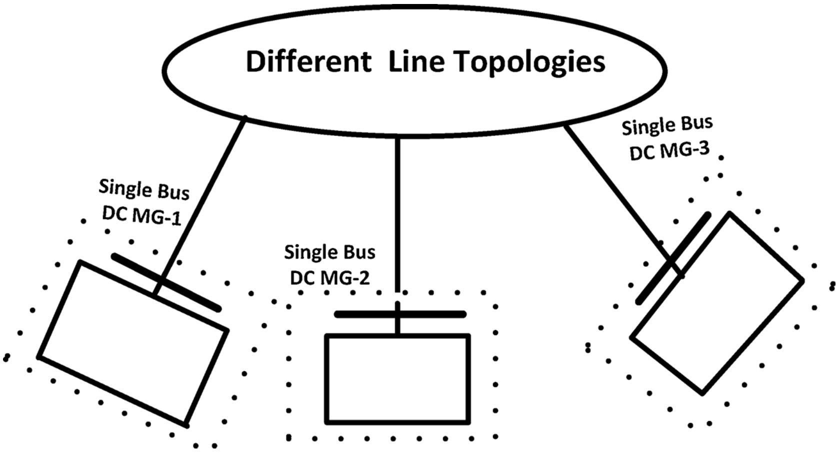


Fig. 3. General Multi-bus DCMG Structure.

convertor regulates voltage on DC bus and allows application of more flexible control [85,86]. Reliability of the system can be enhanced by including multiple battery slacks [87]. This type of structure is recommended for Low Voltage (LV) DC systems. T. Dragicevic [88] presented two parallel bidirectional DC/AC converters connection to connect DCMG with the utility grid. Two parallel converters connection will increase the reliability and flexibility of the system.

2.2. Multi-bus DCMG structure

DC power systems with multiple buses for redundancy are more reliable and provide reconfiguration options, in order to supply power to sensitive load from different DC buses [83]. This system is more flexible and provides different voltage levels to the consumer, i.e. three wire system, it can be used for realizing a Multiple-DC-Bus can operate V, V/2 and –V/2. Due to its redundancy feature, it is very useful in naval ships applications [67]. An explanatory diagram of multi-bus DCMG system is shown in Fig. 3 Every MG of the cluster is able to absorb or inject power to its neighbouring MG in case of surplus or deficit of power respectively. Although, it is an extension of single-bus DCMG structure, but it is much more reliable and available [89]. Its feasibility, reliability and availability can be further enhanced by connecting it to the main grid. There are several methods suggested for selecting the most appropriate bus in multi bus system to supply the power to the load in literature [90,91].This type of structure is suitable for low and high both types of voltage levels.

2.3. Multi-terminal DCMG structure

Power flow in the multi-terminal system is complex, but simultaneously this system is flexible too. The main purpose of this type of system is to maintain the power balance between different units of the system, reduce voltage and frequency deviation (in case of wind system) and enhance the stability of the system. This type of system is preferred in wind firm systems.The power surplus or deficit within the DCMG is automatically balanced by a voltage source converter through AC distribution grid. This type of structure is generally recommended for high voltage (HV) systems [92–94]. A Schematic multi-terminal DCMG system is shown in Fig. 4. Generally, mess structure is preferred for this type of systems (because in introducing redundancy, which increases the reliability of the system) but many without mesh network is also installed throughout the world [67]. Protection of DC system has been a challenge. The protection problem becomes more challenging when multiple sources get involved in the system. Many researchers are working to find appropriate solutions for the protection problem of multi-terminal DCMG systems [95–97]. Z. Zou et al. [95] proposed a fast protection scheme for multi-terminal DC systems. In which researchers suggest polarity comparison of Initial current traveling wave and sampled value current differential theory for the DC line pilot protection and the DC bus bar protection respectively.

2.4. Ring-bus DCMG structure

This type of structure is proposed for the purpose of increased flexibility during the faults or periodic equipment repair periods. Since the load connected to the common DC bus can be fed bi-directionally, so in case of fault, alternative path is provided. Hence, advantage of this type of structure is high reliability, high resiliency and redundant operation [98]. A schematic diagram of segmented Ring bus DCMG system is shown in Fig. 5 [99]. This structure is useful for both types of systems: high voltage levels and low voltage levels. Its short circuit fault current analysis [99], identification of fault location and protection of dividing the system into segments [100,101], identification and classification of fault based on the voltage prediction method that did not depend on communication [102] or using the Oscillation frequency and transient power [103], classification of permanent and temporary faults and fault rid through capacity of the system [104] have been discussed in literature. A Distributed coordinated control is proposed by C. Dou et al. [105] by claiming improvement in the voltage performance.

2.5. Ladder-bus DCMG structure

Basis of ladder bus structure is a ring bus structure. The output of distributed generation sources is connected to the rings of the laddered DC structure. Then, the rings of the ladder are connected to two buses, either of which can provide DC power to other rings of the ladder. In this way redundancy of the system gets very much improved. A typical structure of ladder bus DCMG structure is shown in Fig. 6. This system has highest redundancy compared to any other system which made system capabilities to effectively eliminate single points of failure and open circuit faults, and achieve high availability [81,98].

Its scalability is high that makes capable to add distributed sources easily without affecting other parts of the system [106]. A. Kwasinski [107], introduces Multi Input Multi Output (MIMO) converter in place of Single Input Single Output (SISO) converter to enhance, its fault tolerant capability and make capable to withstand against extreme events such as natural disasters. Its merits such as high availability, high scalability, high reliability, free from open circuit faults, fault tolerant capability made a preferred choice for modern systems such as electric ships, data centres and telecom appliances.

2.6. Zonal DCMG structure

Another DCMG architecture that features high reliability is based on

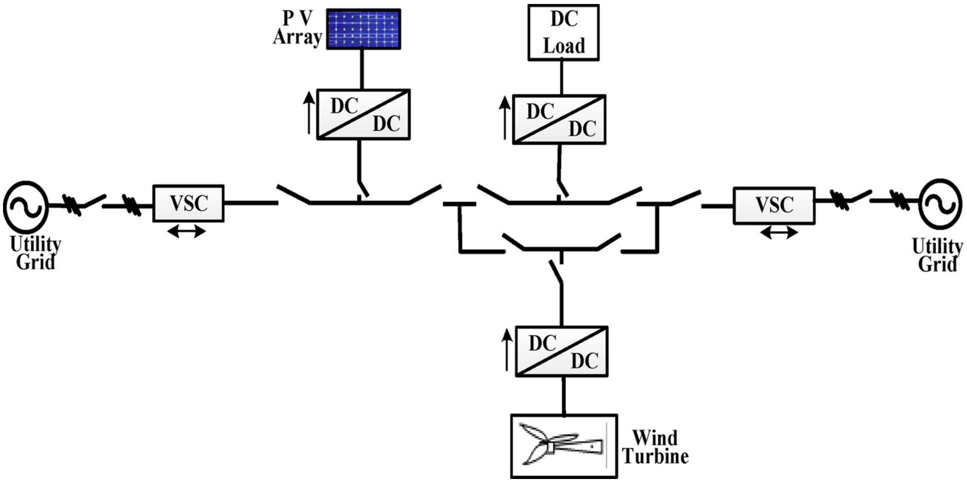


Fig. 4. Schematic multi-terminal DCMG Structure.

zonal configuration, as shown in Fig. 7 [84]. DCMG is divided in zones by introducing redundant buses, each zone having its own protection and load centre. Each building or a group of buildings can be considered as a zone, within which the power is balanced. The Zone can supply its own power demand through Distributed Energy Resources (DERs) and ESDs [84]. The drawback of zonal DCMG structure is that it will suffer the problem of power supply reliability because of the intermittent nature of distributed resources if no power supply back up is provided. This problem of zonal MG structure can be removed by introducing the Solid State Transformer (SST) in the system [108]. Z-source breakers improve the protection of the DCMG system because it offers autonomous instantaneous isolation of the load from the fault [80].

As a final remark, although the power structures were discussed in this section within the MG framework, they have a quite general structure. M. Barnes, et al. [109] discussed the some real world MG structures. A ccomparative analysis of all discussed DCMG structures is presented in Table 1.

3. DCMG control

In order to have an efficient operation and guarantee for stability of a DCMG, effective control strategies should be implemented. Interfaced converters play key role in operation of a DCMG. They not only insure proper local operation, but also enable coordinated interconnection between different units of a DCMG. In DCMGs, different units are connected in parallel. So, flexible voltage and current control and precise power sharing among parallel connected converters should be achieved. It is well established that converter acting as loads adds nonlinear effect caused by its constant power behavior in system that make system unstable, so it should be considered in the control strategy [110–112].

3.1. Control objectives

The increasing distribution generation and nonlinear loads have made control structure very important. The control objectives of a DCMG system are given below [81,111–116].

- Efficient voltage and current control in both operating mode i.e. grid connected and Islanded mode.
- Proportional load sharing.
- Stable operation with the Constant power load / Non-linear loads.
- Coordination among different DERs and ESDs.
- DCMG synchronisation with the Utility grid.
- Power flow control within DCMG and with the Utility Grid (if grid connected).
- Smooth transition between Grid connected to Islanded mode.

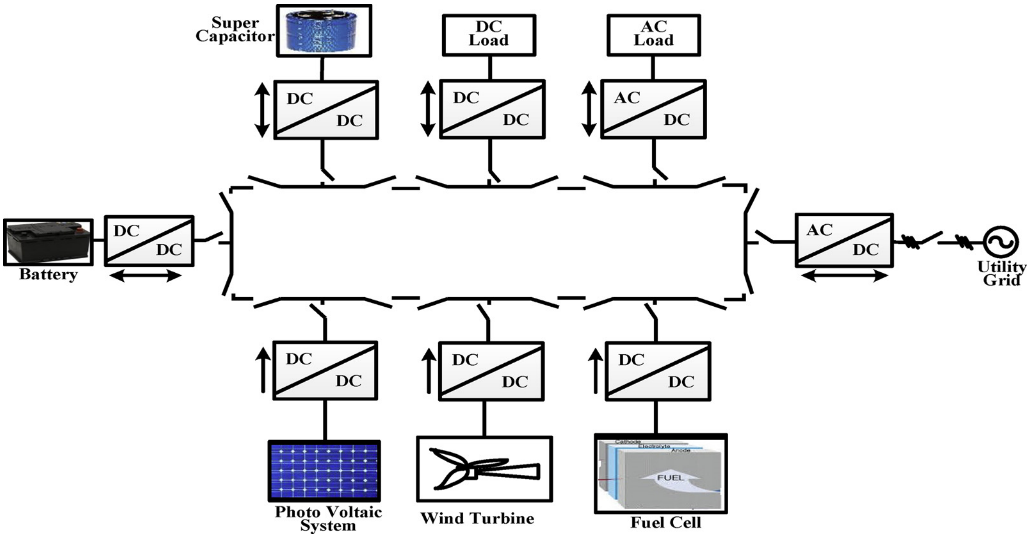


Fig. 5. Typical ring-bus DCMG Structure.

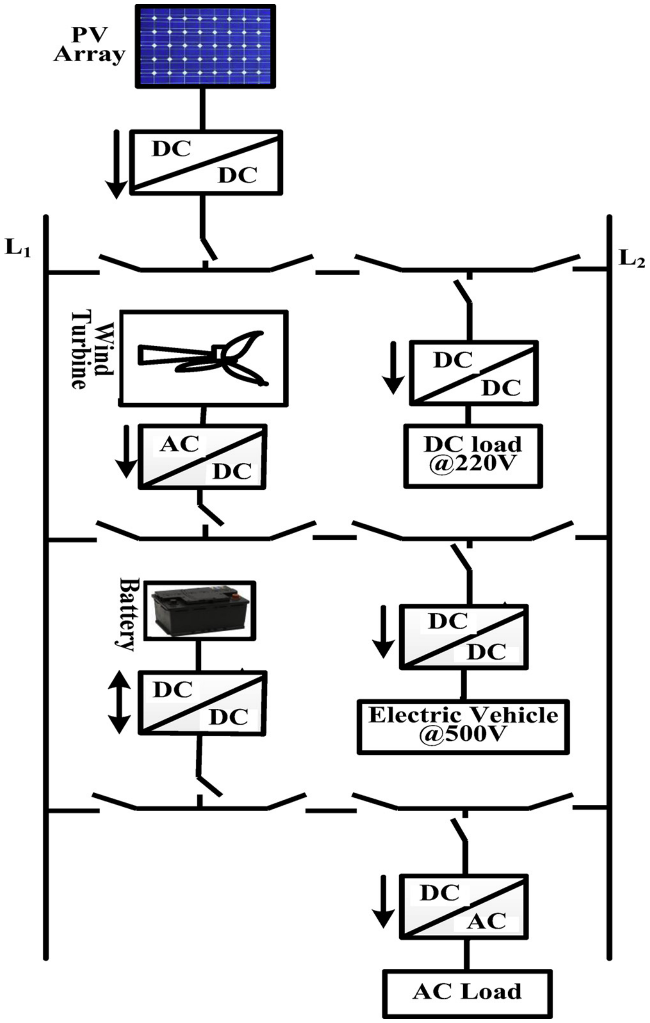


Fig. 6. Typical ladder DCMG Structure.

- Economic Dispatching and optimization of generation cost.
- Maximum utilization of potential of DERs.
- Minimization of transmission losses.

3.2. Control strategies

Whole DCMG control strategies can be categorised into two sections: Basic control strategies & multilevel control strategies. Basic control strategies can be implemented through centralized control, decentralized control and distributed control. Basic control has been discussed in detail in Section 3.2.1. Multilevel control is implemented through different level of control in hierarchy. Each level of control uses one of the basic control strategies. Almost all the proposed /developed Hierarchical control strategies can be covered in two levels and three levels of control. Multilevel control strategies are discussed in detail in Section 3.2.2. Control strategies used for DCMG control have been described through Fig. 8. [66,114,117].

3.2.1. Basic control strategies

Communication is the main element of control. The basic control is performed by three methods, distinguished by communication level.

1 Centralized Control
2 Decentralized Control
3 Distributed Control

3.2.1.1. Centralized control. Distributed units are controlled by a central controller. Data from the distributed units of DCMG is collected; processed and commands are sent back to them through Digital Communication Links (DCLs).Communication is the heart of the central control scheme. The advantages of this scheme includes strong observability and controllability of the whole system. It also suffers from many disadvantages such as, single point failure of the system; reduced reliability, flexibility and scalability. Therefore, this control scheme is suitable for small size of DCMG systems where the information to be collected is limited and control can be performed with LBC structure [117–120].Schematic basic configuration of the centralized control scheme is shown in Fig. 9.

Master slave control strategy is a typical example of a centralized

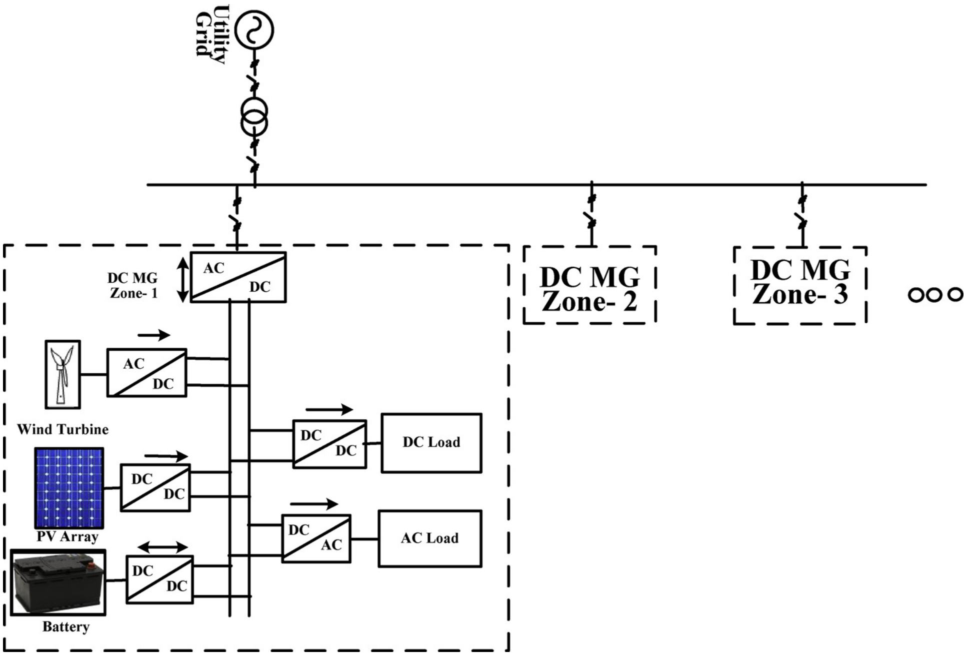


Fig. 7. Typical Zonal DCMG structure.

Table 1
Comparative Analysis of DCMG Structures.

DCMG Structures	Voltage level	Direct ESS Connection	Inherent Stability	Expandability to multiple buses	Reliability
Single bus DCMG Structure	12, 24, 48	yes	yes	no	high
Multi-bus DCMG Structure	48, 380	no	no	yes	medium
Multi-terminal DCMG (mess topology)	380 or higher	no	no	yes	high
Ring-bus DCMG Structure	24 V or higher	no	no	yes	high
Ladder DCMG Structure	24 V or Higher	no	no	yes	Very high
Zonal DCMG Structure	24 V or Higher	no	no	yes	medium

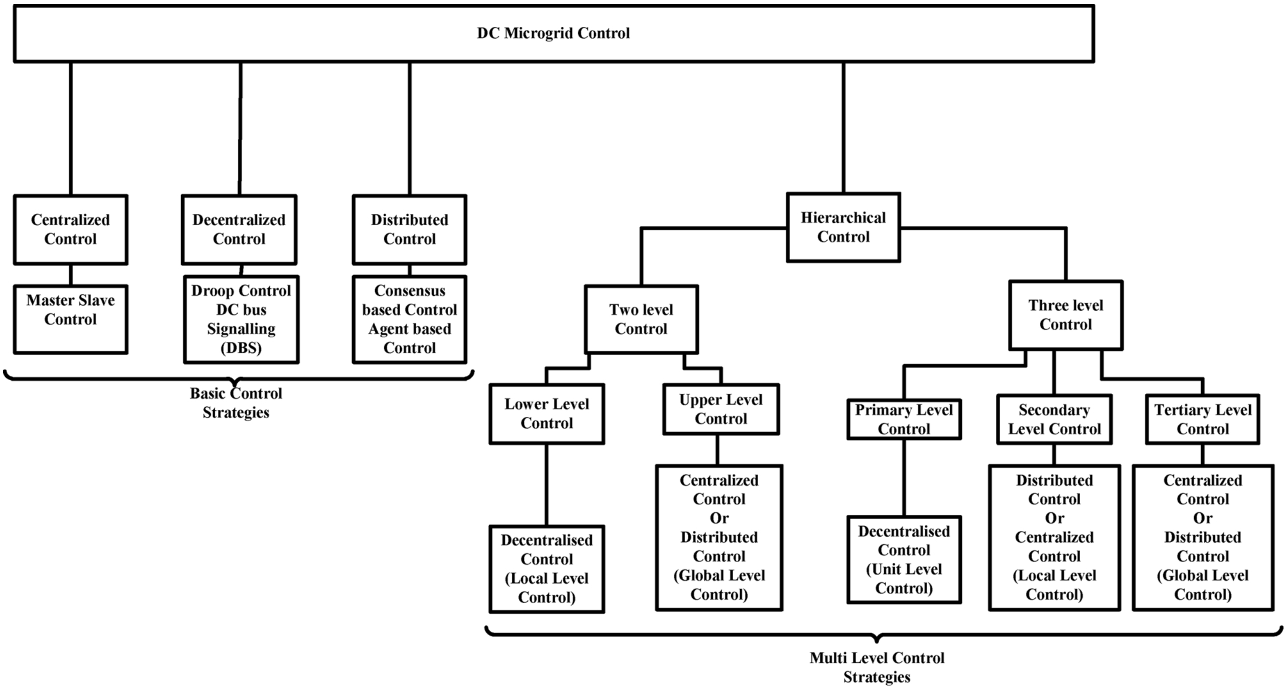


Fig. 8. DCMG Control Strategies.

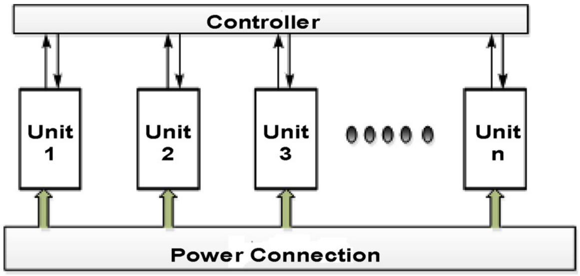


Fig. 9. Schematic Diagram of Centralized control Scheme.

control scheme as shown in Fig. 10. [121]. In this control strategy, one converter considered master, operates as a Voltage Source Converter (VSC) and responsible for DC bus voltage regulation while others work as a Constant Source Inverter (CSI) and follow the pattern of master converter. This control strategy relies on the High Bandwidth Communication (HBC) [122]. The drawbacks of this control strategy include, possibility of single point failure due to the system reliability mainly depends on the master converter, and requirement of supervisory control, poor scalability, responsible for shorter battery life [123]. The method is further categorized on the basis of role of the master converter: (i) dedicated (ii) rotary and (iii) high-crest current. A master slave coordinated control is proposed in [124] in order to regulate dc bus voltage. Here, ESS units are considered as master and remaining units such that RES and loads are considered slave to regulate

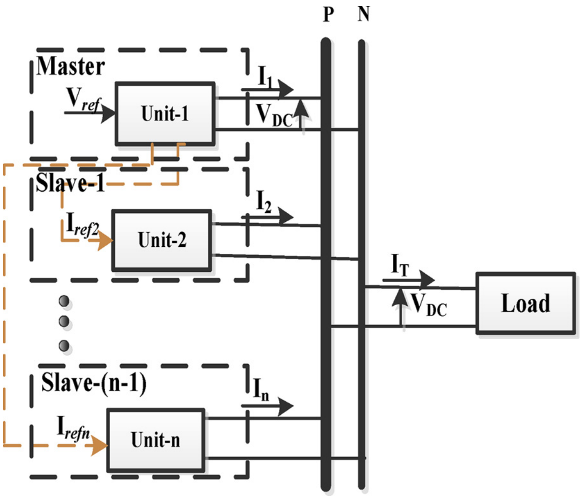


Fig. 10. Schematic diagram Master slave control.

their power. I. Federico et al. [125]. Proposed a master slave droop adding with traditional droop control for the application of electric bus and claimed 3% efficiency improvement.

3.2.1.2. Decentralized control. There is no communication link in this control. The distributed units are controlled by independent controllers

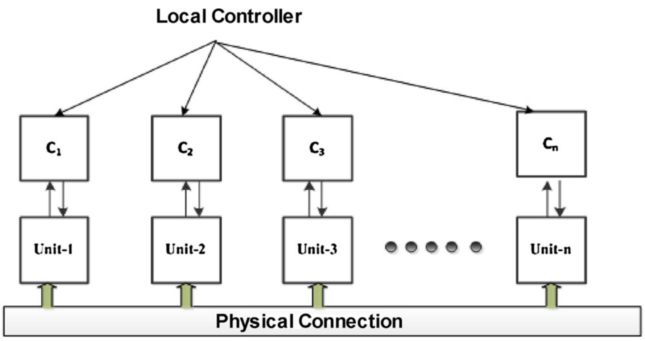


Fig. 11. Schematic diagram of decentralized control scheme.

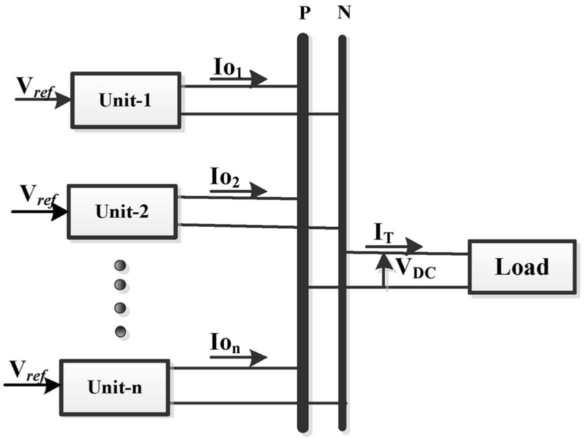


Fig. 12. Schematic diagram of voltage droop control.

through their local variables. Although, this control scheme has some performance limitation because of insufficient information about other units of the systems, it is considered most reliable control scheme due to not requirements of communication links between different units of the system [117]. Basic configuration of decentralized control scheme is shown in Fig. 11. A popular decentralized control strategy is droop control strategy where the converters are connected parallel with the DCMG as shown in Fig. 12 [121]. This strategy is usually adopted to avoid circulating currents between the converters without the use of DCLs. Output power or output current is selected as the droop feedback in droop control strategy [66]. The output power is used as feedback control signal in Constant Power Loads (CPLs) and the output current feedback signal is used for other than CPLs. Corresponding diagram representations of droop principles for power droops and current droops are shown in Fig. 13 and characteristics is represented by Eqs. (2) and (3).

$$V_{DCk} = V_{DC} - m_{cp} p_{ok} \tag{2}$$

$$V_{DCk} = V_{DC} - m_{cc} i_{ok} \tag{3}$$

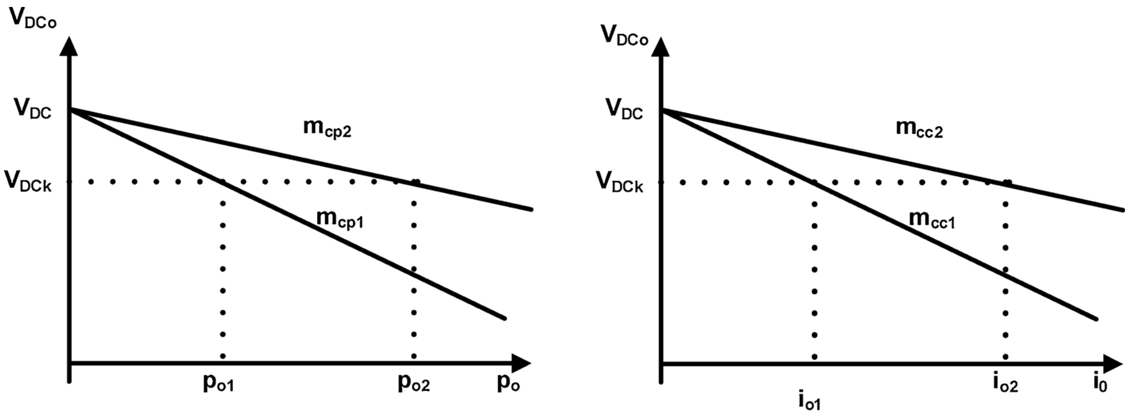
Where, V_{DCk} is Reference value of output voltage of kth converter, V_{DC} is Bus voltage, m_{cp} and m_{cc} are power droop and current droop coefficients of the Converter respectively, and p_{ok} and i_{ok} are Output power and output current of kth converter.

The droop coefficient values affect the current sharing, accuracy and stability of the system [126]. Higher the droop a coefficient, more the damped system is and the result is higher accuracy in current sharing. But it simultaneously increases the voltage deviation. So, a trade-off between current sharing, accuracy and voltage deviation is required. By imposing anticipated voltage deviation in the DC bus, the power flow of the other droop controlled converters can be regulated. Generally, the droop coefficients are selected to achieve optimal co-ordinated operation and current sharing with minimum error. To regulate the Common DC bus voltages and control the load sharing in DCMG a droop control method using Proportional (P) and Proportional Integral (PI) controller is adopted [126,127].

Though, this control strategy has high reliability and flexibility due to absence of DCLs, but simultaneously it suffers from many drawbacks such as load dependency, i.e. voltage of the common bus, changes with the load (In Islanded mode), accuracy of load sharing can be achieved with the compromise of deviation in the voltages compare to their rated values, unsuitability with the non-linear loads due to harmonics, responsible for the circulating currents in DGs, inability to achieve co-ordinated performance of multiple components with different characteristics, poor transients performance, etc.. Recently, some modifications have been proposed to deal with the circulating current problems, supervisory control to deal with the coordinated performance to make this control method more effective [88]. In [127] a Low Bandwidth Communication (LBC) droop control method is proposed, in which author claims improved performance and no need of secondary control, The LBC network and local controllers are sufficient to exchange information between converter units.

A decentralized droop control strategy [126] is proposed in which secondary voltage control uses an average voltage sharing scheme to compensate the voltage deviation created by droop control result precise terminal voltage and enhance system reliability. In [128] author proposed a power sharing control structure for MTDC grid based system.

Besides droop control, DC Bus Signaling (DBS) is another useful, reliable and low cost distributed control scheme. It is efficient in both modes of operation, i.e. grid connected and Islanded mode. The control strategy depends on the local measurements of the DC bus voltage. DC



(a)
(b)

Fig. 13. Droop Curves (a) Power Droops (b) Current Droops.

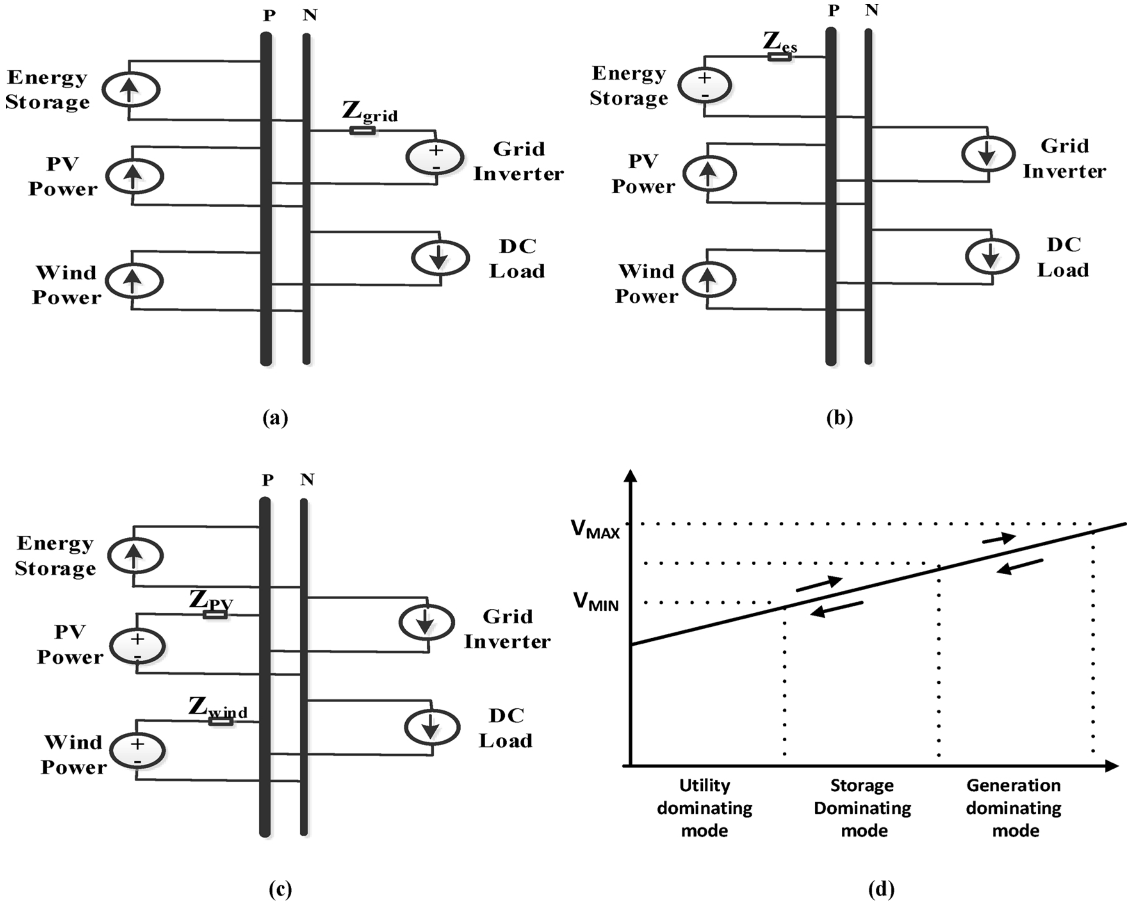


Fig. 14. Different operation modes in DBS control strategy (a) Utility dominated Mode (b) Storage dominated mode. (c) Generation Dominated mode (d) Operation Mode selection based on DC bus voltage.

bus voltage serves as an information carrier and dictates the different operation modes. It is executed by setting the voltage thresholds at which the source and/or storage interface converter become active and priority of devices for different modes of operation. These voltage thresholds should be fairly distinctive and tight enough to avoid the stability problem for the system, i. e. if the difference among the voltage levels is too high, the DC bus voltage fluctuation will exceed the permissible range; if the difference among the voltage levels is too small, it will affect sensor accuracy. The shift of modes of operation for the power converters is made after measuring the bus voltage without DCLs [129].

In general, there are three types of source, i.e. DGs, ESSs and utility grid in a DCMG system that could be responsible for regulation of DC bus voltage. There should be at least one bus regulating unit in the system to retain DC bus voltage stable. The DBS control of a typical system having all three types of regulating units is shown in Fig. 14 [131], where units are represented either by current sources/sinks or by Thevenin equivalent circuits based on the operating mode. Thevenin equivalent shows the particular unit is in droop control mode. The voltage source corresponds to voltage reference and series impedance for virtual impedance [130,131]. In [132], a flywheel storage based DBS control strategy is proposed for public fast charging EVs. N. Zhi*et.al.* [129] discussed DBS control strategy and its linear stability analysis for subsystem and Lyupunoy stability analysis for switching system.

An adaptive DBS power management strategy [130,133] for solar PV and multi battery storage based system is discussed in which the power is managed in four different modes, in each mode of operation PV operates at Maximum Power Point Tracking (MPPT) and battery modules charges and discharges differently based on common DC bus voltage, i.e. Mode I: both batteries in droop charge, Mode II: both batteries in droop discharge, Mode III: one battery in CC charge, one battery in droop charge, Mode IV: one battery in CC discharge, one battery in droop discharge. Battery charging and discharging operations curves are shown in Fig. 15. A four mode power management strategy is also discussed in [131], in which DC/DC converter switches between MPPT and Constant voltage (CV) mode. Power management in DCMG can be made more flexible, less complex and more reliable by enabling SST into the system [134].

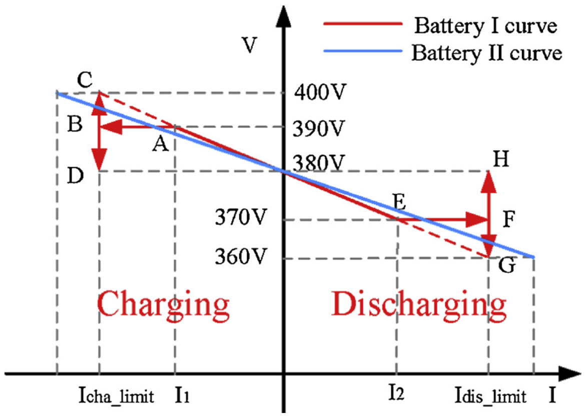


Fig. 15. Battery modules operation curve [131].

Except droop control and DBS, Power Line Communication (PLC) is another decentralized control strategy that sometimes uses to regulate the DC bus voltage. But it is more complex and costly to execute

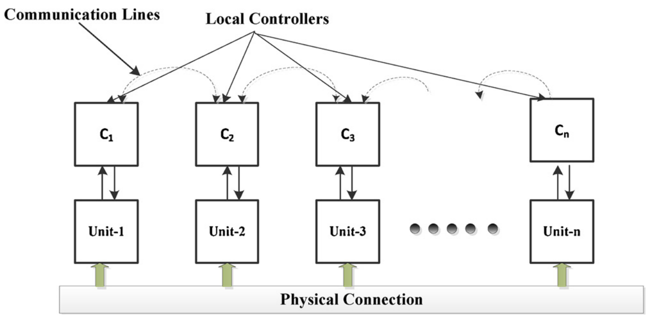


Fig. 16. Schematic Diagram of the distributed control scheme.

compared to other control strategy such that Droop control and DBS. It is still a research topic for LV distribution system. Though PLC relies on digital communication, it is reference here because it uses the power network in the only communication medium [135,136].

3.2.1.3. Distributed control. There are some advantages of centralized control and some decentralized control. This scheme includes advantages of both schemes. The controller of each unit exchanges data with only its neighbours units via available limited DCLs. So, objectives such as proportional load power sharing, voltage restoration, current sharing, SoC balancing can easily be performed [137,138].Sometimes it is very difficult to implement centralized control scheme due to the significant increase in DG units, In that case distributed control scheme is a good option. This strategy is immune to single point failure because the system can keep full functionary even if the failure of the some DCLs. The main drawbacks of distributed control schemes are bus voltage deviation, power tracking error and complexity of analytical performance [131]. Schematic basic configuration of the distributed control scheme is shown in Fig. 16. Consensus based control strategies and agent based control strategies are the typical example of a distributed control scheme.

A consensus algorithm is an interaction protocol which specifies the information exchange between a unit and all its neighbour units. It is an approach for solving distributed optimization problem and offers a flexible control [137]. The purpose of consensus is to have different units to reach an agreement. A power consensus algorithm is proposed for DCMG [139,140]. This algorithm is analysed by using Lyapunov functions, so it is considered a push for nonlinear consensus type system. The principle of consensus algorithm can be understood by (4).

$$\dot{x}_i(t) = \sum_{j\in N_i} [x_i(t) - x_j(t)] + k_i(t) \tag{4}$$

Where, $x_i(t)$ and $x_j(t)$ are variables of interest in unit i and j respectively and $k_i(t)$ is optional input bias for unit. It can be observed that $x_i(t)$ is mutually adapted with respect to values of its neighboring units. So, analytically it can be proven that all variables will converge to a single point after some time [140,141].

Agent based control strategy is another popular distributed control used in DCMG. Each unit is considered as an agent. So there are many agents in a DCMG system. Therefore, generally it is called multi agent system control. It includes many intelligent entities that can be software or hardware with local knowledge. Multi Agent System (MAS) technology is an excellent instrument for collecting and controlling distributed information. So, they are good for Supervisory Control and Data Acquisition (SCADA) [142–145]. Its advantages include; survive from single point failures and decentralised data processing which results is efficient assignment of works between its agents, fast operation, improve reliability [146,147]. D. D. sharma et al. [148] proposed two schemes based on agent based distributed control for distributed energy storage systems to decide power exchange by distributed storage units under cyber-attacks scenario. In [149], a survey on application of agent technology in industrial process control is presented. The survey is mainly focused on the technology applications in the automation of continuous industrial processes.

Besides consensus control and agent based control, some other distributed control schemes such that decomposition based approaches in which original problem is disintegrated into many sub-problems and then apply the algorithm [139].

3.2.2. *Multi-level control*

Power systems require higher intelligence control systems to realize several basic objectives: voltage control, current control and power control as well as advance objectives: Power sharing between Distributed Generations (DGs), Power Quality control, Provision for ancillary services, participation in energy markets, minimization of operating cost etc. it is very difficult to realize these objectives through a single level control such as Centralized or distributed control. Even basic control such that droop control for load sharing can better realize by multi-layer control, i.e. in droop control, its known drawback of load dependent voltage deviation, and propagation of voltage error along resistive transmission lines leads to deterioration of current sharing. So, a secondary controller require to be employ in order to restore the voltage and a tertiary controller to ensure accurate current flow among different power system buses. Consequently, a multilevel control system is the need for our modern power system such as DCMG where simple functions can be executed through local controllers to surety of a basic operation of the system and advance functions can be executed through central controller [126,150].

Recent developments in communication technologies made multi-level control configuration preferred choice for large scale DCMGs structures. Multilevel control introduces a certain degree of independence among control levels. It is more reliable because even in failure of upper level controls, system operation continues due to lower levels of controllers [117,151,152].

The Control of DCMGs can be divided into four levels. Each level has the obligations of a command level and gives supervisory control over lower-level frameworks. So, it is important to guarantee that the reference signals and command from one level to the lower levels will have low effect on system's stability and robust performance [153,154].

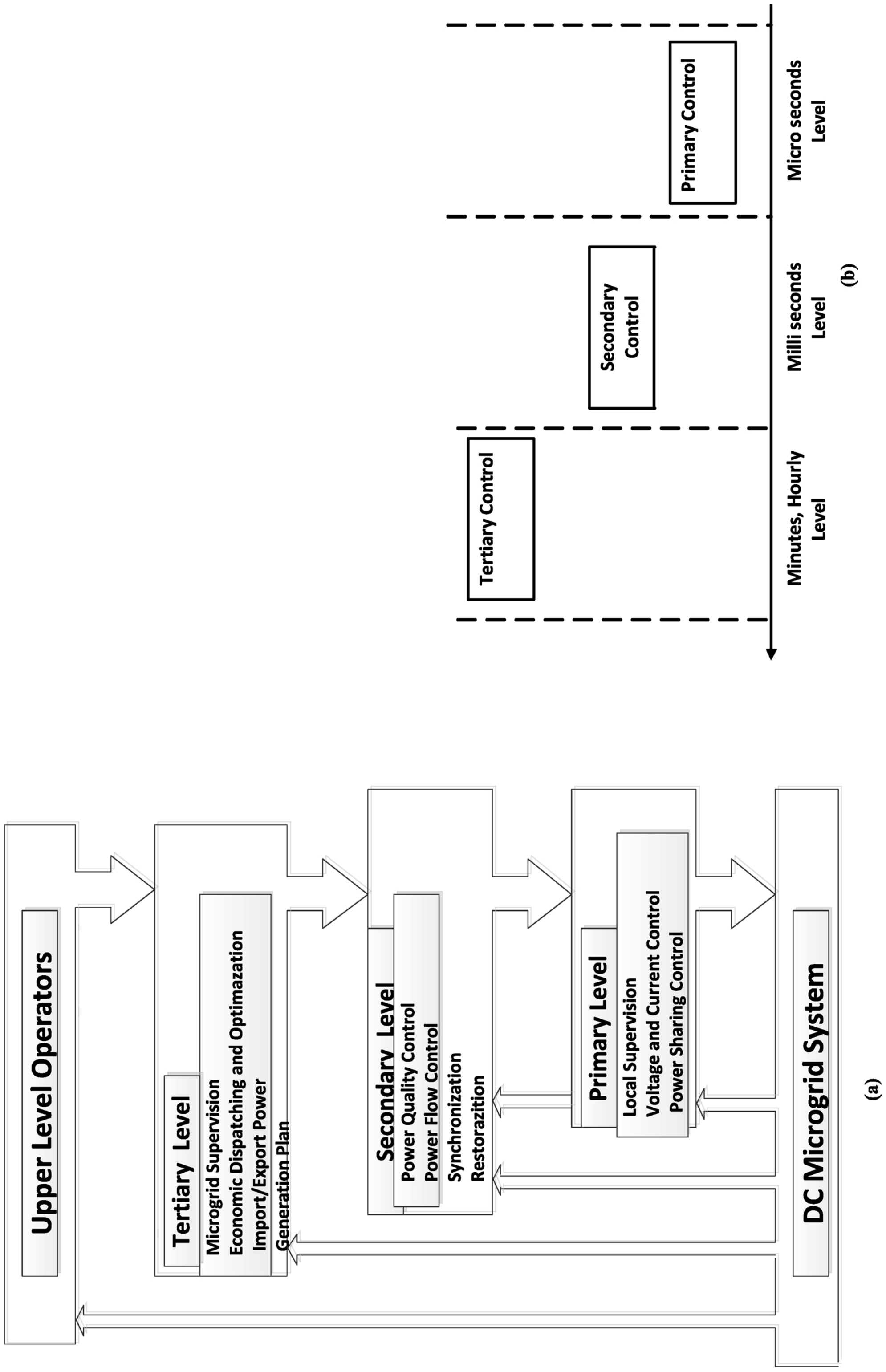
Level 0 (inner control loop): this level determines the operating state of devices and involves voltage and current controllers.

Level 1(local control loop): This level is considered decentralized control, which is usually based on droop control equations deals with the power flow control and makes the system more stable and more damped. It can incorporate a virtual impedance control circle to imitate output impedance.

Level 2(secondary control loop): Guarantees that the electrical levels into the MG are inside the required limit. This level control can interface or separate the MG to or from the distributed units. It is centralized control responsible for adjusting the references of the local layers. Hence, it requires communication infrastructure. This layer is responsible for the reduction of reliability of the system.

Level 3 (global control loop): This controller supervises the power flows between the DCMGs and the utility grid. This layer requires communication infrastructure too, so it also reduces the reliability of the system.

To develop control system more advanced and suitable for all type DCMG systems (small, medium or large) for flexible operation in grid connected mode as well as Islanded mode, it is a good idea to combine centralised and decentralized control, decentralised and distributed or all three centralized, decentralized and distributed into a hierarchical control framework [153,155–158]. In the hierarchical structure, the control functions are shared by different levels of hierarchy. Generally, three levels of hierarchy are considered for a hierarchical control framework and different levels are assigned with their respective task to perform in their time frame as presented Fig. 17 [152]. Though, few literatures adopted two level of hierarchy in control: High level control,



(a)

(b)

Fig. 17. Hierarchical Control (a) Schematic Diagram (b) Time frame diagram.

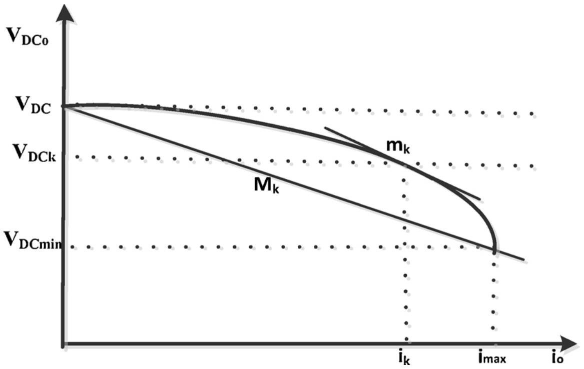


Fig. 18. Principle operation of nonlinear Droop Control.

for that centralised control is opted and low level control for which distributed control is preferred [88,151,159–161]. A review on the hierarchical structure for the DC bus voltage control is carried out by Z. Shuaia et al. [161]. In which they presented both type of typical structures for three level controls and two level controls in detail.

3.2.2.1. Primary level control. Primary level control is the first layer of control in a hierarchical control structure which is responsible for current and voltage control of the system. It also damps the oscillations in the DCMG system created by the CPLs. Sometimes, decentralized load sharing schemes are also employed in this layer to achieve proper power management in the system. Some popular primary level control methods are Droop Control and DBS control method.

Droop control is the common control method for the first layer of control. This method is preferred over other conventional methods because it is decentralized control and does not depend on communication Structure. However, due to its drawbacks such as deviations in voltage and inaccurate current sharing, some researchers proposed the nonlinear control to lessen its drawbacks [152,162,163]. Nonlinear droop control operation for DCMG is shown in Fig. 18. Non-linearity in droop characteristic guarantees that droop gain is high at full load and low at light loading, Thus, overall operational performance of droop control get improved. Corresponding equation for calculation of reference voltage of a converter is given by Eq. (5) [162].

$$V_{DCK} = V_{DC} - m_k(i_{ok})i_{ok}^{\alpha} \tag{5}$$

Where, m_k is A Positive function, α is A positive constant and other variables are same as used in Eq. (2). In [112], a primary control based on decentralized droop control for MTDCMG structure is proposed. This control method is based on custom droop characteristics achieved by combining concepts of droop and DBS approach. Here, elements connected to the DCMG structure are categorized into three types of droop, i.e. bidirectional droop, Pseudo-critical droop and critical droop.

DBS scheme is employed by measuring the voltages at local coupling points. Numerous DC voltages are predefined to decide the operation modes. Based on energy sources which are responsible for establishing the DC bus voltage, three operation modes are normally utilized: Utility dominated mode, Storage dominated mode and generation dominated mode.

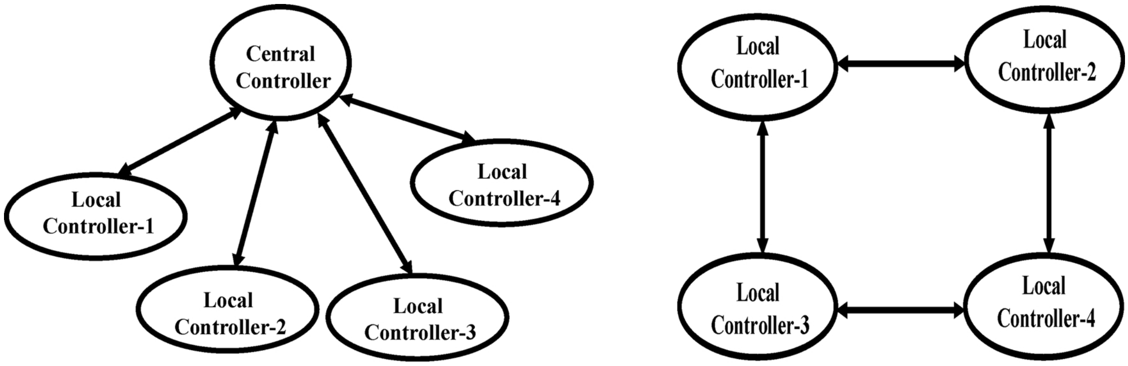
The active load sharing methods mainly include master slave control, Droop control, average current method and circular chain control. Master slave control is mostly employed in the centralized DC system with small scale, such as DC electrified aircraft, DC server systems, etc [117,131].

In this control strategy, the controller on every converter contains two modules, i.e. the voltage controller and the current controller. The voltage controller uses a cooperative observer to estimate global voltage and estimated data is used for boost the local voltage set point to achieve the global voltage regulation. The current controller compares the current with its neighbours and on the basis of it, modifies the local virtual impedance to carry out proportional load sharing. For load sharing through droop control method a supervisory control is recommended to improve the accuracy in estimation of global voltage and consequently accurate load sharing [128,163].

Current control is a basic function used for switch mode power supply. Previously, peak current control has been used for current control in DC to DC converter because of its robustness [164,165]. But due to its drawbacks such as low noise immunity, peak to average current error, variations in ripple current with the input and output voltages, slope compensation required etc. many authors proposed average current control [166], which operates by comparing inductor average current to the required set current. Due to complexity increased in power system and loads, Later it is found that average control has also limitations such as limitations in switching frequency. Then some authors proposed nonlinear current control scheme for current control [167,168], with the claim of no limitation on switching frequency. This control method includes advantages of both, i.e. peak current control method and average current control method.

The circular chain control method has been proposed to enhance the reliability and resilience of the system. This method formed a control ring, by taking current reference of one module from other module. In order to form a ring, the current reference of first unit is acquired by that of the last unit. Due to its circular communication structure its fault detection and isolation capability enhanced [169].

3.2.2.2. Secondary level control. It is a second layer of control in a hierarchical control structure which is responsible for restoring the voltages of DC buses to the nominal value. Conventional secondary level control has been performed by the MG central controller, which is



(a) (b)

Fig. 19. Communication topologies (a) Traditional Central control (b) Distributed control.

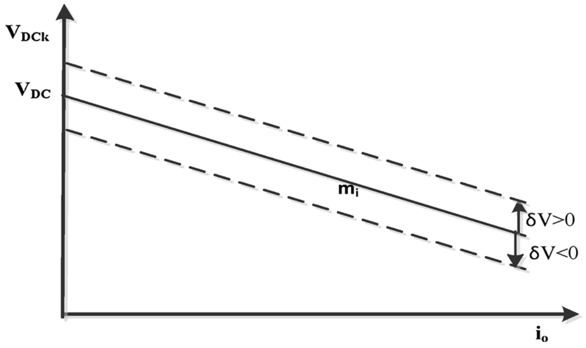


Fig. 20. Droop Shift in voltage restoration control with secondary control loop.

based on LBC to exchange control information. It is considered less reliable because of its well-known drawback of single point failure. To mitigate this, the distributed control for secondary level control has been proposed which uses LBC for exchange information among the units of the MG. The distributed controller mitigated the drawback of central controller, i.e. single point failure, but it is failing to address the effect of line resistance in the system. The LBC is more effective to be utilized the secondary control structure. It can be implemented by using a CAN or PLC [135]. Communication topology for centre controller and distributed controller is presented in Fig. 19 respectively [170]. A. Ingle et al. [171] proposes a distributed secondary controller based on quality index claiming that it achieves the objective of reduction in both current sharing error and voltage regulation for all the converters with reduced cognition in communication because this algorithm does not requires the knowledge of system parameters.

To wipe out voltage deviation caused by primary level control, i.e. droop control, a secondary voltage control loop is usually applied. This controller allocates legitimate voltage set point for essential control of every converter to obtain global voltage regulation. To obtain global voltage, secondary control exertion changes the voltage reference of local units by sifting the droop line up or down, regulating the voltage to the nominal value [127,162] as shown in Fig. 20.

Appropriate current sharing is a very desirable feature for operation of MG to avoid circulation current and overloading of the converters. To enhance the current sharing accuracy another secondary control loop is utilized [151,172]. There are two ways that this current converter improves the current sharing accuracy: 1). It creates another voltage correction term, δV_c to be added in the droop control system, Fig. 21(a) and 2) It modifies the virtual impedance, Fig. 21(b) [163].

In this method, the secondary current controller generates δr_c to adjust virtual impedance. Corresponding equations are given below.

$$V_{DCk} = V_{DC} - r_c i_o + \delta V_c \tag{6}$$

$$V_{DCk} = V_{DC} - (r_c - \delta r_c) i_{ok} \tag{7}$$

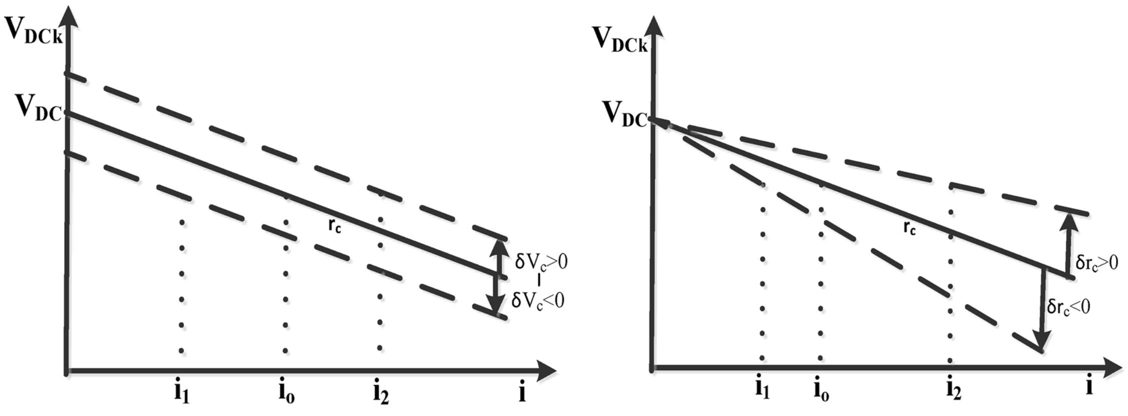
Where, δV_c is Voltage correction term for converter generated by secondary controller, r_c is Virtual impedance of the converter, δr_c is Virtual impedance correction term and other variables are same as used in Eq. (2). Though the secondary control guarantees proportional current sharing, it might inversely affect the voltage regulation. So there would be trade-off between voltage regulation and current sharing accuracy.

3.2.2.3. Tertiary level control. This is considered as third and the last layer of control in a hierarchical control structure which manages the power flow among the MGs and utility grid. The fundamental role of tertiary controller is management of power and energy with determined objectives such as coordination of energy storage devices, minimization of operation costs and minimum power flow losses [152,173–175].

3.2.2.3.1. Power flow control. Power flow analysis plays important role in the design and planning of a MG system to power flow control and protection. It also provides assistance to the optimization algorithm and power loss minimization. Although it requires wide computation and collection of global information, offers necessary information for system operators to safe operation [176].

The Newton-Raphson method and its extended version provide relevant power flow analysis for DCMGs. Features of power flow analysis of DCMGs are similar to the HVDC systems [177]. Various power flow algorithms and strategies for DCMG have been proposed and demonstrated [178,179].

3.2.2.3.2. Power and energy management. In MGs, the expressions "energy management" and "power management" are distinct considering control tasks and time scale. In energy management strategies, main factors are capital cost, fuel cost, maintenance cost, the lifetime of the systems, etc. while in power management strategies, key parameters are current, voltage and power, which affect the instantaneous operational conditioning. Power management is the concept of continuous adjustment of DC bus voltage by making the balance between the power generation units and power consumption units with the cooperation of energy storage system and utility grid (if grid connected).The energy storage system is the basic component of the system to operate MGs independently. In order to limit the cost and size of energy storage system, communication among the different component of the MG is important to do fast response which follows the power and energy management needs. Another consideration should be made on the load characteristics because different loads have distinct critical level. Centralized controllers are used to do this task, because



(a) (b)

Fig. 21. Droop Shift in Current sharing control with secondary control loop (a): By generating Voltage correction term (b): By generating virtual impedance correction term.

power and energy management requires global information [119]. Due to its drawback of single point failure some researchers have proposed distributed controller. Still, Distributed controller are not well mature to perform this task, lot of research is needed to make distributed controller suitable for tertiary level control [139,148,170]. More details on power and energy management have been discussed in section 4 & 5 respectively.

3.2.2.3.3. Optimization and scheduling. The objective of optimization is to minimize the operating cost of the MG. System operating cost can be divided into fixed and variable cost. Fixed cost incorporates the cost of installation and maintenance cost of the system while variable cost refers to the cost that varies with the accumulated output of the system such as fuel cost. The power is supplied by programmable sources such as fuel cell and non-programmable sources such as wind and solar. In order to minimize operational cost, system unit with lower marginal cost (marginal cost refers to increment to increase generation of one unit energy) is allotted with higher use need, e.g. marginal cost of solar PV and wind is zero as no fuel charge should assign highest utilization priority. Centralized control is needed to perform the optimization procedure to dispatch the distributed generator. There are several methods have been used to solve the optimization problem such as deterministic methods, stochastic methods and preservation methods. Deterministic optimization methods and stochastic methods are popular and quite mature, but they suffer from drawback of convergence to local optima. To overcome from conventional methods, preservation methods such as Niching method have been introduced [120,180]. Generally, Islanded operation capability of MG is a desired attribute of MG. So, the pre-store of energy and schedule utilization of energy sources are essential. The power and energy scheduling is basically an optimization based decision making process, keeping a rough prediction of future conditions such that weather, energy availability and load. Taking motivation from conventional power systems, a multi-level management is normally adopted with Unit commitment (UC) and Economic dispatch (ED) [179].

Though, higher complexity and need of global information limits the applications of tertiary optimization and scheduling, some researchers carried out their research to solve this issue with the appropriate formulation of optimization problems [181]. L. E. Zubi et al. [182] presented an optimization concept for minimization of the size and cost of energy storage system, in which author emphasised on importance of fast response of communication for optimum energy and power management. In [183], a scheduling for efficient charging of EV has been discussed. Here, the author discussed the appropriate time for charging of electric vehicles and absorbing the grid power at reduced operating cost.

3.3. Stability and dynamic response of DCMG control

A Typical cause of instability in DC Microgrid is impedance mismatch between lightly damped filter on the source side and tightly regulated power converters on the load side. Stability analysis becomes important when constant power loads (CPLs) are connected to the DC bus because of its impact of negative impedance. In practice, Speed regulated motor and electronics loads come under this category [111,123]. One of the most critical issues of the DCMGs is remain steady after subjecting a large disturbance such change in loads, witching of operation mode and short circuit faults. So, for safe operation of MGs in all operating modes, dynamic behavior and transient stability of DCMG is important [184]. Models of individual parts can be assembled into full system model. Generally, any system model is divided in two subsystem models for analysis purpose: Source subsystem and load subsystem. Analytical expressions of output impedance of source subsystem (Z_S) and input impedance of load subsystem (Z_{in}) are derived. Dynamic behavior of the system can be observed by looking the ratio (Z_S/Z_{in}). In order to protect the system stability, the ratio (also refer to minor loop gain) should meet the Nyquist stability criteria [66]. Small Signal models and State Space approach are available methods for system analysis [185,186]. Some authors have developed few stability improvement strategies which are categorized passive and active strategies. In passive strategies, resisters are added with respective inductors and capacitors in series/parallel to meet the impedance criteria. Active strategies are performed by introduction of linear feedback loop (for small signal stability) and nonlinear controller (for large signal stability) [66,184].

L. Guo et al. [186] developed a small signal model in z plane considering the discrete sampling and control algorithm in digital system. Then, they describe the stability problem of this DCMG with master slave control. Results of simulations show that system stability and dynamic/transient response is affected by DC load parameters and no. of slave DGs.

M. V. Gururaj et al. [187] proposed a decentralized coordinated voltage control scheme for a distribution system consisting of a DCMG. The proposed scheme is implemented in modified 33 bus distribution system. Its steady state and dynamic response are analyzed through real time digital simulator (RTDS) and hardware results. *J.* A. Belk et al. [188] design an ad hoc DCMG and proposed a decentralized control to achieve a coordinated power dispatch from each sources. To find out the asymptotically stable equilibrium point, they applied some control techniques such as Brayton Moser potential theory and primal dual dynamics.

J. Xiang et al. [189] simulated a DCMG with four buck converters and its stability with distributed cooperative control is investigated. They also described its two semi stable conditions. C. Dong et al. [190] perform the stability analysis of a distributed control to eliminate the DC bus voltage deviation considering time delay. A neutral delay system model is developed; by applying neutral linear matrix inequality (LMI) stability criteria, time delay stability analysis is performed. Some authors perform the stability analysis of DCMG of distributed control with constant power loads (CPLs) [110,191].

C. Dong et al. [192] discussed about the instability in hierarchal control caused by the time delays during signal transfer from one level to other level. Then, they proposed a small signal stability model to determine the maximum delay time for a HESS to retain its stability.

3.4. Case study

A case study of Lab set up of Laboratory DCMG for Renewable Energy Systems (LARES) has been studied [193]. The control of DCMG has some limitations such as overload of MG components which can affects life of components. To avoid such limitations, it is necessary to detect the cause of limitations, for that dynamic analysis is required. It's simulation for decentralized, centralized and distributed control configurations is realized through droop control and results for dynamic

Table 2
DCMG Components.

DCMG Components	Components Ratting	Interfacing Converter
Photovoltaic Array	$P_{MPP} = 1520\ W_p$, $V_{OC} = 119.2\ V$, $I_{SC} = 16.7\ A$	DC/DC Buck Unidirectional
Fuel Cells stack	$P_{FC} = 500\ W$, $V_{FC} = 30\ V$, $I_{FC} = 30\ A$,	DC/DC Boost Unidirectional
Battery bank Stank	$V_{OCn} = 48\ V$, $C_{10} = 200\ Ah$,	DC/DC Buck-Boost Bidirectional

Where, P_{MPP} = PV Array power at maximum power point, V_{OC} = PV array open circuit voltage.

I_{SC} = PV array short circuit array, P_{FC} = Fuel cells stack maximum power, V_{FC} = Fuel cells stack voltage.

I_{FC} = Fuel cells stack current, V_{OCn} = Nominal open circuit voltage.

C_{10} = Capacity when battery stack is discharge in 10 h.

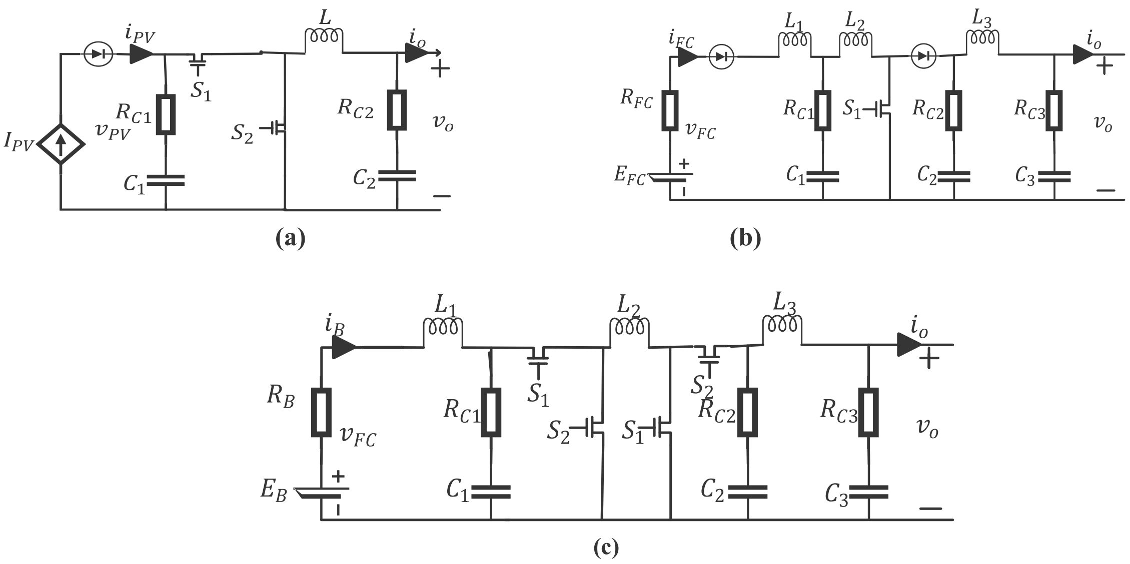


Fig. 22. Equivalent Electrical Models (a). PV array with DC/DC buck converter (b). FCs stack with DC/DC boost converter (c). Battery bank stack with DC/DC buck boost converter.

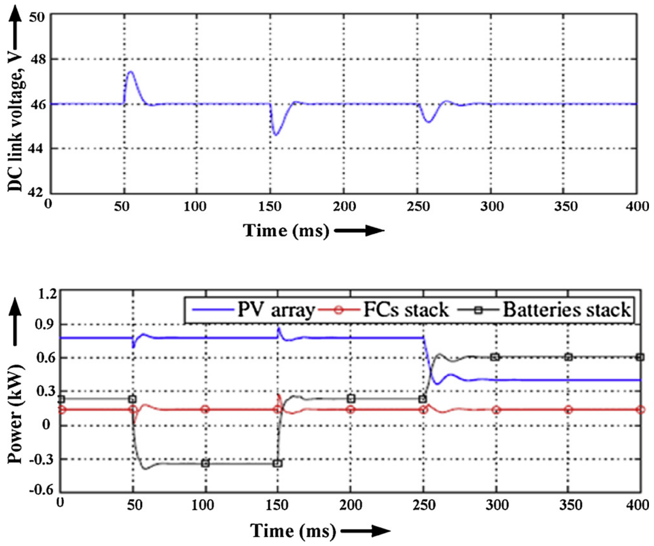


Fig. 23. Dynamic response of Centralized control.

behavior has been analyzed.

3.4.1. Components of DCMG

DCMG components with rating capacity have described in Table 2.

3.4.2. Modeling of DCMG system

a *PV array with DC/DC buck Converter*

PV array can be modeled as with an irradiance-temperature-voltage dependent current source. Equivalent electrical circuit model is shown in Fig. 22(a).

- *Fuel cells stack with DC/DC Boost Converter*

Since controlled fuel cell current is permitted to change gradually, the fuel cell voltage also changes gradually (According to V-I characteristics). So, Fuel cells stack can be modelled as constant voltage source and internal resistance. Equivalent electrical circuit model is shown in Fig. 22 (b).

- *Battery Bank Stack with Buck Boost Converter*

The battery bank stack can be modeled as equivalent constant voltage source with internal resistance. Both these parameters mainly depend on battery SoC. Equivalent electrical Circuit model is shown in Fig. 22(c).

3.4.3. Simulation based dynamic behavior analysis of different control of DCMG

In order to perform the dynamic behavior analysis of DCMG, first dynamic behavior of each component is analyzed independently. It is concluded that in input current control mode, fuel cells stack duration is quite large due to current rate limiter and in output voltage control mode fuel cells stack shows poor performance in regulating the output voltage. Although some assumptions have been considered, i.e. do not considered technical constraints such as DC link voltage deviation.

Simulation conditions are same for both the control configurations (distributed and centralized). DCMG first brought to a steady state, and then two abrupt load changes are applied.

$$R_L = \begin{cases} 2\Omega, & t \le 50ms \\ 4\Omega, & 50ms \le t \le 150ms \\ 2\Omega, & 150ms \le t \end{cases} \tag{8}$$

Followed by solar irradiance halved from t = 250 ms onward.

3.4.4. Centralized control

A master slave control technique is implemented to control the DC link voltage. Battery bank stack operate as master, regulate the DC link voltage. Other units such as PV and FCs operate in current control mode to inject constant power in DC link. Dynamic response of centralized configuration is shown in Fig. 23, whereas virtual output impedance used for (R_D = 1 Ω) used for battery bank stack. This configuration is considered better configuration compare to above discussed configurations in voltage regulation point of view. However, this configuration is more proms to failures since only one unit regulates the DC link voltage and leads to reduce life spam of Battery bank stack.

3.4.5. Decentralized control

All the system units (PV, FCs stack, Battery bank stack) participate in voltage regulation of DC link voltage without a need for intercommunication links between units. Due to absence of communication, system reliability improves without restricting the location of the units.

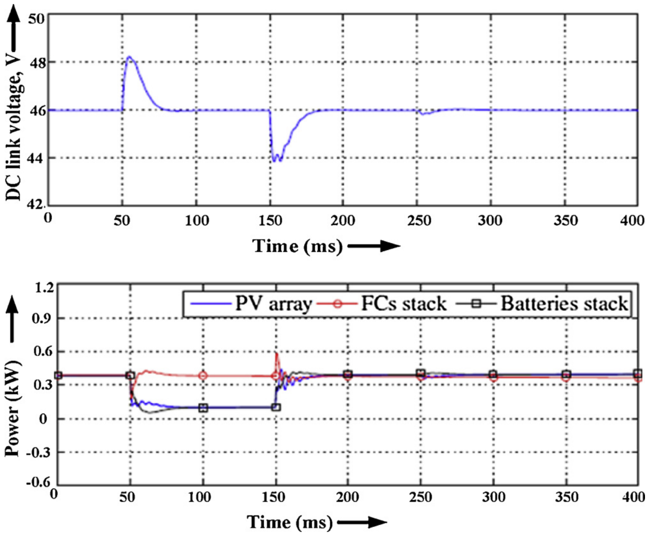


Fig. 24. Dynamic response of decentralized Control.

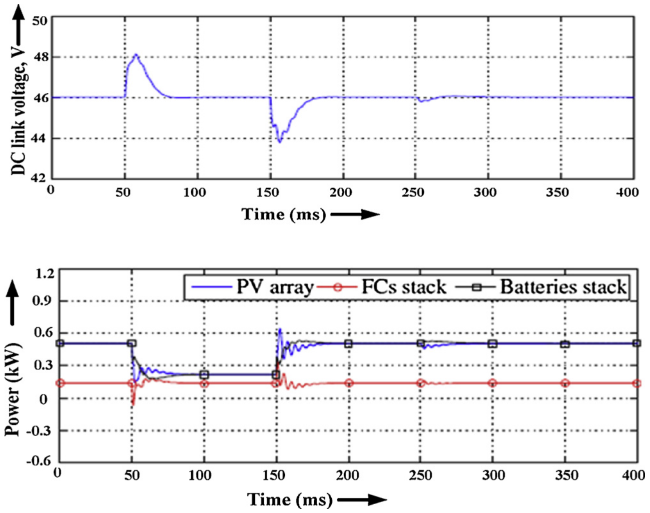


Fig. 25. Dynamic response of Distributed control.

Contribution of each unit depends on droops of the units (virtual output impedance). Dynamic response of decentralized configuration is shown in Fig. 24, whereas virtual output impedance used for (R_D = 1 Ω) all the units.

3.4.6. Distributed control

Only two units (PV and Battery bank Stack) are permitted to participate in voltage regulation of DC link. Fuel cells stack allow to injecting constant power into DC link. Dynamic response of distributed configuration is shown in Fig. 25, whereas virtual output impedance used for (R_D = 1 Ω) PV and battery stack.

4. Power management

In DCMGDGs units such as PV and wind are used to provide clean energy, while energy storage devices are used to compensate power fluctuation between power generation and load consumption. The primary goal of power management is to enhance the dynamic response of DCMGs under different load conditions. There are some essential requirements of MGs such that since MGs operate in both modes, i.e. Grid connected and Islanded mode, so smooth transition between Grid connected to Islanded mode and vice versa is required, second one is maximum utilization of RESs, which is intermittent in nature, another one is MG should be compatible when some device connected or disconnected into/from the system without losing its stability. All above discussed issue can be solved by proper power management [6,73,134]. In other words, proper power management is the need of technical support, i.e. safe operation and economical support, i.e. Maximum utilization of RESs for the DCMG System. In grid connected DCMG system operation, the power fluctuations are managed by both grid connected and ESDs to maintain balance between power generation and load. However, in standalone operation, the power fluctuations are managed by only through ESDs [7]. Power management strategies can perform through different control strategies such as centralized, decentralized, distributed and hierarchal control. Various power management strategies in grid connected as well as islanded mode have been discussed with their one application.

- Centralized Control: A. G. Tsikalakis et al. [119] developed a central controller based optimization algorithm for the low voltage distribution networks. The purpose of optimization during interconnected operation is to maximize power exchanges with the main distribution grid and optimize the generation of local DGs. The proposed algorithm is developed by considering two market policies, i.e. realistic spot market prices and DG bids reflecting realistic operation costs assumed by demand side bidding options for controllable loads. The developed algorithm is applied in a typical LV network operating under various market policies and its effect on the distribution network operation are presented and discussed.
- Decentralized Control: Q. Xu et al. [194] proposed a simple decentralized scheme to solve issues related to a hybrid energy storage system in DCMG such as effective power split, bus voltage deviation and SoC violation. A high pass filter based droop controller to regulate the battery converter (HPFD) and a virtual capacitance droop controller (VCD) for a supercapacitor (SC) converter is proposed. Through cooperation of HPFD and VCD, power fluctuations are managed. High frequency power fluctuations are managed by SC and low power fluctuations are managed by battery. The proposed decentralized control scheme is validated through simulation and hardware results.
- Distributed Control: D. –H. Dam et al. [139] proposed a power distributed control method to share the load power proportionally according to distributed source ratings. Based on distributed generators instantaneous power, a voltage shift is obtained and this is added to the DC bus voltage to compensate the voltage drop caused by the droop controllers and maintain DC bus voltage constant regardless of load change. The required information is transmitted through LBC. The proposed method is verified by 2.8 kW prototypes.
- Hierarchical Control_Two Levels: X. Lu et al. [172] proposed a two layer hierarchical control strategy: droop control for load current sharing at primary level and LBC based distributed control to enhance the current sharing accuracy at secondary level in DCMG. The proposed strategy is verified by implementing on 2 x 2.2 kW prototype.
- Hierarchical Control_Three Levels: X.Yu et al. [158] proposed an SST enabled hierarchical power management strategy. The authors claim that this is the first time when SST enabled MG system is presented. The functions of each level are assigned, i.e. to local control, DC bus voltage recovery and manage the battery state of charge for the primary, secondary and tertiary respectively. The DCMG can reliably operate in islanding mode by primary control and seamlessly transferred SST enabled mode through secondary control. To verify system performance, a hardware setup has been constructed.

4.1. Grid-connected mode

This mode refers to the utility grid connection operation through the G-VSC. In the grid connected mode of operation, the DG MG dynamics such as voltage regulation and power balance are controlled by energy ESS and utility Grid. The G-VSC limits the power exchange between the DCMG and utility grid. In this mode of operation, DGs always operate at MPPT. As discussed earlier that power management is the strategy that maintains balance between power generation and load demand. So there will be two conditions, either power generation is more or load demand will be more. Both two cases are discussed below [74,116,195].

***Case – 1*:** Power generation is more

If the power generated through connected DGs is more than the load demand, then excess power will be transferred to ESS where it will be utilized to charge the ESDs.

$$P_{Excess} = \sum P_{DGs} - \sum P^{Loss} - \sum P^{Load} = \sum P_{ESDs}^{ch\,arg\,ing} \tag{9}$$

Since ESS has limited charging capacity (I_{max}) and storage capacity (SoC_{max}), if ESDs reached its full charging capacity or storage capacity then the excess power will delivered to the utility grid via interlinking converter (IC).

$$P_{Deficiency} = \sum P_{DGs} - \sum P^{Loss} - \sum P^{Load} = \sum P_{Grid} \tag{10}$$

***Case – 2*:** Power demand is more

If the load demand is more than the power generation then this deficiency of power will be supplied by ESS through bidirectional DC to DC converters.

$$P_{Deficiency} = \sum P_{DGs} - \sum P^{Loss} - \sum P^{Load} = \sum P_{ESS}^{disch\,arg\,ing} \tag{11}$$

But in such situation when power demand is so high that cannot fulfil by the ESS then remaining power will be supplied by grid through IC.

$$P_{Deficiency} = \sum P_{DGs} - \sum P^{Loss} - \sum P^{Load} + \sum P_{ESS} = \sum P_{Grid} \tag{12}$$

A. J. Datta et al. [196] proposes a method to connect DCMG with the utility grid. Two converters are proposed: one is interlinking converter (DC to AC) and other is DC to DC converter. They are connected in cascaded manner. Interlinking converter maintains the DC bus voltage constants and DC to DC converter draws the desired amount of power from the utility.

4.2. Islanded mode

This mode refers to disconnection with the Utility grid. In Islanded mode of operation, The DG MG dynamics such as voltage regulation and power balance are controlled by energy storage system only. As above discussed, power management is the strategy that maintains balance between power generation and load demand. So, in this mode, it is not necessary that all the DGs always operate at MPPT. Here will be two possible conditions too [116,130].

***Case – 1*:** Power generation is more

If the power generated through connected DGs is more than the load demand, then the surplus power will be transferred to ESS where it will use to charge the ESDs.

$$P_{Excess} = \sum P_{DGs} - \sum P^{Loss} - \sum P^{Load} = \sum P_{ESDs}^{ch\,arg\,ing} \tag{13}$$

As discussed earlier, ESS has limited charging and storage capacity. So, if ESDs are reaching its full charging capacity or storage capacity, then we have to limit the generation according to SoC conditions.

***Case – 2*:** Power demand is more

$$P_{Deficiency} = \sum P_{DGs} - \sum P^{Loss} - \sum P^{Load} = \sum P_{ESS}^{disch\,arg\,ing} \tag{14}$$

But it may be a possible condition when power demand is so high that cannot fulfil by the ESS alone or SoC of ESS is too low. So in this case we have to cut down some loads to maintain power balance and system stability of the system. That should be done on the noncritical priority of a load basis. Therefore, a proper load shading scheme is required for Islanded operation of DCMG.

4.3. Power management for the duration of transition between grid-connected and islanded operation modes

The transition between grid-connected and Islanded operating modes should be smooth, so that voltage disturbance and in the DCMGs system would minimum and guaranteeing balance power flow between different units of the DCMG. Islanding detection algorithms for DCMGs are very necessary for guaranteeing a smooth transition between Grid connected and islanded operation modes. Here, power management at two different transition modes: from Grid connected to an Islanded operation mode and Islanded to grid connected operation mode is discussed separately.

4.3.1. Transition from grid-connected to islanded mode

It is further divided into two categories, namely, 1) Switch of the control strategy from the current control mode in grid connected operation to the voltage control mode in Islanded operation. 2. Uniform control in both grid connected operation as well as Islanded operation.

4.3.1.1. Switch of control strategies from current control mode in grid connected operation to the voltage control mode in islanded operation. DGs are operating in current control (MPPT operation) mode in grid connected operation mode to inject power into utility grid, while they operate in voltage control mode in islanded operation mode to share the load demand among the voltage controlled DGs. Different control strategies are used to switch between these two controllers [197].

Different authors have proposed various schemes for smooth transition from grid connected to islanded operation mode [198–201]. Some authors proposed scheme, which requires DC line current reduced to zero before switching to islanded mode [198]. In contrast, some authors proposed schemes, in which transition operation can be implemented without reducing DC current zero. Although it is fast transition, but it requires careful coordination among the DCMG units to avoid voltage spikes during transition [199]. Islanding detection algorithm is required to detect the disconnecting time instance which is utilized to switch the MG controller from grid connected to Islanded mode [202].

4.3.1.2. Uniform control in both grid connected operation as well as Islanded operation. The power management and control strategies are same in both modes of operation: grid connected and islanded. So, modifications in control strategies during transition are not required. A proper robust controller still is a challenge for researchers. Some robust scheme has been proposed in which it is recommended that small DGs should operate as current control mode (MPPT operation) in both grids connected and islanded operation modes. And larger DGs should operate in a voltage control mode to avoid control transients. Some modifications should be done with the voltage control strategies to implement in grid connected, islanded and transient operation modes. In these types of power management strategies, islanded detection algorithm is not required for the transition purpose but it should be employed for better control performance [203].

4.3.2. Transition from islanded to grid-connected mode

As discussed above in transition from the grid connected to Islanded operation mode, it also be done by two groups of control strategies: Switch of control strategies from voltage control mode to current control mode or uniform control in islanded operation as well as grid connected operation modes. Here, one additional important task is that the DCMG voltage should be synchronized with the grid voltage before reconnection. There are two types of synchronization methods are used: passive synchronization and active synchronization. Passive synchronization is performed by monitoring the DC bus voltage and it is connected when its voltage is same as grid voltage. It is the most used practical method so for [204,205]. However, it leads some transients in the system. Active synchronization is performed by proper coordinating DGs and ESDs [206]. General criteria for selecting the synchronization method is that when all DGs are operating in a voltage control mode active synchronization is utilized, when some DGs are operating in a current control mode, the passive synchronization method is utilized.

5. Energy management

In a grid connected DCMG systems, energy management is not a big issue because energy unbalance between distributed generation and load can be supplied/absorbed by the utility grid through a bidirectional IC. While, energy management plays very important role in Islanded MG systems as maintain DC bus voltage, power quality and continuous supply to the load. There are many control strategies have been developed to manage the energy in DCMGs in grid connected as well as islanded mode of operation. These Energy management strategies can perform through different control schemes such as centralized, decentralized, distributed and hierarchal control. Various energy management strategies in grid connected as well as islanded mode have been discussed with their one application.

- Centralized Control: C. Chen et al. [120] proposed a Smart Energy Management System (SEMS) to minimise the operation cost of MGs by optimally coordinate the power production of DG sources and ESS. The authors considered all the relevant technical and economic constraints, i.e., power forecasting, management of ESS, economic load dispatch and operational costs, to development the system. The SEMS consists three modules to perform different task, such as forecasting module for the study different weather conditions and forecast the power one day ahead, Energy storage system management module performs the optimal operation accordingly multiple time set points of the storage device and a matrix real coded genetic algorithm optimization module is described to achieve load management.
- Decentralized Control: J. P. Torreglosa et al. [207] developed a decentralized energy management system strategy for electric vehicle charging station to regulate the energy flow among Photovoltaic Solar Panels, Batteries and Grid. The DC bus voltage is the key parameter for controlling the system. Model predictive controller controls the battery SoC in order to keep the bus voltage at its reference value. SoC of battery decides the mode of operation of PV i.e. Maximum power point tracking mode, Bus voltage sustaining mode or grid support mode.
- Distributed Control: S. Boudoudouh et al. [145] presented a multi-agent system solution for the management of the hybrid energy storage system. A new architecture using multi-agent system solution is proposed to supply vital and sensitive loads. The system simulation is performed by MATLAB SIMULINK, required calculation is done by JADE. And the communication between JADE and MATLAB SIMULINK is supported by MACSIM JX.
- Hierarchical Control_Two level: T. R. Oliveira et al. [151] proposes a secondary distributed control based on virtual droop resistance to achieve two purposes such that charge/discharge control and SoC equalization simultaneously. SoC imbalance compensation alters the energy storage unit virtual droop resistance according to the difference between the unit SoC and microgrid average SoC. This control is very suitable for the DC bus signalling controlled MG because of the dependency of compensation on the SoCs.
- Hierarchical Control_Three level: J. Xiao et al. [150] proposed a three level hierarchical HESS to remove the bus voltage deviation and power sharing error. Distributed control is scheduled for primary control. Bus voltage restoration and power sharing error compensation is provided by secondary control. Tertiary control limits the SoC variation of ES with high ramp rate. The proposed method enhances the system reliability because it is independent from the communication. The proposed method is verified by a lab scaled DCMG model.

5.1. Energy management system (EMS)

The power losses of the storage devices, state of charges and their response times, the power-energy limitations and in some cases predictions of the power generated by the DGs are a portion of the ideas that must be considered by the EMS. It has several significant roles that are illustrated below [14,51–53,120,150,180,208].

1 Efficient management of ESDs to minimize the size and rating of ESS and power conversion units, reduce the charging and discharging frequency of ESDs; improve the life of Storage devices and maintain the power quality.
2 Full utilization of DGs and ESS to continuous supply to the load and minimum operating cost.
3 Keeping DC-link voltage constant under normal operation fast regulation under capricious changes of distributed generations and loads.
4 Regarding to system reliability, EMS must guarantee system operation in all conceivable loading conditions and protect the ESDs from extreme conditions.
5 Reduced complexity of the system and proper scheduling.
6 Maintain system stability.

5.2. Management of energy storage units

Energy storage is an important component of DCMGs for the stable and reliable operation in the face of a fluctuating power generation and load. In Islanded operation mode, it is the only responsible unit which limits the DC bus voltage and maintain power quality. It acts as a buffer to store surplus energy and supply it back to the system when it is required [51].

MG net power which is decomposed into two parts: high frequency components and low frequency components. Power fluctuation in short duration is considered as fast frequency components, while slow power fluctuation is received as low frequency components. Slow power fluctuation should be handled by the storage devices which has high

Table 3
Characteristics of ESDs.

Energy Storage Devices	Energy Density (W.h/kg)	Power density (W/kg)	Response time	Efficiency (%)	Cost
Lead-Acid Battery	35–50	75–300	$< 10s$	60–80	low
Lithium-Battery	150–200	200–315	$< 10s$	85–95	medium
Super Capacitor(SC)	0.2–10	$10^2 – 5 \times 10^3$	$< 1s$	80–95	medium
Flywheel	40–230	$> 5 \times 10^3$	$< 1s$	70–80	high
Super conducting magnetic Energy Storage (SMES)	1–10	10^7–10^{12}	$< 5ms$	85–95	high
Compressed Air Energy Storage (CAES)	–	–	10s-4 min	60–70	medium
Pump Hydroelectric energy storage	–	–	1–10min	40–60	medium

capacity devices with low ramp rate while fast power fluctuation should be handled by the storage devices which has high power density and ramp rate. Unfortunately, there is no any single storage device (as discussed in Table 3) which can fulfil all required features for both types of power fluctuation components or it would be very expensive in order to meet all needs such as energy capacity, power density, ramp rate etc. with a one type of devices. Hybrid energy storage system has been coming up with the effective and economical solution that can include the advantages of all the energy storage systems. HESSs with different combinations of storage devices among battery, Super-capacitors, flywheels, super conducting magnetic storage system, etc. being discussed [209–211]. A battery Supercapacitor combination is considered as most preferred HESS because of various reasons such as their availability, relatively low cost, similarity in working principles and most importantly their complement attributes over each other's limitations; Battery has high energy density but limited ramp rate, while Super capacitor has high power density and ramp rate but low energy density (see Table 3) [14,51,43,211].

The energy management of the HESS influences the size, efficiency and life cycle of the storage systems. Therefore, the choice of an appropriate energy management scheme is crucial for the proper size the HESS and to get an optimised use of the entire system. The coordination of storage systems in HESS can be categorised on the basis of their connections as passive, semi-active and active topologies. In comparison, it is found that all types of topologies are application specific, but the overall Active topology of HESS is superior as it eliminates the match between the storage system's terminal voltages and DC common bus voltage. Furthermore, it provides the facility, so that the output power of storage systems can planned effectively to fully use their power and energy capacities [212,213].

It has been discussed that a battery and SC combination is the most developed HESS so far. Here, different topologies of battery-Super capacitor HESS are discussed. A passive connection topology of battery and Super-capacitor (SC) is the simplest and least expensive HESS topology as shown in Fig. 26 [51]. The battery and Super-capacitor are connected with the DC bus directly. It effectively handles the transient under pulse load conditions, increase the peak power and reduce the internal losses because of absence of DC to DC converters. They share a similar terminal voltage that relies upon the condition of- charge (SoC) and charge/discharge characteristics of the battery. The system current will be drawn from or feed into the battery and super capacitor on the basis of their internal resistances. Consequently, the Super-capacitor's transient power handling capability is not fully utilised. Moreover, since the voltage variation of the battery terminal is small, the Super capacitor won't be working at its full SoC which brings about poor volumetric efficiency [213].

To improve utilization of storage system components in passive HESS, power electronics converters are incorporated in between the ESS components and DC bus. This permits the power flow to be effectively controlled. In semi active HESS topology, only one component (Either Battery or SC) of the HESS is effectively controlled. The Super capacitor interfaced HESS topology is presented in Fig. 27(a). In this topology, the battery is directly connected to the DC bus and super capacitor is connected through a bidirectional DC to DC converter. So, The Super capacitor can be worked in a wider range of voltages, as a result, its volumetric efficiency will be enhanced. In addition, direct connection of battery to DC bus guarantees stable DC bus voltage [212–214].

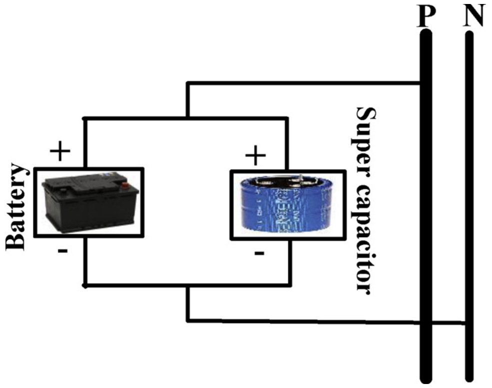


Fig. 26. Passive Battery-Super capacitor HESS topology.

Another configuration for semi-active topology is presented in Fig. 27(b), in which battery is connected through interfacing bidirectional DC to DC converter and Super capacitor is directly connected to the DC bus [214].So, battery power/current can be controlled smoothly as load fluctuation and need not to match the battery terminal voltage with the DC bus voltage. This topology is generally avoided due to its drawbacks such as less volumetric efficiency of Super-capacitor. And direct charge/discharge of it, additionally causes variation in the DC Bus, which may bring about poor power quality and system stability. To keep up relatively stable DC bus voltage, large capacity Super-capacitor will be required that leads high cost [212].

In fully active HESS topology, both battery and Super-capacitor are connected to the DC bus through interfacing bidirectional DC to DC converters. So the power flow in both battery and super capacitor can be effectively controlled. As a result, it improves the overall system performance and flexibility of HESS. Two configurations are possible for the active topology of HESS. First one as shown in Fig. 28(a) is called parallel active HESS topology, in which both battery and super capacitor are connected to the DC bus through DC to DC converters. Since the battery has high energy density, it programmed to handle slow power fluctuations and Super-capacitor has high power density so it is programmed to handle fast power fluctuations. Decoupled operation of battery and super capacitor permits both components of HESS to operate at a wider range SoC. Consequently, improves the volumetric efficiency of the HESS. Another configuration is known as cascaded active HESS topology. in which two bidirectional DC to DC converters are cascaded as shown in Fig. 28(b). The converter that connects battery is usually current controlled to give smooth power exchange [213–216].

The converter that connects super-capacitor to the bus is usually operates in a voltage control mode to regulate the DC bus voltage and deal with the high frequency power exchange. It relaxes the battery from charging and discharging process due to variation in output of DGs or variation in loads, as a result, it improves the battery life. This configuration is generally avoided because higher losses in DC to DC converter due large voltage variation in between super capacitor and DC bus [51,212]. *Y. Wang et al.* [217] proposed Markov random prediction for an active parallel battery - ultracapacitor based on fuzzy logic.

A typical HESS based EMS is presented in Fig. 29 for islanded DCMG applications. The EMS system can be separated into two levels: low level control system and high level control system. The low level control system regulates the DC bus voltage and on the basis of reference signal generated by the high level control system, it controls the current flowing in/out of ESS components. The high level control system performs the SoC monitoring and control and perform the power and energy management strategies to accomplish the set objectives.

One of the popular strategies to allocate the power among storage devices is the linear filtering strategy. Using the linear filters, the power reference for the components of the HESS is generated and based on their response times power is allocated. The low frequency power part is allocated to the high energy density device such as a battery and remaining power is supplied/ absorbed to the high power device such as super capacitor [218]. Because of the complex and nonlinear behaviour of the battery and super capacitor, simple power allocation strategies such as linear filtering are not adequate to allocate the power among the energy storage elements of HESS. Thus advance supervisory

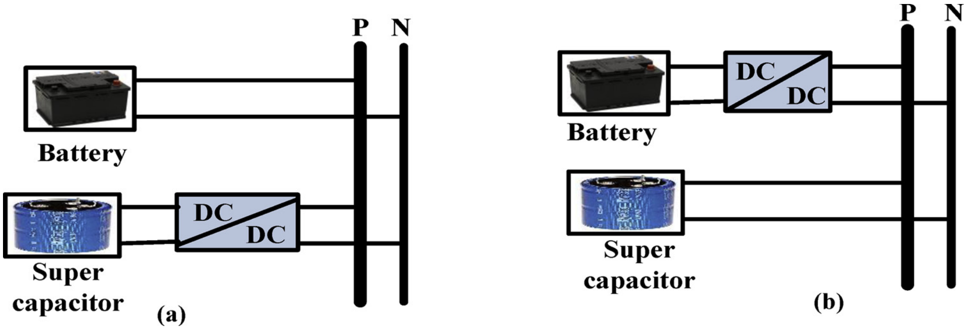


Fig. 27. Semi active topologies (a) Battery Semi active HESS topology (b) Super capacitor Semi active HESS topology.

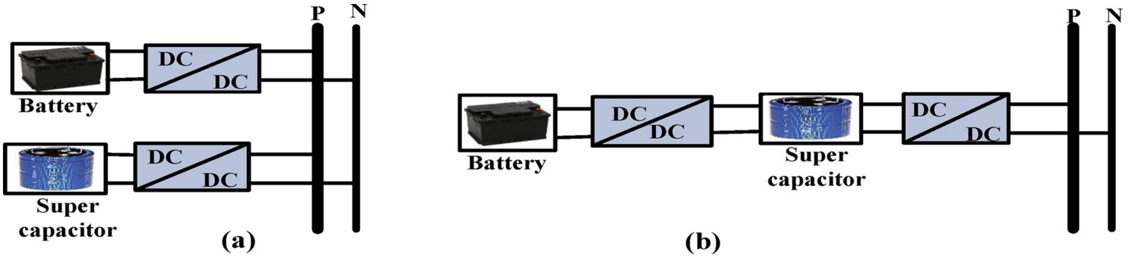


Fig. 28. Active topologies (a) Parallel Active HESS topology (b) Cascaded Active HESS topology.

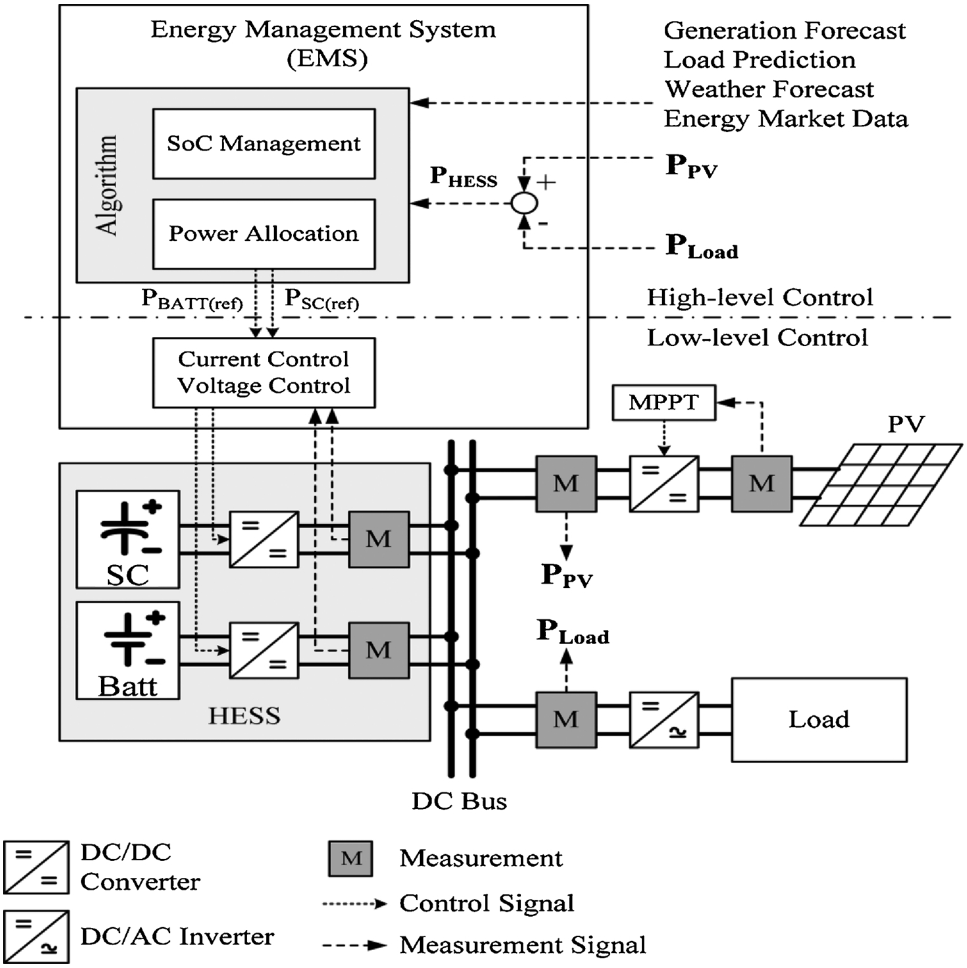


Fig. 29. A typical EMS for islanded DCMG with Parallel active HESS [51].

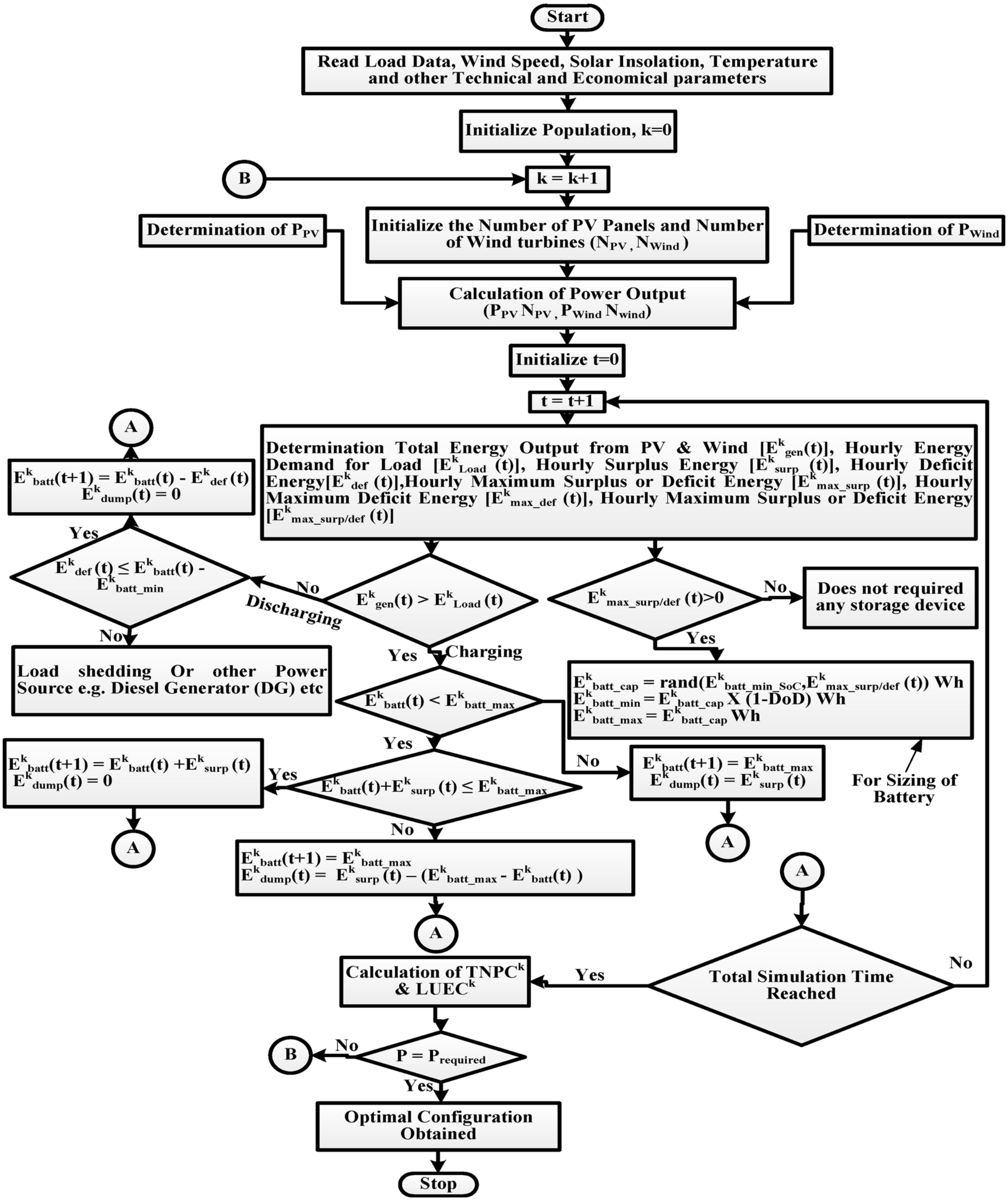


Fig. 30. Flow chart for determination of optimal size of PV, Wind and Battery.

strategies have been proposed. In general, all linear and supervisory power allocation EMS strategies can be divided into groups: Rule based control strategies such fuzzy adaptive, power follower, etc. and optimization based control strategies such as linear programming, optimal predictive etc. [219]. The rule based EMS control strategies are widely used because of its simplicity and reliability [220,221].

In spite of the fact that there are numerous technical and economic differences among the different topologies, there is not a unique solution for all the applications of HESS. To select the best topology for particular application is the matter of analysis on the basis of their pros and cons in technical and economic grounds. Sizing of Hybrid Energy system component has attracted my researchers and they proposed various topologies/strategies for determination of it [13,222–226]. Optimum size of components yields a reliable operation, lowest cost system and minimum load rejection. B.Tudu et al. [222] presented a strategy for determination of optimal size of PV-Wind-diesel generator-Battery system components. A flow chart has been prepared for the determination of the size of components of the PV-Wind-battery hybrid system. Initially, a random number between maximum and minimum value of surplus/deficit energy is considered for the sizing of the battery. The hourly maximum surplus or deficit whichever is higher is considered as the reference value to decide the size of battery and converter. If the maximum surplus/deficit is directly chosen to size the battery, there will be chance of oversize of battery that result is increase in cost of the system.

The main algorithm begins with the initialization of population with various control variables with the random generation of solar PV panel and wind turbine and calculation of output energy from these sources for each step. The sizing algorithm operation is described with the help of flowchart in Fig. 30.

The system total net present cost (TNPC) and levelized unit electricity cost (LUEC) are considered as the selection criteria for the optimal configuration of the system. TNPC and LUEC are defined as given below.

$$TNPC = IC + PWc_{rec} + PWc_{non-rec} \tag{15}$$

$$LPEC = \frac{TNPC \times CRF}{\sum_{t=1}^{8760} E_{gen}} \tag{16}$$

$$CRF(d, \lambda) = \frac{d(1+d)^{\lambda}}{(1+d)^{\lambda} - 1} \tag{17}$$

Where, IC = Investment Cost,
PWc_{rec} = Recurring Cost in PV and Wind system,
$PWc_{non-rec}$ = Non Recurring Cost in PV and Wind system,
CRF = Capital Recovery Factor,
E_{gen} = Energy generated from PV and Wind system,
d = Rate of Interest, λ = Inflation rate

6. Discussions and future trends

Many papers has been reviewed related to DCMG structures, Control methods used in DCMG, power and energy management, storage devices and its sizing are explained along with following observations.

- Power system structure influence many other things such as cost of the project, robustness, resiliency, reliability, flexibility, scalability, controllability and hierarchy of the system. Six types of MG Structures, namely, Single bus DCMG structure, Multi-bus DCMG structure, multi-terminal DCMG structure, Ring-bus DCMG Structure, Ladder-bus DCMG structure and Zonal DCMG structure are discussed with their comparative analysis. All these structures are application specific and having their own drawbacks. Research work is needed to remove their drawbacks, introduce more redundancy and reduced complexity and develop standard structures for DCMG.
- Control objective along with different strategies have been discussed. Overall control is systematically classified into basic and multilevel controls. On the basis of the communication link, three basic control methods can be distinguished, i.e. centralized, decentralized and distributed control. In centralized control, data from the distributed units of DCMG is collected; processed and commands are sent back to them through DCLs. A popular centralized control, master-slave control strategy has been discussed in detail. Decentralized control is considered most reliable control scheme due to not requirements of communication links between different units of the system. Droop control strategy and DBS control Strategy have been discussed under decentralized control methods. In distributed control, the controller of each units exchange data with only its neighbors' units through available limited DCLs. Consensus and agent algorithms based control strategies are discussed in detail under distributed control methods. The realization of basic objective, such as voltage control, current control and power control as well as advance objectives: Power sharing between DGs, Power Quality control, provision of ancillary services, participation in energy markets, minimization of operating cost, etc. cannot be performed by a single controller, i.e. Centralized controller or decentralized control. So, in this scenario, multilevel control is considered as a standard control for DCMGs. Hierarchical control with its every layer's control role has been discussed in this paper. Conventionally, centralized control has been used in secondary and above level control, but due to its inherent drawbacks such as single point failure and complexity, some authors putted efforts to make distributed control suitable for higher level control in multilevel control methods.
- A lot of research work is needed to make distribution control effective for secondary and higher level control. And, mathematical analysis for distributed control strategies is still complex and challenging. Conventional small signal based linear control such as droop control, master slave control is suitable for local control, but for global control, they might be failing to produce appropriate results for MG applications. Nonlinear control such as fuzzy and neural based control, Lyapunov-Function-Based control and other high order control algorithms provide to possibility to relieve this problem. Nonlinear control strategies require still lots of research work to make them in real time implementation.
- Power management is the concept of continuous adjustment of DC bus voltage by making the balance between the power generation units and power consumption units with the cooperation of energy storage system and utility grid (if grid connected). Much research work is still needed management of power and Energy in MG cluster. The distributed secondary control with DBS power management in the DC distribution system might be the future trend. Robust control for power management strategies that work for all modes of operations; Grid-connected, islanded and transient mode, still suffering from many problems need to be solved. Invention of SST has made flexible DCMG integration with the utility grid, but it is still in early development stage and attracting many researchers.
- The power losses of the storage devices, SoC and their responses time, the power-energy limitations and in some case predictions of the power generated by the DGs are a portion of the ideas that must be considered by the EMS. Energy management plays very important role in optimizing the size and rating of energy storage system and their maximum utilization, improving its life and providing power to critical load.
- Different energy management strategies have been presented. The energy management of a battery super capacitor based HESS in all configurations with their pros and cons have been discussed in detail. It is found that simple power allocation control algorithms such as linear filters are not adequate for HESS system, nonlinear power allocation algorithms need to be developed more.
- Sizing of renewable energy system components is an important issue of hybrid energy storage system to develop it because it affects system cost. Most of the developed systems are over rated lack of a proper strategy to determine the system components. Although some authors have proposed different strategies for it, still it required a lot of works, i.e. hardware implementation of proposed strategies, Develop a generalized Algorithm/Strategy.

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