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A Review on DC Microgrid Control Techniques, Applications and Trends

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Abstract- The DC Microgrid concept has been flourishing in the recent times due to its intrinsic advantages like Renewable Energy Source (RES) compatibility, easier integration with storage utilities through Power Electronic Converters (PECs) and distributed loads. In-depth researches are going on in this field, as the concept of DC Grid can be considered as a master foundation in the realization of Smart Grid (SG) technologies. To achieve this, a number of constraints such as voltage regulation, islanding detection, allowable transient levels, etc. are to be met in accordance with globally accepted standards. The system should have a proper control scheme to keep the things reliable, fault-free and interoperable. In order to meet the constraints as per globally recognized standards, quite a few classes of control algorithms are adopted namely, Centralized, Decentralized and Distributed control. A standardized review of these control strategies is discussed as part of this work. A comparative study among these techniques is made so as to help a designer to choose the apt technique for controlling the microgrid.

Keywords DC Microgrid, Centralized control, Decentralized control, Distributed Control, Droop methods.

1. Introduction

The proliferation of Renewable Energy Sources (RES) makes the concept of Micro Grid (MG) reliable, resilient and cost-effective along with several eco-friendly benefits compared to the conventional utility systems. Among the conventional power generation and load demand, an immense gap arises at an annual load growth of 2.5% [1]. To integrate distributed generation, the concept of MG was revived by Lasseter R. H in the year 2002 as a low voltage distribution network [2-4]. These electric networks have the capability to work in both grid-tied and islanded conditions [5] depending on the consumer and utility conditions. The recent advancements in the field of Power Electronics (PE) [6] have made DC electric grid systems to meet the standards in a cost-effective and seamless manner. The DC MG paradigm paved way for extensive use of DC loads [7] for industrial as well as residential applications like Telecom stations [8, 9], Data centers [10, 11], Electric Vehicles (EV) [12], Electric ships [13], Renewable energy park [14-17], DC powered houses [18-21], Hybrid energy storage systems [22-27], Railways [28-31] and zero-net electricity energy buildings [32-35]. The various Energy storage devices were able to naturally interface with the DC microgrid system more effectively as compared to AC system [36, 37]. The evolution of DC microgrid paved the way for development and research of electric ship [38] and applications for smart and better charging of EVs [39]. Most of the present-day electronic equipment such as LED lamps, laptop/phone chargers, televisions, etc. need DC voltage levels for its operation. Currently, controlled AC-DC converters are used in the front-end sections of this electronic equipment to get DC voltage levels for its working [40].

The varying generation characteristics and intermittency of power delivered through RESs connected to a microgrid network require voltage leveling systems that are kept on the low voltage feeders through storage elements like Battery Energy Storage System (BESS), flywheel and Super Capacitors (SCs) along with the power electronic interfaces (PEIs) [41]. A Distributed Energy Resources (DERs) is defined as the combination of these entities. Fig.1 shows the schematic of a DC MG with RESs, battery unit, and supercapacitors. There are three different levels of control for DC MG as per the International Society of Automation-95 (ISA-95) standard [42], namely primary, secondary and tertiary levels of control. The primary level control aids in proper load power-sharing among two or more parallelly connected converter interfaces. The parameters for primary control are made by the secondary control, while the dispatching of storage and source is scheduled by the tertiary control, which is decided by the transmission and distribution system operators. The controller proposed in paper [43] is a modified PI controller to reduce transient and steady-state voltage oscillations and voltage ripples.

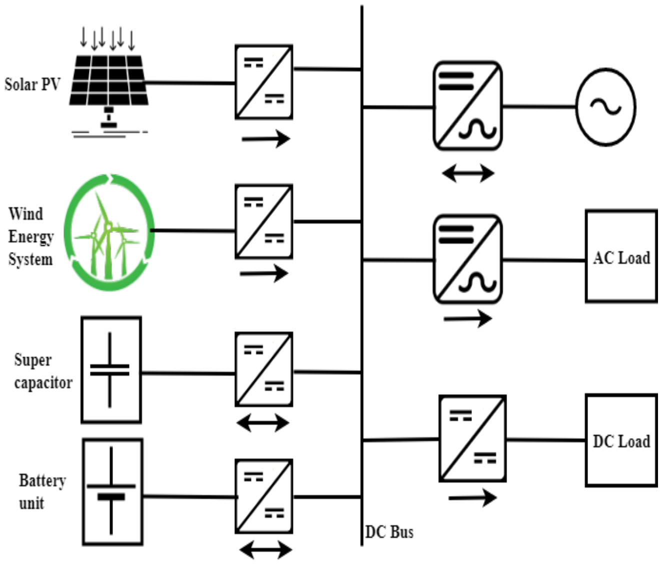

Fig. 1. A DC MG Structure

In an AC microgrid system, control operations require frequency control (P/f) and voltage control, where two control units are required which receives information from a hierarchical entity or supervisory control entity based on which control algorithm gets implemented to maintain system stability, reliability and operability. Whereas in a DC microgrid, control aspect boils down to a single entity rather than two different entities (Frequency and Voltage) in AC microgrid control. This indirectly makes distinction in implementation of control algorithms in DC microgrid as compared with AC microgrid based control systems. The aforementioned literature describes the principles behind these control techniques. A plethora of the existing MG control techniques by acknowledging some of the prominent applications, modeled by adopting both modern and classical control strategies are brought together in this paper; as a detailed and systematic extensive review is lacking. The ongoing development in DC MG is hence estimated with the help of this comprehensive review. Section 2 details a comprehensive survey of various control strategies adopted in DC MG. In section 3, a few miscellaneous functions of DC microgrid are presented. Section 4 throws light into various technical challenges in the DC microgrid. Finally, section 5 and 6 presents the discussions and future research trends with the conclusion.

2. Control Techniques for DC Microgrid

The DC Microgrid Control topologies as shown in Fig.2 plays a key role in the better, stable and efficient operation of DC MG. The power electronic converters act as an interface to properly control the grid with better voltage regulation and current sharing. They not only act as interfaces but also facilitate the proper interconnection among various units present in the DC MG. A better control strategy needs to be developed so as to reduce the non-linearity effect created by the power converters due to its constant power behavior. The rapid rise in non-linear loads and distribution generation made the control structure more complex which is inevitable too.

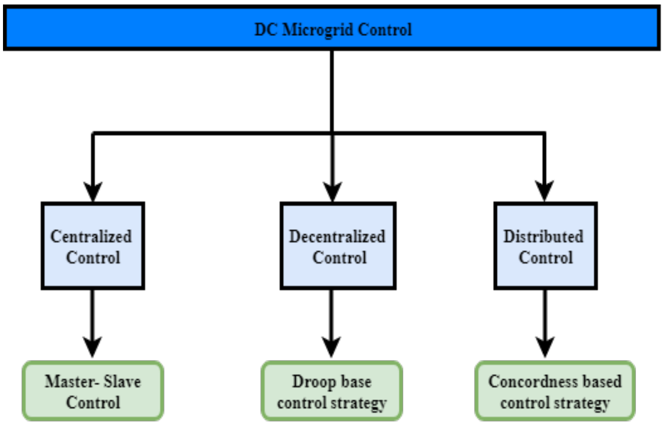

Fig. 2. DC MG Control strategies

The various control targets are [44]:

- Smooth switching from islanded to the grid-connected method of operation;
- Regulation of voltage and current sharing;
- Stable operation with non-linear as well as constant power load;
- Optimizing the Micro Source (MS) production to participate in the energy market;
- Controlling the power flow among MG and the rest of the network using an effective and proper Energy Management Scheme (EMS);
- Efficient load power-sharing and proper communication medium between DERs;
- Proper control mechanisms to prevent grid failure and potentiality to black start;
- Generation cost optimization and economic dispatching of loads;
- Maximizing the potentiality of DERs and reducing the transmission losses;
- Capability to provide uninterrupted power supply to critical loads like hospitals, industries, and other crucial utilities.

2.1. Centralized Control

The networked units [45] situated at a particular location achieve intelligence that is controlled by a microcontroller, switch or even a server. Communication is the core element of such a system, that helps in the easier operation of the centrally controlled system. The data from different units of a DC MG is initially collected by the system operator. Then, the collected data is processed and necessary control commands are transferred to them via a proper communication medium. Some of the advantages of the centralized controller are: strong controllability of the entire system, desires a single controller, the ability to define broad strategies for controlling the system and observability.

A Master-slave control as depicted in Fig.3 mechanism is a prominent technique that is widely utilized for attaining parallel operation of multiple sources. In this mechanism, one converter serves as a Voltage Source Converter (VSC), which acts as a master and commands slave units for regulating the DC bus voltage. The remaining converters act as slaves, that feeds necessary current support as per the instruction from the master controller. The master converter operates in such a way that the grid voltage is maintained within the tolerance band, and the remaining converters that act as slaves support the master in achieving the same.

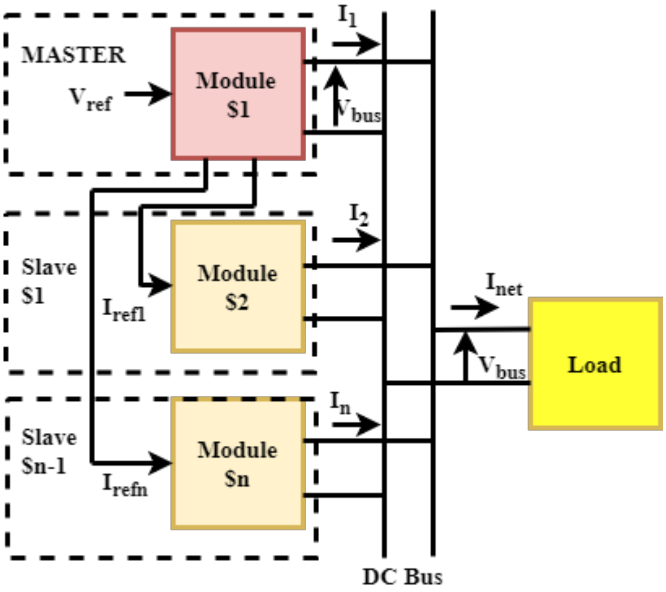

Fig. 3. A schematic for Master-Slave controller

The control mechanism totally depends on a high-speed communication platform, and any failure in proper communication affects the overall system performance and may even result in complete black-out of the entire system. The major drawbacks of this control strategy include reduced battery life, low scalability, need for supervisory control, expensive and poor fault tolerance capability.

A master-slave control algorithm for input-series and output-parallel full-bridge converter is discussed in [46], which is controlled by a phase-shift controller. The limited range of output voltage regulation is mitigated using the master controller. Some of the advantages include flexibility and easy implementation, that makes it suitable for high power and high voltage utilities. Federico et. al. [47] proposed a master-slave control for the electric bus application and assumed to have achieved an efficiency of more than 3% as compared with existing conventional strategies.

2.2. Decentralized Control

In a decentralized controller [48], the distributed units are controlled by the autonomous local controllers via independent local variables and there is no communication medium in the control. This control strategy is considered to be the most reliable, despite its limitations due to the absence of a communication link. A switched current mode based decentralized controller is proposed in [49] where the voltage-controlled source is replaced by a current-controlled source. The results claim that the proposed control advance in better transient response, plug-in and plug-out capacity, better voltage regulation and adequate current distribution.

A Multi-Agent System (MAS) [50] based control was proposed by researchers that combines the advantages of both centralized as well as decentralized control systems. Some of its merits include better fault tolerance capability, more flexible and scalable, easy to implement, sot-effective and good power management ability. Some of the widely accepted decentralized control schemes are described below.

2.2.1. Conventional Droop Control

The droop characteristics are based on the performance pattern, when a current is injected to the grid it produces a dc grid voltage that is proportional to each other. It is one of the popular decentralized control strategies [50] adopted to minimize or eliminate the circulatory current between converters without communication medium. They also provide good voltage regulation in microgrids. The equation governing the same is given as,

$$V_{ref} = V_o + (I_{ref} \times R_{droop}) \qquad (1)$$

where V_{ref} is the reference DC grid voltage, V_o is the output voltage of the PEC, Io is output current and R_{droop} is the virtual resistance. Fig.4 depicts the conventional droop control scheme. The improper selection of droop resistance results in poor load sharing and voltage regulation, poor performance with RES units.

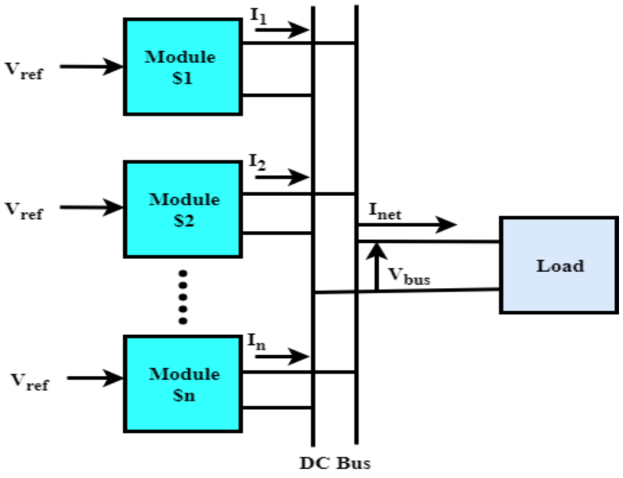

Fig. 4. A conventional voltage-droop control scheme

Figure 5 depicts the voltage control scheme of a DC-DC converter. [51] proposed a decentralized droop method for a low voltage DC microgrid. All the grid parameters like SoC of BESS, the effect of feeder resistance, etc. were taken into account. To perform better power sharing among the DERs, three modes of operation and fault condition were taken into consideration.

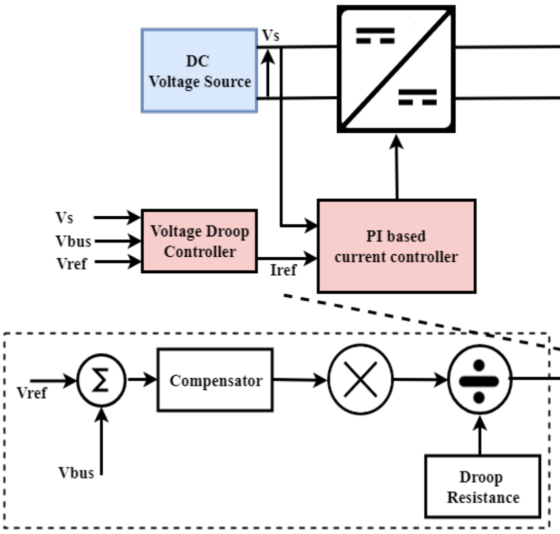

Fig. 5. Voltage control scheme of the DC-DC converter

2.2.2. Virtual Resistance based Droop Control

The demerits of the droop control mechanism are solved by proposing a virtual droop resistance [52]. The proposed method introduces a virtual resistance called droop resistance (R_{droop}) which is a function of the terminal voltage.

$$I_{ref} = (V_{ref} - V_o) / R_{droop} \tag{2}$$

$$R_{droop} = func(V_o) \tag{3}$$

This is done to achieve a non-linearity in the droop characteristics and hence voltage regulation is improved.

2.2.3. Adaptive Droop Control

An adaptive droop strategy for DC MG is discussed in [53] where solar PV, fuel cells and BESSs are taken into consideration. For proper power-sharing, the charging and discharging of the BESS units are managed using a bidirectional adaptive droop strategy. In [54], a closed-loop reference model (CRM) adaptive droop strategy was used to realize the DC MGs droop function. To achieve simultaneous voltage stability and current sharing, a time-varying model is acquired, a projection algorithm and a normalization technique with the above-mentioned adaptive droop strategy is used.

Paper [55] proposed an adaptive droop strategy for low voltage DC MG that is based on super-imposed frequency along with a virtual resistor. An AC current is injected on both primary as well as the secondary sides using local measurement data to accommodate the droop gains in order to achieve better voltage regulation and load sharing. The voltage regulation and load sharing are achieved by injecting an ac power at both primary and secondary levels using locally available measurements to adapt the droop gains. This made the system free from any communication links and more economic. Another parameter that concerns the effectivity of the proposed controller is the AC power injection to a DC MG, which creates stability issues and lowers the power quality.

2.3 Distributed Control

A network of several controllers equipped in each PE sources forms a distributed control, which helps in proper load sharing to maintain steady grid voltage. This control mechanism has the advantages of both centralized as well as the decentralized controller. The controller of each PE devices communicates via a communication medium same as that of a decentralized controller, but with limited bandwidth. This helps in performing the vital operation like SoC balancing, restoring the voltage, load power-sharing, etc. Any significant increase in Distributed Generation (DG) units makes it complex to implement centralized control scheme. During such a crisis, the distributed controller proves to be a better competitor. An added advantage of such a controller is that even if the communication link breaks, it makes the system functions as it is immune to a single-point failure. The major drawbacks include deviation in bus voltage, complex analytic behavior, and error in tracking power.

In Ref. [56], an advanced droop architecture for DC MG is proposed. The enhancement of voltage regulation and optimal power is done with the aid of a non-linear optimal controller. All the information regarding MG operation is necessary for the controller to convert them into a linear near-optimal control issue. The proposed controller proves to be better than the conventional droop methodologies even for intermittent communication medium and is found to be more stable and robust in nature. The system proves to be more stable by working as a conventional droop control methodology under some special cases. A novel approach to a distributed droop control and Energy Storage (ES) in a DC MG forming a networked grid is proposed in [57]. The droop characteristics are actuated with the aid of local BESSs for each MSs. A feed-forward approach is utilized to match the MSs voltages to the grid voltage by altering the duty cycle of PECs periodically. The proposed controller claims faster update rates and reduction in the number of ES units.

A distributed control strategy is proposed in [58] that helps in enhancing the voltage regulation and local power-sharing in a DC MG. A dispersed cyber-network is utilized for the exchange of data, where the average voltage across the grid is estimated using a voltage observer. It uses a PI control and adaptive droop, where the virtual impedance of DERs are regulated by the current regulators. Table 1 shows a detailed description of the various control schemes discussed in this section.

Table 1: Summary and comparison of DC microgrid algorithms

Control Technique	Method	Load current sharing	Implementation Complexity	Voltage Regulation	Other Features	Applications
Centralized Control	Phase-shift Control [46]	Fair	Simple	Good	• More flexible • Fault-tolerant	High voltage and power DC Grid
	Proportional Integral Control [47]	Fair	Moderate	Good	• Robust • Improved efficiency • Eliminates extra wiring	Low voltage DC Electric bus system
	Multi-stage Control [65]	Good	Complex	Better	• Faster transient response • Minimize load-shedding • Reduced cost of operation	Islanded DC microgrid with Plug-in EVs
Decentralized Control	Conventional PI Control [50]	Poor	Easy	Good	• Fault-tolerant • More flexible • Scalable	DC system
	Adaptive-droop strategy [53]	Good	Easy/ moderate	Better	• Robust • Integrates RESs like SOFC, PVs, and BESS	DC system only
	Closed-loop reference model adaptive control (CRM) [54]	Better	Moderate/ Complex	Better	• Robust under noise disturbances and uncertainties. • Better power-sharing. • More effective than linear control strategy.	High Voltage DC MG
	Adaptive droop controller based on super-imposed frequency [55]	Better	Moderate	Better	• More economic • More reliable.	Low voltage DC MG
Distributed Control	Non-linear optimal Control [56]	Good	Moderate	Better	• More stable. • Robust	DC MG
	PI controller with HSS [57]	Good	Moderate/ Complex	Better	• Flexible and adaptable. • Reduced use of energy storage elements.	DC MG
	PI controller with Adaptive-droop control [58]	Good	Complex	Better	• Proportional load sharing. • Plug-and-play compatibility	Low voltage DC MG

3. Extensive Operation of DC Microgrid

3.1 Battery Management System (BMS)

There are numerous scenarios where the above-mentioned control strategies are applied. In the modern power system environment, the integration of ES units [59] has been increasing rapidly due to the advent of innovations and advancements in the deployment of DERs. Using the SoC level, a BMS controlling circuit is developed in [60] for each cell's charge-equalization. A dual step-down half-bridge bidirectional ac-dc converter is utilized, that enables high power flow and is able to precept the functioning of allied circuitries like the inverter and BMS. The control of a hybrid energy storage system (HESS) for a battery-supercapacitor (SC) units is discussed in paper [61]. The SC converter is regulated by a virtual capacitor droop while a high-pass filter droop is implemented for controlling the battery converter. The proposed system mitigates various issues like SoC balancing, dynamic power-sharing, steady-state grid voltage restoration, etc. The controller also helps in efficient power buffering due to the rapid dynamics of SC included and also ensures continuous and long operation of HESS.

3.2 Load Management

The overall stability and reliability of the MG are greatly influenced by the loads. During proper load scheduling and management, the grid operating parameters widely influence the consumer's energy usage [62]. During system failure or permanent blackout, proper control strategies need to be taken by the grid operator and thereby the existing loads can be diminished to reduce the risk of power failure. In [63], the issue with frequency and power fluctuations is eliminated using proper management of active load. The existing scenario can be widely exploited to increase the grids reliability, stability, optimizing generation and allow RES integration on a large scale [64].

3.3 Electric Vehicle (EV) Integration

The EVs are gaining popularity in the current market due to the depletion of fossil fuels and low efficiency of IC engines. They can enact the role of a generating unit, controllable load, maintaining supply-continuity and backing the grid. A multi-stage centralized control algorithm is developed in paper [65] to allow extensive use of EVs in a microgrid. The system is designed in such a way that, several objectives are fulfilled using a 3-stage droop-based power control scheme. The system starts by minimizing load-shedding whenever the power generation is low, and then it minimizes the grids operating cost and maximizes utilization of EVs in an extensive manner. In order to validate the robustness and effectiveness of the system, two operating scenarios i.e., a grid without and with sufficient generation were considered for the study.

3.4 Utilization of RESs and ESS

The current energy scenario demands more utilization of RES like solar PV, wind energy systems (WESs), hydropower, etc. The synchronized operation of numerous components like BESSs, RESs and loads using a centralized controller is discussed in paper [66]. The controller performs three main tasks including equalizing SoC, to prevent battery overcharging by active power interruption and load-shedding to avoid battery discharge. The proposed system leads to increased life-span of energy storage units and optimal scheduling of loads.

3.5 Control and Protection of Microgrid

Another major safety-critical feature which is inevitable for microgrid operation is protection. This feature requires much more attention in DC microgrid as compared to AC systems due to the absence of zero-crossing current. Research gap is still open in this area of DC microgrid protection scheme for better operation and safety of the operators, end-users and other participants involved in the utilization of the microgrid and its associated entities. The protection devices deployed in the microgrid may not be able to sync with the speed of response of these advanced control mechanisms. But there are advanced protection devices that respond quickly, but the cost of such devices increases with the advancements in technology. Along with protection, bi-directional communication schemes, EVs [67] as active power load, MG cluster control and utilization of smart meters are the other areas which have advanced research capability. For implementation in a real-world scenario, stability analysis is also required to ensure system reliability. The voltage must be stable or should be within the limits for better operation and reliability under sudden disturbances in the grid. Another issue arises when constant loads with PE interfaces are deployed which leads to reduced voltage stability. So, thorough research needs to be investigated to mitigate all these issues.

4. Technical Hindrances involved in DC Microgrid Implementation

There are several technical challenges present in the current DC grid scenario. The centralized controller may not be viable without proper communication medium. The communication medium or link used for achieving better reliability and operation of the system should be optimal, economical [68], more feasible and should have reduced complexity level. Another key feature is better to load current sharing and proper voltage regulation, which is a major hindrance for conventional controllers. The controller should also ensure that the utilization of storage technologies, RES and DC grid voltage maintenance remains optimized and under control.

4.1 Stability issues in DC microgrid

The presence of constant power loads can yield to instability issues in a DC microgrid since these loads may get coupled with a negative impedance characteristic [69]. Presence of resonant condition caused due to virtual negative inductance induced during the operation of a constant power load have adverse effect in a DC microgrid from stability perspective [70]. Increasing damping mechanism in the system is a commonly adopted measure overcome such situation. But this can in turn result in a voltage sag. A proper tradeoff is required between allowable swing range and duration of voltage sag in order to meet the allowable system standards [71].

4.2 Challenges involved in protection of a DC microgrid

Primary and secondary level control algorithms in are usually computed using advanced microprocessors which takes decision in pace faster than the allowable response time in a protection device. In such an environment, in a DC network, designing circuit breakers is always a big challenge as it has to be economical and effective. This is mainly because the current levels need not be damped to zero as the DC voltage levels are not falling to zero. This can act as one of major hindrance in DC micro grid protection. Operator personnel safety is key essential requirement which is challenging as it is difficult to minimize DC stray current by proper grounding. The integrated local controllers and other control functions should ensure that the system is stable during islanded and grid-connected modes and should transfer seamlessly. The battery characteristics like charging, discharging should be done with the utmost care and proper measures should be taken to prevent overcharging and undercharging by choosing a better control strategy. The battery units [72, 73] connected in multiple stacks should always have the same State of Charge (SoC) to prevent further damages.

5. DC Microgrid: Future Trends

Several research works are undergoing in the field of control strategies adopted in DC grids, their structures, various energy management schemes, energy storage techniques. The structure of any power system attracts many parameters such as robustness, reliability, scalability, cost, the resiliency of the system. The microgrid comes in various structures, namely Single-bus, Ring-bus, Multi-bus, Zonal-bus, Ladder-bus, and Multi-terminal DC MG structure. All these structures have their own applications and drawbacks. More and more research needs to be done in this area to mitigate their drawbacks, reduce complexity-level and introduce redundancy. From the above surveys, it is clear that a single controller alone cannot ensure the following functionalities such as voltage regulation and control, current and power control, proper current and power-sharing, PQ control [74], ancillary services provisions, energy market participation, operation grids. A future trend in the DC system may be secondary distributed control with DC bus signaling (DBS) power management [75]. The DC grid voltage is balanced between power consumption and generation units with the aid of a storage medium for power management. Some issues that still persist in the robust control of all modes of operation such as islanded [76], grid-connected and transient modes. The EMS [77, 78] should consider power losses in storage devices, reaction time, SoC levels and charging schemes adopted. Thus, energy management plays a crucial role in reducing the overall system size and power ratings of devices, improving storage unit's lifespan and feeding critical loads. A critical primary objective of the future DC grid is a plug-and-play capability, from various hierarchy level. The DG units and power electronic converters [79] should be able to effortlessly disconnect and connect in component level from a DC MG. Similarly, the MG should seamlessly switch between grid-connected to an islanded mode [80] in the system level. A controller is effective if it coordinates the system and components and maintains stability.

In the future, the concept of MG can be a combination of several grids that provides resiliency, reliability, and flexibility. More and more researchers would get attracted to the issues in controlling and maintaining the stability of the MG systems. These clusters are the future of the energy economy and would devise a flexible integrated grid. The key to this achievement is the well-designed management and control principle but needs further development and research efforts.

6. Conclusion

Smart Grids are the future of conventional grid networks, and a better possible way to realize them is through the advent improvement in MGs, which are a bunch of numerous electrical and electronic devices. The distributed paradigm is gaining popularity due to better flexibility and autonomous operation needs in both consumers as well as utility side. An abundant amount of research works are undergoing in the field of DC microgrid system, as they possess more features than the AC system. The heart of MG control is the energy management scheme for the case of a centralized controller. But, in the case of decentralized, it is less reliable than the above control strategy. There is a wider scope of research for DC grids in this scenario. The depletion in traditional energy sources, need for storage devices, the increased popularity of RESs etc. paves way for DC grid as the future grid.

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