A Critical Survey on Control Strategies of LVDC Microgrid Systems

Prtima Gakhar¹ and Rajashekar P Mandi²

¹School of Electrical & Electronics Engineering, REVA University, Bangalore, Karnataka, India.
²School of Electrical & Electronics Engineering, REVA University, Bangalore, Karnataka, India.

Abstract

DC microgrids have many advantages over AC microgrids and are more appropriate for distributed energy sources. The topic of DC microgrids in place of AC microgrids becomes even more important with increasing penetration of the renewable energy sources. AC microgrids have been in existence for ages and have well established and standardized control techniques. DC microgrids are still evolving and a lot of research is going on in the operation and control techniques. Advanced control strategies are vital components for realization of microgrids. A critical review of various control techniques applied on DC microgrids by various researchers are discussed and identified. Research gap for further research work has also been summarized in this paper.

Keywords: DC microgrids, distributed energy resources, energy storage solutions, droop control, hierarchical control, plug and play, fuzzy control, multi-agent system

I. INTRODUCTION

The electrical energy is the richest form of energy, majority of which is generated by the conventional electrical power systems. These systems are facing a lot of environmental and energy concerns like depletion of fossil-fuel based energy sources that are of finite in nature, greenhouse gas emissions, imbalance between energy supply and demand due to ever increasing demand and ageing of existing transmission & distribution (T&D) infrastructure, etc. Therefore, there is a need for innovation to develop energy sources that provide clean, reliable and stable power for energy growth.

Although promising solutions have been shown by recent developments in grid connected renewable energy resources (RES) but the integration of these RES into grid in a larger share could cause voltage rise and protection issues that adversely affect the security, reliability and quality of the utility grid. To overcome these challenges a new power utility shift known as ‘smart grid’ is evolving. These attributes of reliability and sustainability expected from this intelligent network are realized through microgrids that facilitate the effective integration of RES.

A microgrid is a power center consisting of distributed generation (DG), load and energy storage devices. It normally operates in synchronization with the central grid, but can disconnect and function autonomously as a stand-alone grid. Microgrids emerge as a suitable solution for the installation of low-voltage distributed energy resources (DERs), where most consumers are sparsely located. They ease the integration of DERs with energy storage systems (ESS), especially renewable sources like solar, wind, etc. at consumption level. Due to this decentralization of electricity, production of electricity is possible in the close proximity of the consumers. This helps in minimizing T&D losses, increase the energy efficiency and reliability of the grid.

Due to increase in use of DERs, a need for LVDC microgrids is emerging. There is a need to reconsider employing DC distribution instead of AC distribution as many of the homes and office equipment like laptops, computers, mobile battery chargers, electronic lights etc., are DC powered. In this case the load and DER can be interfaced to a common DC bus with minimum power conversion stages that leads to simplicity and economy. The problem of synchronization and reactive power compensation issues can be eliminated. The decrease in distortion caused to the voltage signal at the point of common coupling (PCC) due to the reduction of power electronic converters lead to preference of DC microgrids over AC microgrids. Also, in a DC system the current will flow in entire conductors due to absence of skin effect that also reduce the conductor loss.

This paper presents an exhaustive literature survey and summary of the research work done by various researchers on operation and control of DC microgrids. The objective of the paper is to give a thorough background on what has already been accomplished in this field recently. In this paper the critical analysis of the various control schemes in LVDC microgrid systems along with research gaps is discussed in detail.

II. DC MICROGRIDS

The main components of DCMG are DERs like solar PV systems, wind turbines, etc. Here the generating resources operate in maximum power point tracking (MPPT) mode to deliver maximum power to the grid. They might be operated in derated conditions under certain network conditions. The batteries act as ESSs and are connected to a DC bus using bidirectional converter. If the energy demand is less than the generation, the battery charging takes place. During the absence of power generation, the battery will supply the power to load in standalone or isolated mode. Different loads of different ratings can be connected accordingly in a multilevel system. A bidirectional grid connected voltage source converter (VSC) is used to connect AC utility grid to the DC bus with the help of transformers and circuit-breakers. Basic structure of a DC microgrid is shown in Fig. 1.
DCMG operates in generally following three modes:

**Uncontrolled grid connected mode**: AC utility grid balances the power in DCMG system. Whenever the power generation by DER exceeds the demand, power is fed for battery charging. A bidirectional VSC regulates the voltage of DCMG and the power transfer through AC-DC converter doesn’t exceed its maximum power limit.

**Controlled grid connected mode**: When the power flow from AC utility grid exceeds the maximum power rating of AC-DC converter or under any fault condition that cause voltage dip in the utility grid, the DC bus voltage cannot be regulated by grid VSC. In such conditions ESS plays an important role of regulating the DC bus voltage.

**Stand-alone/Isolated mode**: AC utility grid is disconnected from the DC link and power to various loads is provided by DERs and ESS. The DC bus voltage is regulated by ESS when-ever there is no power generation by DERs. But DERs have to be operated in de-rated condition and the over-charging of battery is avoided.

The existing power systems which typically employ DC distribution are spacecraft, data centres, telecommunication, traction, shipboard power systems, etc. The DC power can be extended to lighting loads, electronic loads and variable speed drives. The basic types of DC links adapted to LV distribution levels are Monopolar, Bipolar and Homopolar DC links. Consortium for electric reliability technology solutions (CERTS) has also defined a microgrid concept for integration of DERs into the electrical power systems. The static switch and the micro sources are the key components in CERTS microgrid. Here a peer-to-peer and plug- and- play models are incorporated for each component to enhance the reliability of the system [1].

### III. DCMG OPERATION AND CONTROL

The DCMG operation and control consists of coordinated control of DERs, ESSs and grid connection interface to achieve system reliability, stability and economy. The main objectives of control techniques in a DCMG are:

- Equal load sharing by DERs.
- Maintain the voltage regulation of the system.
- Seamless plug and play of various DERs and/or ESSs.
- Proper integration and power flow between DCMG and the utility grid.
- Optimize DCMG operating cost.

Unlike in AC grid, there is no problem of synchronization in DCMG and also the number of variables to be controlled is less in DC systems that helps to improve the controllability and reliability. The DC voltage at the point of common coupling (PCC) is main variable to be controlled by adjusting the set points of voltage or current dynamically to compensate load deviation. DC bus voltage must be in limited range to ensure normal operation of a DCMG. When more number of converters are connected to a DC bus in parallel, they act as voltage sources. But this may give rise to circular current due to the impedance of distribution cables [2]. Therefore, an appropriate current sharing scheme must be adopted to distribute power and current among various DERs. A proper DC bus voltage variation control scheme is essential otherwise it may mal-operate the protective system.

The operation and control of DCMG should ensure a good quality of power supply, stability of the system during connection or disconnection of micro sources or loads and also during proper transition between grid connected and islanded modes of microgrid. During the islanded mode of operation, the lower capacity of DERs can cause voltage flicker or collapse, so the ESS must help to maintain the power quality and also provide the power to critical loads.

Some of the control strategies adopted for DCMG are:

- Droop control
- Hierarchical control
- DC bus signal (DBS) control
- Communication link based (Centralized and Decentralized) and communication-less controls
- Power injection control
- Fuzzy control
- Multi- agent system (MAS) based control

#### A. Droop control

Conventional droop control is one of the most popular control strategies in recent years. Droop control system utilizes the droop characteristic of the power electronics converter. Droop is nothing but the variation in voltage due to virtual impedance of the converter. In this case the feedback current signal or series resistor is used to change the output resistance of the converter to facilitate proportional current sharing. In this method, the power is shared by reducing the reference voltage linearly as the output current increases. It is widely applied as a decentralized method for load power sharing but has a few limitations.
Fig. 2 shows the simplified model of a two node DCMG, where each converter is expressed in the form of Thevenin’s equivalent circuit.

![Two-node DC microgrid diagram]

The main limitation of conventional droop control is the current sharing accuracy degradation due to the influence of voltage drop in the line impedance. The equations governing the system are:

\[
V_{dc1} = V_{ref} - k_{d1} (R_1 + R_i) \quad (1)
\]
\[
V_{dc2} = V_{ref} - k_{d2} (R_2 + R_i) \quad (2)
\]

Where \( V_{dc1} \) is the converter output voltage (V), \( V_{ref} \) is the reference DC output voltage (V), \( k_{d1} \) is the output current (A), \( R_d \) is the line resistance (Ω) and \( R_i \) is the virtual resistance (Ω) and \( i = 1, 2 \).

The output resistance of the Thevenin’s equivalent circuit is equal to virtual resistance of module and the output voltage of voltage source which is equal to \( V_{ref} \).

The other major limitation in this method is the deviation of DC output voltage, which is product of \( i_{dc} \) and \( R_i \).

In order control the voltage deviation within its maximum acceptable value, the droop coefficient value can be limited by the equation:

\[
R_i \leq \frac{(\Delta V_{dc1}/i_{dc1})}{k_{dc1}} \quad (3)
\]

where \( i_{dc1} \) is the output full load current of i\(^{th}\) converter.

If droop gain is less, it will result in better voltage regulation but current sharing error will increase. Similarly, for high values of droop gains, poor voltage regulation and better current sharing is achieved. Hence, there is a trade-off between the current sharing error and voltage regulation in case of a conventional droop control. The droop technique for paralleling of power supply modules can be classified into five main types - Inherent droop feature converters, voltage droop due to series resistor, voltage droop via output current feedback, Current mode with low DC gain and Programming control via nonlinear gain respectively [3].

To overcome the limitations of conventional droop control, an improved droop control technique is proposed which is based on Low Bandwidth Communication (LBC) with DC bus voltage restoration and improved current sharing. In contrast with the conventional approach, here local controllers and LBC network are used to exchange information between the converter inputs. In this case, centralized secondary controller is not required and decentralized scheme is achieved. In this scheme, average voltage and current PI controllers are used in each local control system. The average DC output voltage is controlled in each voltage controllers. So, the average value of the output voltage can be restored to desired reference value. The reference value for each current controller is \( i_{d1}/k_1 \) and \( i_{d2}/k_2 \), where \( k_1 \) and \( k_2 \) are the current sharing constants, and \( i_{dc1}/k_1 \) and \( i_{dc2}/k_2 \) are the feedback variables which guarantee the proportional output current sharing [4].

Another distributed control technique suitable for DCMG system is presented by (Sandeep Anand, et al., 2013) [5]. In this case, the droop control and a decentralized average current sharing (ACS) control for parallel DC-DC converters are used together as the overall control strategy. The local control is achieved using droop control without need of any communication system. It delivers good current sharing but at the cost of good voltage regulation. Moreover, voltage level is not constant in microgrid, so achieving current sharing is difficult when sources are located at considerable distance. To overcome this limitation, another loop has been applied, using low-bandwidth digital communication between DERs which averages the total current supplied by DERs.

### B. Hierarchical control

In order to overcome the drawbacks of conventional droop control scheme like current sharing accuracy degradation and DC voltage deviation which leads to trade-off between voltage regulation and current sharing among different converters, a three-level hierarchical control based on ISO-95 is worked out by (J. M. Guerrero, et al., 2011) [6].

Level 1 is basically a primary control that adjusts voltage reference provided to inner current and voltage control loops (level 0). Level 2 is a secondary control that ensures electrical levels are within required range for microgrid. To solve the problem of voltage deviation, a secondary control is considered. Level 3 is a tertiary control which is an energy production level that controls power flow among microgrid and utility grid. When microgrid is DC source connected, power flow is controlled by altering microgrid bus voltage.

Flexible microgrids, which can operate in both island and source connected mode can be controlled efficiently by using this proposed technique. Also, a seamless transfer from one mode to another is possible.

Implementation of hierarchical control in a practical DC microgrid is proposed by (Chi Jin., et al., 2014) [7]. The coordination control among multiple DC sources and ESSs is possible using a unique hierarchical control technique.

An extensive review on various control strategies and architectures applied to DCMG operations have been carried out by (Lexuan Meng, et al.) [8]. Multi-layer hierarchical control schemes, coordinated strategies, plug and play capability, islanding concepts are also discussed. The three principal control levels - primary, secondary and tertiary controls have been widely adopted solutions for efficient control of microgrids. Primary control, a basic layer regulates the voltage, current and power, defines the dynamic performance of the local unit. On the other hand, the
secondary and tertiary controls provide the advanced functions like voltage quality maintenance, current sharing improvement and optimal operation. Based on the same hierarchy as represented in Fig. 3, the control levels can be implemented as centralized, decentralized, distributed or in a hierarchical fashion as shown in Fig. 4.

C. DC Bus signal (DBS) control

An autonomous power management strategy (PMS) for DC microgrids - adaptive DC bus voltage signal (DBS) is another control technique proposed by (Xunwei Yu, et al., 2013) [9]. Here a 380V DCMG system which includes two DERs and two ESSs is proposed with an adapted DBS scheme. In this control, the DCMG can work in islanded and DC source-connected modes and flawlessly switch between different modes without significant voltage or current fluctuations. Plugging and unplugging more DERs and ESSs into DCMG without communication links and intelligent control of more number of ESSs according to their ratings and DC bus voltage level is also possible.

In this algorithm, the DCMG can operate in islanded mode and DC source with seamless changeover between these two ways. The authors concluded that a DBS power management strategy with two unidirectional DC-DC converters for PV, and two bidirectional DC-DC converters for ESS (battery) can help a DCMG to operate stably in islanded or source connected ways without significant voltage or current fluctuations. They also propose to use plug and unplug methods without communication ports for easy integration of more and more ESSs and DERs in the DCMG.

D. Communication link based (centralized and decentralized) and communication-less controls

A combination of communication link based (CLB) and communication-less controls (CLC) technologies for better control and resilience have been proposed by (Yunwei LI, et al., 2014) [10]. In the CLB energy management schemes, operation point of each DG is determined by using the information of system current, voltage, power, etc. This scheme can further be classified as centralized and decentralized. These communication schemes utilize fiber-optics, microwaves, PLC and/or wireless radio networks based on the distance of power sources, level of security, cost, and available technologies. Here internet protocols (IP) with prevailing industry protocols are combined for communication.

i) Centralized energy management scheme (communication link based):

As it can be seen from the Fig. 5 that a centralized control center makes decisions and determines operation points of
DERs based on the objectives and constraints to minimize O&M costs, maximize system efficiency, control of environment impact, etc. The main advantage of this system is that it collects all data and information, based on available information, EMS system achieve global optimization. But this system has the disadvantages of heavy computation burden and reliability of data that cause the failure of communication system that may lead to shut down of the system.

A decentralized control method for a large and low-voltage DCMG including a PV system, ESS (battery) and grid converter is discussed by (Amir Khorsandi, et al., 2014) [11]. In this method, both accurate current sharing and desirable voltage regulation are obtained considering the effects of line resistances. In this scheme, four operating modes are adopted. The line resistances are computed based on information obtained in the grid connected mode.

In other modes, computed line resistances are used to adjust droop gains such that PCC voltage reaches its minimum (or maximum) acceptable value when the current from/to each DER which is at its maximum charge (or discharge) current. The state of charge (SOC) of the batteries is considered to ensure reliable and prolonged operation of the system. For this purpose, the limits of acceptable PCC voltage considered by each converter are changed according to the SOC of battery.

### iii) Communication-less systems:

When communication becomes too costly or complex then every DER unit be able to operate independently. In such cases, each energy source has its own local controller without having communication links with other controllers. The most suitable example of communication-less scheme is droop control method. This scheme is more reliable due to no communication requirement and expandable with plug- and-play capability but the optimal operation of MG system is difficult with this system. Fig. 7. shows the basic architecture of such a scheme.

### E. Power injection control

Another new technique i.e., Power injection control of DERs in an islanded LVDC microgrid is proposed by (Andres F. Moreno, et al., 2015) [12]. In this scheme, the controller is analyzed with simple parameters, multiple loads and sources connected in parallel as an uncertainty. It also avoids the communication between controllers. Any number of sources and loads can be plugged into the DC system. In this scheme, the author concluded that controlling the power delivered in the form of DC current, allows bus voltage regulation. This is equivalent to the $P - \omega$ relationship in AC systems. In this scheme, by adding more sources, the good power quality can
be achieved. Many converters can be plugged-in to provide energy, due to increasing the power supply capability and contributing to stability of voltage at PCC.

In the proposed technique the behavior of the open and short circuit conditions of a particular energy converter from given source is simply analyzed by $I_N$ and $R_N$ of Norton equivalent circuit (Fig. 8). The maximum power is delivered to the load when it has exact same resistance of model $R_N$.

\[
\begin{align*}
\text{Fig. 8. Norton equivalent model of the converter.}
\end{align*}
\]

The main primary control objective is to inject all available power into microgrid along with desired voltage regulation and stability. In order to achieve these goals, controller must calculate current, $I_{\text{ref}}$ as reference variable for model of equation. The desired current is the quotient of available power of energy source and output voltage. This power injection control scheme is presented in Fig. 9.

\[
\begin{align*}
\text{Fig. 9. Basic power injection control loop.}
\end{align*}
\]

F. Fuzzy control

The traditional control doesn’t suit if the system is too complex or uncertain. For such cases a fuzzy control system is suggested. A fuzzy control system is based on fuzzy logic system which observes and analyzes analog values of logical variables which operate on continuous values between 0 and 1. Whereas a traditional digital logic controller operates on discrete values of either 1 or 0. This new control system that combines fuzzy control with traditional gain-scheduling methods is proposed by (Hiroaki Kakigano, et al., 2013) [13].

A fuzzy control technique jointly with gain-scheduling control is reported by (Hiroaki Kakigano, et al., 2010) [14]. It helps in managing the stored energies by electric double layer capacitors. With the fuzzy control strategy, a bipolar-type LVDC microgrid, which can supply high quality power with three-wire DC distribution line, is proposed by (Hiroaki Kakigano, et al., 2010) [15].

G. Multi-agent system (MAS) based fuzzy control

As per Wikipedia, “A multi-agent system (MAS) is a computerized system composed of multiple interacting intelligent agents within an environment. Multi-agent system (MAS) can be used to solve problems that are difficult or impossible for an individual agent or a monolithic system to solve.”

Intelligence may include some methodic, functional, procedural approach, algorithmic search or reinforcement. MAS consists of several intelligent software or hardware entities or units with only limited abilities and local knowledge. These are able to interact with each other. MAS is a decentralized energy management system (EMS) in which autonomous computational and intelligent agents make decisions based on goals or targets within an environment, and they broadcast information about their goal achievement to other independent agents. MAS systems are very suitable for artificial-intelligence based methods such as neural networks or fuzzy systems which are typically deployed in very large and complex microgrids. Conventional control strategies as well as some advanced control methods like artificial intelligent based techniques and expert systems, can be applied to make these agents work intelligently. Using fast communication devices, MAS can be integrated into power system applications given by (A.L. Kulasekera, et al., 2011) [16].

In a typical distribution network, the power resource and power dispatch controls are managed centrally. Distributed generators are emerging as an alternative to the above mentioned typical approach and help in reduced voltage drop and loss. But, as these DGs are usually not owned by the utility company and face uncertainty of availability of solar or wind. Therefore, they behave differently than the typical centrally controlled utility grid and need different kind of controlling and management. These new operation and control techniques are becoming significant research topics. In another paper, MAS has been proposed for solving this problem using a prototype of five types of autonomous agents, agent cooperation strategy, electrical management system and agent communication ontology [17].

IV. RESULTS AND DISCUSSIONS

AC grids are existing for ages and are well standardized in terms of operation, control and energy management aspects. LVDC concept has recently become a matter of interest due to sudden and vast emergence of renewable and distributed power generation. Many of the existing researches are in ideation or nascent stages for LVDC and are not tested in a real-world implementation. The techniques which have been frequently discussed and researched on are - Droop Control architecture, Hierarchical control architecture, DC Bus Signal (DBS) control architecture, Communication link based and communication-less controls, Power injection control, Fuzzy control and Multi-agent Based (MAS). Depending on the deployment architecture, level of accuracy in DC bus level, integration needs with the main grid and size of the microgrid and the cost, any of above techniques can be used.
Every strength of a given technique comes at a cost. Droop control, being the most cost-effective control (not the most effective though) is that’s why the most popular one.

In order to satisfy the requirements of a distributed configuration, droop control without communication or with LBC is commonly accepted as an efficient power sharing method. The hierarchical control is found to enhance DC microgrid stability and supply quality. The droop control technique is more effective to improve the reliability and flexibility of system and this does not require communication network. In order to mitigate the voltage stability issue, droop control technique along with decentralized average current sharing loop based on LBC can be used.

As present-day power systems are becoming more and more complex, it may not be possible to achieve all functions in a distributed or decentralized manner, so hierarchical control structure is being most widely used which is becoming a standardized configuration in most of the microgrids. Considering limitations of communication-based and communication-less controls, a combination of droop control with communication-based control can enhance reliability and control performance. In such a combination strategy, with the help of communication-based energy management, the DER operation point in both grid-connected and stand-alone modes can be determined more accurately. Also, with droop control as backbone, the communication requirement (such as speed and bandwidth) can be reduced and failure of the communication links will not cause a system collapse. But at the same time addition of higher levels of control along with communication channels in droop control scheme dilutes the core principles of modularity, simplicity and decentralization in the control strategy of microgrids. For very large and complex systems, the upcoming control techniques like fuzzy control and MAS control can also be utilized.

V. CONCLUSIONS

The use of power from central power generation and transmission & distribution through lengthy lines cause more losses. The use of microgrids at remote areas reduce the losses but the use of AC microgrids has drawback of reactive power compensation, synchronization issues, skin effect in conductors, etc. The use of DC microgrids has an edge over the AC microgrids. Among all the control strategies, the adoption of control strategy depends on the cost effectiveness, power reliability, voltage stability of the system and power quality. The droop control strategy improves the reliability and flexibility of the system, the hierarchical control enhances DC microgrid stability and supply quality, combination of droop control with communication-based control improves the reliability and control performance and for very large and complex systems, fuzzy control and MAS control techniques are more suitable. There is a need of further research to enhance the performance, reliability, stability, cost effectiveness and power quality of DC microgrids.

REFERENCES


