Power Management, Control and Protection of DC Microgrids

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***Abstract*--DC microgrids have been gaining a continually increasing interest over the past couple of years both in academia and industry due to the provision of numerous benefits in comparison with AC ones. The most important ones include higher reliability and efficiency, simpler control and natural interface with renewable energy sources, and electronic loads and energy storage systems. With rapid emergence of these components in modern power systems, the importance of DC in today's society is gradually being brought to a whole new level. In this study, first, the power management issues in a DC microgrid is discussed. Subsequently, a review on available techniques used for addressing the control and protection challenges microgrids is provided. Apart from describing the most relevant options presented to date and classifying them in specific groups, the most important benefits and drawbacks of each approach are presented. Finally, some conclusions and research directions for implementation of future DC microgrids are pointed out.**

***Index Terms*--DC microgrids, grid-connected mode, islanded mode, power management, control and protection approaches.**

I. Introduction

MICROGRIDS (MGs) are novel form of distribution systems, which belong to the wider concept of smart grids. The microgrid can be considered as a small-scale electricity grid at the distribution voltage level, which can operate either in grid-connected or islanded mode. It consists of Distributed Generation (DG) units, such as renewable energy generators and combined heat and power units, along with storage devices and controllable loads (e.g. air conditioners) [1]. Their unique characteristic is that they can be islanded, especially during fault incidents to increase the supply reliability. Currently, the most common application of DC MGs is the electric power supply of isolated systems like vehicles, space crafts, data centers, telecom systems, while they have been proposed for rural areas and islands [2]- [4].

The DGs are interconnected via an AC link forming an AC MG, or via a DC link forming a DC MG. While a lot of work has been performed in the operation, control and protection of AC MGs, DC MGs have started attracting attention recently, due to their potential advantages over AC MGs, such as: (i) The incorporated DGs can be easier coordinated, as their control is based on DC voltage without the need for synchronization. (ii) The corresponding primary control is notably less complex as the reactive power flow control is absent. Yet, the DC link can suffer from harmonic content. (iii) As the DC electronic domestic loads dominate today, unnecessary AC/DC power conversions are avoided as most DGs generate DC outputs. This has a direct effect on system cost and losses. Also, the converters used for the DC microsources interface, are mostly transformer-less reducing further the size and cost of the system. (iv) DC protection in general is difficult due to no zero crossing to interrupt on. But the DC system does not experience high fault currents as the contribution to faults by the converters of the power electronic interfaced load or DGs is limited [2], [5], [6].

Figure 1 shows the structure of a typical DC microgrid. It should be noted that the DC MG topology may differ from the radial single feeder configuration to two-pole or ring configuration. In these topologies either unipolar or bipolar configurations can be implemented. Bipolar configurations can provide more voltage level options in comparison with unipolar connections. With respect to the voltage levels, they can differ in accordance with the operating requirements of each system. For example, 380 V is a typical voltage level for data centers, while 20, 230, 325 V are typical voltage levels for house installations. Other levels could be 1500 V, ±750 V, ±230 V, ±170 V etc. The components of a MG, as shown in Fig. 1, can be mainly categorized into four types: DG units, AC and DC loads, Energy Storage Systems (ESSs), and upstream main grid connection using a bidirectional AC/DC converter.

Microgrid control must insure that: (i) new distributed generation and storage systems can be added or removed from the microgrid seamlessly, (ii) equal and stable current sharing between parallel power converters (i.e. sources) is enabled, (iii) output voltage fluctuations can be corrected, and (iv) desired power flow from/to the microgrid together with technically and economically viable operation is enabled.

For safe and reliable operation of DC MG, a well-functioning protection system is instrumental in any topology. Its principal objective is to minimize the propagation of disturbances by detecting and isolating faults within the

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minimum time frame [7], [8]. Protection of DC systems is in general a challenging task due to difficulties in extinguishing arc, which on the contrary happens naturally in ac systems. Accurate short-circuit current calculation and fault detection are the most important prerequisites for the good design of protection system [9]- [11]. Moreover, an assessment of the influence of realistic protection devices and grounding methods on the total system performance becomes critical when deploying a protection system in real-world environment. Up to this point, protection of DC MGs was designed based on technologies and strategies taken over from existing matured solutions developed for auxiliary DC systems in big power plants and traction power systems [12]. However, a number of new coordinated protection strategies have been proposed in the recent years.

The remainder of this paper is as follows: Section 2 discusses the power management in grid-connected and islanded mode of operations. In Section 3, the available methods for control of DC microgrids are presented. Section 4 describes the key protection issues and challenges in DC microgrids and introduces the existing protection devices and approaches. Finally, in Section 5 conclusion is reported and some research directions and open issues for the realization of future DC microgrids are pointed out.

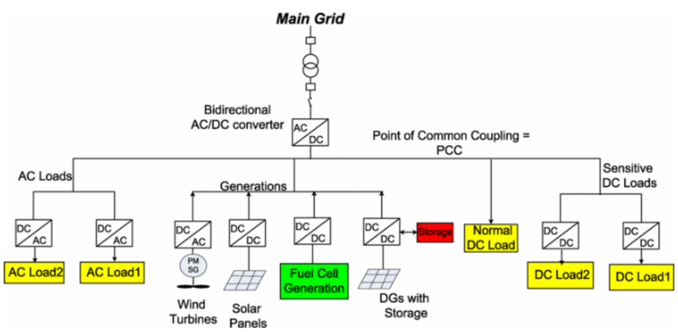

Fig. 1. Structure of a typical DC microgrid

II. Power Management in DC Microgrids

A microgrid is connected into the utility grid through a bidirectional power converter, that continuously monitors both sides and manages power flow between them. If there is a fault in the utility grid, the power converter will disconnect the microgrid from the grid, creating an islanded energy system. The microgrid can continue to operate in the islanded mode, that is primarily intended to enhance system reliability and service continuity, and it is typically unplanned. However, it can also be introduced intentionally for maintenance purposes through the main switch. In some cases, islanded operation is the only mode of operation, e.g. in off-grid remote electrification system. As a result, there are two operation modes for a microgrid: (i) grid-connected, and (ii) islanded mode.

In a DC microgrid which consists of: (i) distributed generation sources such as photovoltaic panels, wind turbine and fuel cells stack with electrolyser, (ii) distributed storage devices such as batteries and supercapacitors, and (iii) critical and non-critical loads, all are connected in parallel into the common DC link through corresponding power converters. The power flow of the systems in the considered DC microgrid is shown in Figure 2.

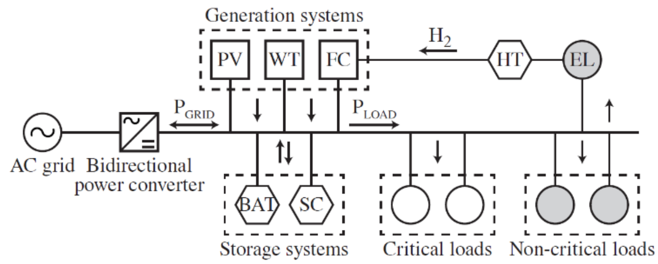

Fig. 2. Power flow in a DC microgrid

The sum of the output power of the photovoltaic panels, the wind turbine and the fuel cells, i.e. distributed generation sources, is defined as:

$$P_{DG} = P_{PV} + P_{WT} + P_{FC} \tag{1}$$

Where $P_{PV}, P_{WT}, and\ P_{FC}$ are photovoltaic panels, wind turbine and fuel cells output power.

The distributed generation systems supply unidirectional power to the DC microgrid and play a role as the main energy source. Since energy storage devices control the power balance of a DC microgrid by charge and discharge, the power flow is bidirectional and the reference power for energy storage devices is defined as:

$$P_{DS} + P_{BAT} + P_{SC} + P_{EL} = P_{GRID} + P_{DG} - P_{LOAD} \tag{2}$$

Where, P_{BAT} and P_{SC} are batteries and supercapacitors charging power, P_{EL} is the electrolyser power, P_{LOAD} is the required power of all loads connected into the DC microgrid, critical and non-critical, and P_{GRID} is the utility grid power.

The loads are assumed to demand unidirectional power from the microgrid. According to a varying local demand, the distributed storage systems realize a power balance, and thus make a continuous high-quality power supply to the load possible [6]. In a case of power shortage that can occur when utility grid is not available, non-critical loads can be disconnected from the microgrid. In the following subsections, a simple algorithm of power management for DC microgrid is described. However, the problem of the optimal power management will be handled by the control algorithms.

A. Grid-Connected Mode

In the grid-connected operation mode, the grid-tied power converter has control over the DC link voltage level. If the sum of the output power of the distributed generation systems is sufficient to charge the storage devices, any excessive power is supplied to the utility grid. If the sum of the output power of the distributed generation and storage systems is deficient with respect to the load demand, the required power is supplied from the utility grid. In the grid-connected mode, power management is performed in a complementary manner between storage devices and as a result a DC microgrid can operate safely and efficiently.

B. *Islanded Mode*

When a DC microgrid must be separated from the utility grid and switch to the islanded mode, the grid-tied power converter releases control of the DC link voltage level, and one of the converters in the microgrid must take over that control. Since each converter of distributed generation sources is used for optimal control of its belonging source, only the converters of the energy storage elements are free to regulate the DC link voltage level. During the islanded mode, the battery plays the main role in regulating the DC link voltage level, and the supercapacitor plays a secondary role in responding of the sudden power requirement as an auxiliary source/sag, i.e. for peak shaving during transients.

III. Available Methods for Control of DC Microgrids

A DC microgrid control is often implemented in a hierarchical manner, with three control loops: (i) Primary control: This control deals with the load sharing among the DGs. The DC–DC power converters of the DGs are responsible for this mechanism. (ii) Secondary control: This control is responsible for voltage fluctuations regulation. It is also in charge of synchronization process to reconnect seamlessly the microgrid to the upper grid. (iii) Tertiary control: It sets the power flow between the DC MG and the upper grid. It is also known as energy management system and it communicates with the Distribution System Operator (DSO). The DSO or even the Transmission System Operator (TSO) might decide the schedule of power exchange with the MG. The hierarchal control of a DC microgrid is depicted in Figure 3.

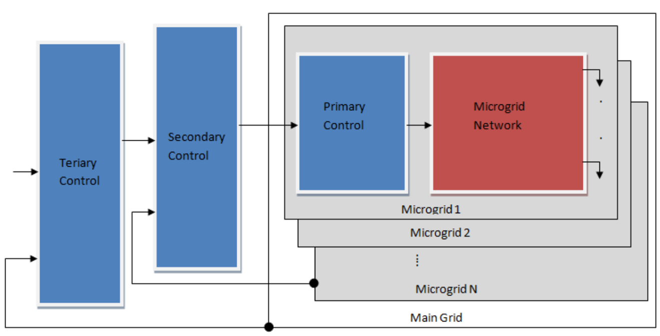

Fig. 3. Hierarchal control of a DC microgrid

In this paper, only primary control is discussed which is categorized into two basic categories: (i) active load sharing, and (ii) passive load sharing or droop control methods. It is also possible to design a hybrid control method combining good aspects of active load sharing and droop control method, but this will not be further discussed.

A. *Active Load Sharing Method*

The first category of primary control is the active load-sharing technique which requires intercommunication link. Although these links limit the flexibility of the microgrid and degrade its redundancy, both tight current sharing and low-output-voltage fluctuations can be achieved. The following section provides a review of the existing active load sharing control methods for parallel converters available in the literature [13]. The active load sharing control methods can be classified into three different types: (i) centralized control, (ii) Master-Slave (MS) control, and (iii) circular chain control (3C).

1) *Centralized control*

A Central Control Board (CCB) is necessary in this scheme in order to set the reference current for each module. The measured load current is driven in the CCB where is divided by the number of the modules in parallel (N), forming the reference current (i_j^*) of each module j. Subsequently, the reference current is subtracted from the current of each module. The error is processed through a current control loop (CL). An outer control loop in the centralized control adjusts the load voltage. The main drawback of this method, apart the central controller, is the need to measure the total load current, so the application of this scheme in a large distribution system is difficult.

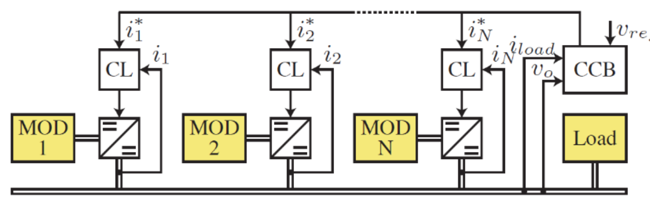

Fig. 4. Centralized control of a DC microgrid

2) *Master-Slave (MS) control*

The structure of a Master-Slave control is shown in Figure 5. As can be seen from the figure, one inverter (master) regulates the voltage and sets the current references of the other units (slaves) [13]. So, the master inverter operates in voltage control mode and the rest of the units in current control mode. The main drawback of this method is the single point failure and the requirement of a supervisory control. The system is also difficult to expand, failing to satisfy the plug and play functionalities.

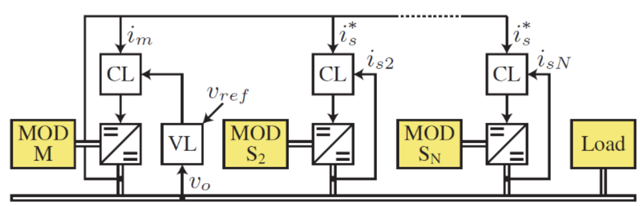

Fig. 5. Master-Slave (MS) control of a DC microgrid

3) *Circular chain control (3C)*

The structure of Circular chain control is shown in Figure 6. In this scheme, the current reference of each module is taken from the other module, forming a control ring [15]. Obviously, in order to form the circular chain, the current reference of the first unit is obtained from that of the last unit. An interesting variant of the circular chain control is the current limitation control. In this case, the master–slave logic is present. The voltage is controlled by the master module (inverter under voltage control) and the slave modules share the load current (inverters under current control). The circular chain in this case is formed only by the slave modules and the master module is exempted. The current command of the slave is generated by its previous module and limited in amplitude forming the circular chain. It should be noted that every module can become the master.

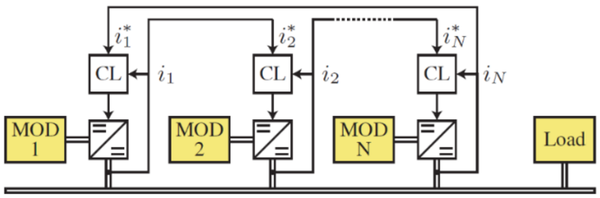

Fig. 6. Circular chain control of a DC microgrid

B. *Droop Control Method*

The basic principle that allows synchronously rotating AC generators to change their power output in response to a change in the system load, without an explicit communication network, is the frequency and voltage variation at the machine terminals. Normally, frequency is linked to active power, and voltage is linked to reactive power. Standard rotating generator systems inherently support these droops (natural synchronizing torque) [1]. Similar droops are also emulated at the DGs inverters for power sharing in an AC microgrid. The droop concept applied at a DC microgrid is slightly different, as the frequency and reactive power are absent and thus, the active power is linked directly to the DC voltage. The droop characteristic of a converter in a DC microgrid can be a linear function between V and I (commonly used) or between P and V. This droop concept can be easily applied at the DG power converters offering independent control and modularity. Load sharing is achieved directly without the need for communication. Application of the droop concept can create circulating currents among the DGs when the power converters are treated as voltage sources. In order to suppress these circulating currents, two solutions are proposed which are discussed in the following subsections.

1) *Virtual output impedance*

In the virtual output impedance control, shown in Figure 7, current at the module output is sensed and sent back to the module input via virtual impedance R_D, where is compared with the output voltage reference at no load [17]:

$$v_o^* = v_{ref} - i_o R_D \tag{3}$$

Where i_o is the module output current, R_D is the virtual output impedance, and V_{ref} is the output voltage reference at no load.

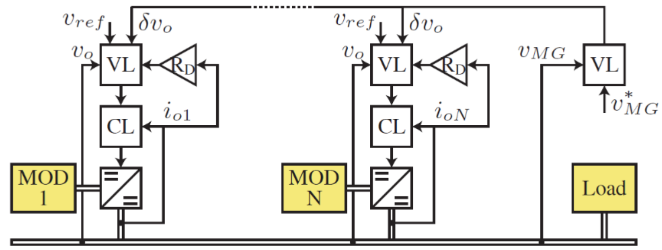

Fig. 7. Droop control of a DC microgrid via virtual output impedance

This control loop has the inherent load-dependent voltage deviation. To solve the problem of the voltage deviation, the voltage level in the microgrid v_{MG} is sensed and compared with the voltage reference v_{MG}^*, and the error processed through a compensator is sent to all the modules to restore the output voltage. The controller can be expressed as follows:

$$\delta V_o = k_p e_v + k_i \int e_v \, dt \tag{4}$$

$$e_v = v_{MG}^* - v_{MG} \tag{5}$$

Where k_p and k_i are the control parameters of the microgrid voltage level compensator. Finally, (3) becomes:

$$v_o^* = v_{ref} + \delta v_o - i_o R_D \tag{6}$$

2) *Series resistor*

In the series resistor control, a resistor is placed in series with the module output to provide a voltage drop in the output. The resistor value is set via a potentiometer so that the voltage drop of the output of all paralleled DGs, are made almost identical. Obviously, the major disadvantage of this approach is the high power dissipation in the series resistor, if the drop in output voltage is large. Because of added power dissipation, this method is used only for low-power linear post-regulators [18]. Microgrid voltage level deviation is corrected in the same way as in virtual output impedance control method.

IV. Available Methods for Protection of DC Microgrids

Protection devices that are presently commercially available for DC systems include fuses and circuit breakers (CBs) [19]. However, they inherently introduce large time constants and time delays before activation, respectively. In addition, interruption of current in both cases is accompanied by the appearance of the arc. While arc gets extinguished naturally in ac systems within the half cycle after tripping by first crossing of the current through zero, it presents a challenge in dc systems since the current has a steady value. Arc occurrence presents a dangerous condition not only from the safety point of view, but also causes contact erosion in CBs and consequently a short lifetime and high maintenance costs.

Protection of DC microgrids by means of fuses and circuit breakers has some performance restrictions due to their inherent large time constants and time delays, respectively. In order to overcome the limitations, Tang and his colleague presented a new current interruption approach for Multi-Terminal DC (MTDC) grids and navy shipboard DC Zonal Electric Distribution (DCZED) systems by means of electro-mechanical switches. In their proposed approach, they split the network into several zones and make use of no-load switches to cease the fault currents [20], [21]. More precisely, once a fault was recognized in a zone, converters supplying the network de-energize the bus(s), and subsequently the faulted zone is isolated by no-load switches. Finally, the rest of network is re-energized to continue its operation. The main problem with the proposed approach is that it entirely shuts down the network after the fault detection which may not be necessary.

An alternative approach was proposed using Solid State Circuit Breakers (SSCBs) at DC terminals of Voltage Source Converters (VSCs) or on the downstream side of DC/DC converters [22], [23]. The approach can be implemented by different solid state switches such as Gate Turn-Off (GTO) thyristors, Insulated-Gate Bipolar Transistors (IGBTs), and Insulated-Gate Commutated Thyristors (IGCTs). However, employment of each of the switch topologies has its own merits and demerits [22]. SSCBs are also equipped with a parallel combination of a snubber circuit and Metal–Oxide Varistors (MOVs) to dissipate power during the interruption of fault currents. Notwithstanding advantages of SSCBs, some of their demerits make them disputable. Contrary to mechanical contacts, the maximum operating voltage and current of SSCBs are limited in order to protect their switching devices. However, in practice, their capacity can be enhanced via series and parallel connection of IGBTs. Moreover, Overrating of SSCBs leads to exponential increase of costs.

In 2009, Salomonsson et al. presented an approach based on proper selection of protective devices corresponding to the fault withstanding capability of each network component [24]. According to their research, ultrafast hybrid CBs are proposed for protection of power electronic devices in order to quickly interrupt the current flowing from their sensitive switching devices including IGBTs and diodes. On the contrary, regular CBs are suggested to protect batteries, since they can withstand drastically large currents without damage. Moreover, they also applied fuses and MCCBs for protection of network feeders. To be more precise, they claimed that MCCBs should install closer to the loads due to their capability in simultaneous interruption of currents in both positive and negative poles, whereas fuses are more suitable to be installed closer to the buses, since their magnetic sensing provides good selectivity.

In 2012, a new type of solid state breakers, termed as z-source breaker, was introduced [25]. The breakers are able to automatically commutate a main-path Silicon-Controlled Rectifier (SCR) during a fault by means of a z-source LC circuit. In spite of swift operation of the z-source circuit breakers, their resonant circuit is strongly dependent on the fault characteristics as well as the parameters of upstream and downstream components. In addition, voltage oscillations resulting from resonant circuit may lead to overvoltage on other network components. The structure of a z-source breaker is depicted in Figure 8.

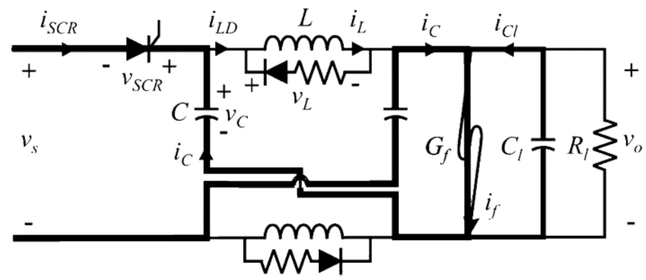

Fig. 8. Structure of a z-source breaker

In [26], Fletcher and his research group proposed unit protection approach against non-unit ones which often overlook the high sensitivity of the network response to the fault impedance. Also, they attempted to identify the means by which the fast and effective protection system operation is achieved, whilst seeking to minimize installation costs, against a set of very strict operating requirements. Finally, they presented a flexible design framework for unit protection of DC microgrids with a high selectivity as well as considering optimum operating speed and total cost of the system. In addition, the results of the study indicated that their proposed protection scheme provides a better fault discrimination in comparison with previous studies.

The authors of [27] developed a new protection scheme for low voltage DC-bus microgrids to isolate the smallest possible faulted area to allow the rest of network maintains operating. In their offered strategy, they make use of a loop-type DC bus along with segment controllers, consisting one master and two slave units, between the loop components. First, the master unit receives the values of current measured by the slave units, and then issues the proper disconnection commands to the bus switches depending upon the difference between these values.

V. Conclusion and Future Research Directions

The Penetration of microgrids is currently growing around the world, since they offer less environmental impact, low running cost as well as high reliability and power quality. a DC system is a reasonable option for microgrids, as many energy sources are DC and require only a straightforward voltage conversion. This paper presented a comprehensive overview of the body of research in the area of power management, control and protection of DC micro-grids. With regard to the analysis of the large number of technical publications presented in the previous sections, implementation of future DC microgrids necessitates simultaneous development of the following fields: (i) communication systems play a key role by providing a bidirectional connection between network components and management unit. Development of communication technologies requires economically analysis of high data rate and coverage technologies as well as energy-efficiency enhancement by means of relaying techniques, Coordinated Multi-Point (CoMP) technology or mobile relays. (ii) combination of control and protection schemes can be effective in resolving many challenges in future of DC microgrids such as self-healing, Low Voltage Ride Through (LVRT) as well as driving current to zero prior to its interruption by circuit breaker.

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