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A Review of Control Strategies In DC Microgrid

Liyue Zhang, Weiliang Zhang, Fanzheng Zeng, Xiongzhen Yang

Faculty of mechanical and electrical engineering, HeZhou University, HeZhou, Guangxi 542899, China

zhangweiliang129@163.com Correspondent author：Fanzheng Zeng，E-mail:94265883@qq.com

Abstract. This paper presents a review of control for dc microgrids (MGs). The control strategies classified into local and coordinate control according to their respective functions. Among the two control strategies, local control method in which the biggest contribution is droop control depends only on local measurements to achieve control objectives. However coordinate control needs some line of communication between the units in order to achieve the coordination in the dc MGs. According to the communication method, there are three basic control strategies which are distributed control, centralized control, and decentralized control. These three control methods have their own features respectively. Their common purpose is to make the dc microgrids can be better and stable operation. The aim of this paper is to provide an overview of control strategies used in dc MGs.

1. Introduction

In recent years, due to the shortage of fossil fuels, serious environment problems and renewable energies such as fuel-cell, wind energy, and solar energy which have more demand, much effort has been focused on the development of environmentally friendly distributed generation (DG) and its technologies have been studying in many countries [1][2]. A large number of distributed power generation units are appearing in the power system that is undergoing tremendous changes and forming the microgrid which get the in-depth study today. the microgrids can be divided into two forms ac and dc, the latter is more superior compared with the former, so the dc MGs is the trend and can provide the energy better for the power users[3][4]. The dc Microgrids enable a coordinated integration of the DG units in the electrical power system and keep the emerging potential of DG to bring more perfect power system[5]. In remote areas, the load demand is quite lower than the developed area. Therefore, both the transmission and daily maintenance costs must be considered, thus supplying power from the grid is not the best choice. Hence, the standalone dc MGs power system serves as most suitable power source in the remote area and offers the advantages , such as reduction in running and maintenance costs[6]. Moreover, dc microgrids can still operate while completely separated from the grid this is called the island operation mode, it is a relative lower-cost choice to provide electrical power for regions in developing countries because conventional ac grids are unavailable or are unreliable. It is a big fact that local distribution units would greatly benefit from using dc MGs rather than ac system as selecting an dc interconnection bus is more simpler, more reliable, and more efficient than using ac to implement microgrids, mentioned in [7]. However, dc microgrids still pose many technical and operational challenges such as smooth transition from off-grid operation to grid-connected. DGs are connected to a dc MG through a controllable power electronic interface converters and used to regulate the common dc bus voltage. Droop control as a

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popular method of achieving cooperative operation among paralleled converters without digital communication links (DCL) is always the best choice. This method is based on adding a so-called virtual resistance (VR) (also called droop coefficient) control loop on top of the converter's voltage regulator which can achieve current equally share and can also provide active damping to the system and have the plug and play capability at the same time [8][9]. This paper is organized as follows. In Section II, basic control principles are presented and analyzed. It has been demonstrated how the overall converter control strategies of the whole system is split into local control and coordinated control. Section III demonstrates a number of functionalities in the local control of the system, while coordinated control another control strategies of the overall system is explored in Section IV. Conclusion and future research direction will be found in section V.

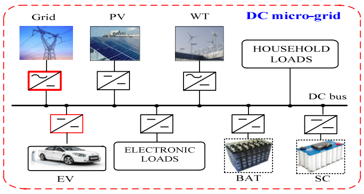

Figure 1 System diagram of a dc MG

2. The Control Principles Of DC MGs

In order to guarantee the dc MG operate efficiently and stably, there should be some effective control strategies to be developed. A general structure of a dc MG system is displayed in Figure1. Generally speaking, a dc MG contains a number of parallel converters which may work in much harmony. The local control strategies of the parallel converters typically include the following sections: 1) the photovoltaic (PV) modules and wind turbines (WT) which usually work in maximum power tracking (MPPT), sometimes they may work to maintain the dc bus voltage or current limiting mode, while the ESSes that is different from PV and WT have to be considered the state-of charge. 2) the common control of the converters is the drop control not only because its inherent modularity and ease of implement but also it can achieve the current coordinate between the different converters. The output voltage of the droop controlled converter is presented as equation (1).

$$V_{\mathrm{i}} = V_{ref} - R_{v_i} \cdot i_{l_i} \tag{1}$$

Where, ilirepresents converter. Vref represents converter terminal voltage under no-load, in this equation the variables can be others which can be seen in the following. Figure 2 only shows the V-I droop characteristics.

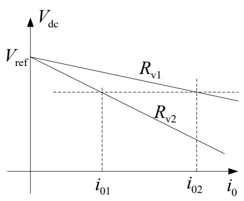

Figure 2 characteristics of droop control

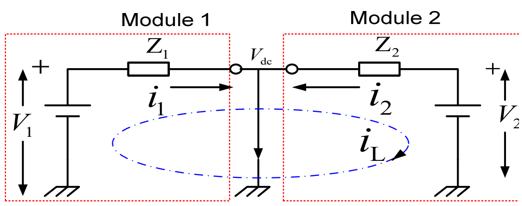

Figure 3 the circulation of parallel units

3) two different converters may exist circulation if their output voltage is different, which is shown in Figure 3, so there are some methods have to be developed to solve this problems, such as dc bus signaling (DBS) control, or power line signaling (PLS) control. In order to achieve the advanced energy management, there must be a digital communication-based coordinated control to be carried out. Via central controller can realized centralized and distributed control, respectively. The distributed control exchanged the variables of interest only between local controllers. In the following section, there is a detail explanation on how to achieve it.

The control of dc MGs will be classified into three categories which are decentralized control, centralized control, and distributed control. A more detailed overview of the significant features of coordinated and local control strategies is provided in the following sections.

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3. The Local Control Of Dc MGs

As already mentioned above, the control strategies of a dc MG classified into local control and coordinated control depending on different control levels. This section will discussed the local control in detail which will be reviewed in current , voltage, and droop control.

In a dc MG, the interface converters can ensure the overall system operate efficiently and reliably. The proper local operation and coordinated interconnection between different modules in a dc MG need flexible local current and voltage control. At the same time, accurate power sharing must be considered and achieved among the parallel connected converters. In Figure 4, this paper showed the basic local control diagram which consists of local voltage and current controller, and a loop of droop control. This control plan based on the P-controller which modifies the effective droop gain to achieve good voltage regulation and accurate the load sharing simultaneously combine conventional droop control with hierarchical secondary control. There is only one communication line which is used to maintain the dc bus voltage. While, it does not require communication between the sources in the single area[10].

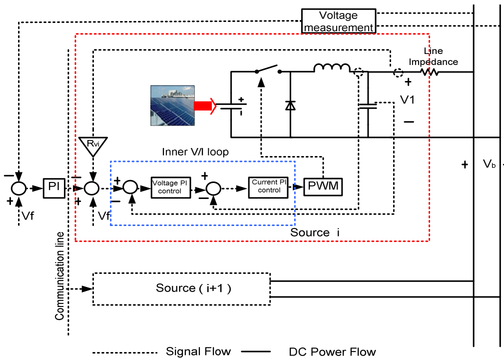
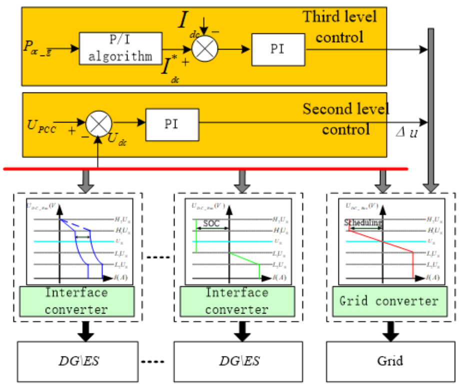


Figure 4 Hierarchical Secondary Control

In addition, there is a method based on no interconnection communication which can allow the bus voltage to fluctuate within a certain range when the dc MG works in island mode, but there are some different things when the dc MG connects to the grid. Figure 5 shows the core idea of the networking mode control program. The possible error in voltage regulation with the PI controller will generate the PWM to regulate the converter which connect to the grid. That is to say, the dc bus voltage is maintained by the grid in this mode. When the dc bus voltage is too high or too low the converter will work in current limited mode which is the third level control.



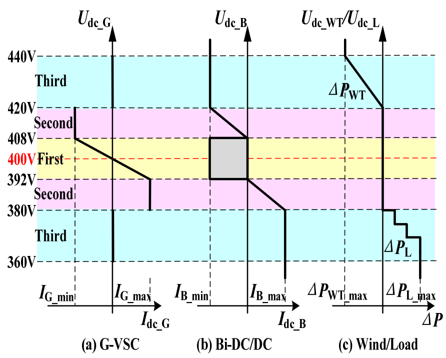


Figure 5 Hierarchical Control of networking mode Figure 6 Hierarchical Control of island mode

Figure 6 shows the control of island mode. In a dc MG system the voltage is the only indicator of the power balance. In this case, the rated voltage is 400V and the allowable range is $\pm 5\%$. This method have the advantage of no communication, micro-source plug and play ,and fast response. The TABLE I shows the different levels and the converters situation.

Table 1 The working state of the converter under the DC bus voltage stratification control strategy

Level	**Converter**				
	G-VCS	***Bi-DC/DC***	***W-VCS***	***L-VCS***	
First	Droop	Constant current charge	MPPT	Rated AC voltage	
Second	Current limited	Droop	MPPT	Rated AC voltage	
Third	Island mode	Constant current charge	Down power	Rated AC voltage	
		Constant current discharge	MPPT	Load shedding mode	

Depending on the feedback variable, the droop control methods for voltage-source converter can be grouped in two types: current-/power-mode droop, they are current-voltage ($I-V$) and power-voltage ($P-V$) strategies, and voltage-mode droop, including $V-I$ and $V-P$ strategies. The $I-V$ and $P-V$ methods are shown in Figure 7 (a) and (b). In the implementation of these control methods, the dc voltage is measured and injected current/power is controlled according to the droop curve. Alternatively, in the $V-I$ and $V-P$ methods shown in Figure 7 (c) and (d), current or power is measured and the dc voltage is regulated accordingly [11].

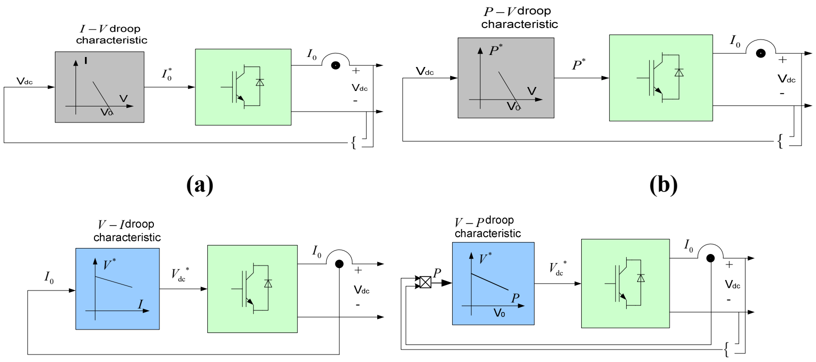


Figure 7 the different droop control method

4. Coordinated Control Of Dc MGs

The control of the local interface converter is an absolutely necessary part of a dc MG. However, the coordinated control should also be implemented in order to achieve an intelligent control. As mentioned above, it can be realized either by using decentralized, centralized, or distributed control depending on the means of communication between the interface converters. The following will introduce the three methods separately. Fig. 8 shows the three operating principles of basic strategies.

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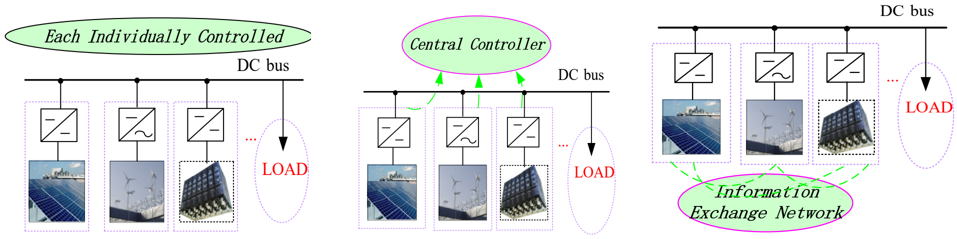

(a) Decentralized control (b) Centralized control (c) Distributed control
Figure 8 Operating principles of basic control strategies

4.1. Decentralized Control
As mentioned earlier，Decentralized coordination is one of the control strategies of the dc MGs, whose strategies is shown in Figure 8 (a). In this part, we may review the decentralized methods which have the ability to coordinate the performance of multiple parallel converters in dc MGs. Currently, the most common ones will be thought including DBS, PLS, and the method of droop coefficient adaptive adjustment[12]-[14]. These methods have some advantages which contain the simplicity of control and not affected by digital communications. But at the same they also inherently have the limitations of performance not only because they do not exchange the information from other units but also their effectiveness and reliability will be impacted by the accuracy of voltage sensors.

For the dc MGs, DBS control is seen as the most significant decentralized coordination approach. By using this method, coordinated operation between different distributed units in dc MGs is achieved by detecting the DC bus voltage variations in the common dc bus voltage. The DBS principle is shown in Figure 9 which is the steady-state model of a DC microgrid. It can be seen from the figure that distributed units are substituted either as current and voltage sources simplified from control block diagram [15] or by The venin equivalent circuits, which depend on their internal operating mode. The equivalent circuit is used to demonstrate the droop control mode of a given unit in the dc MGs. The voltage source U_{N} then corresponds to a voltage reference which is the rated voltage of the dc bus in the dc MGs, while the series impedance k_{d} corresponds to virtual impedance which is used to regulate the output voltage, the L_{d} and r_{d} are equivalent to the line equivalent impedance. Relaying only on local information, the DBS control can make the dc MGs work well , that is to say, it does not need any other components, but interface converters is enough. That is why decentralized control method can be simple to implement and achieve the ideal effect. The main concern here is how to select the appropriate voltage levels which are used to identify different operation modes [as shown in Figure 6]. Because if the difference among the adjacent voltage levels is too large , the dc bus voltage fluctuation will exceed the largest acceptable range. In contrast, if the difference among the voltage levels is too small ,the sensor inaccuracy and the dc bus voltage ripples could then lead to wrong recognition of proper operating modes.

As mentioned above, another method for decentralized control is PLS that can be developed well for coordinated control between the interface converters. Especially, the devices will send and receive the information from the dc bus to make sure its operational mode, performance or status. In fact, PLS is the control of depending on digital communication, but why here it is still categorized into decentralized control only because communication medium is the power network. Generally speaking, PLS control is regarded as the most complex method to be implemented compared with DBS and adaptive droop strategies. In addition, it could not be used for power sharing but only for shutting corrupted components or changing the operating modes of the system.

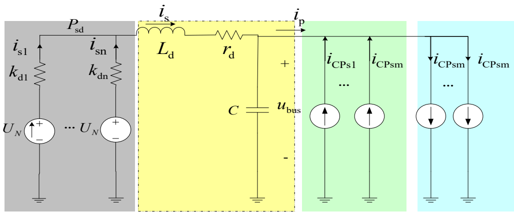

Figure 9 stable model of DC microgrid

4.2. Centralized Control

Centralized control adds a centralized controller to the entire parallel units, each parallel unit according to the centralized controller provide the needed signal to ensure that the output signal is consistent. That is to say, centralized control can be implemented in dc MGs by employing a central controller (CC) and a digital communication network which is used to connect the sources and loads, as shown in the Figure 8(b). For a large dc MGs, the hierarchical control is often a better choice because there is a certain degree of independence introduced by it between different control levels. Moreover, Compared with centralized control, hierarchical control is more reliable since it continues to be operational even in case of failure of centralized control. Coordinated functions of hierarchical control between the parallel units include secondary/tertiary regulation of dc voltage in the dc MGs. However, for the small dc MGs system, the distributed units could be under controlled by the Central Controller directly[16]-[18]. All in all, the single controller can collect and process all relevant data, centralized control can provides the best foundation for using advanced control functions. However, this strategy has a single point of failure which is the most obvious disadvantage. Particularly, it is seriously impacted by the CC and the communication line, since once any of the two devices fail, the information from/to the controller will not be transmitted, thus leading to the corresponding control objectives can not be achieved well.

Currently, the application of centralized control is still very common, since it has its own advantages. [19] proposed a method that can coordinated the integrating massive electric vehicles (EVs) on the charging scheduling of a large number of EVs in the dc MGs. In [20], a centralized model predictive control strategy is developed for vehicle dynamics focusing on autonomous driving vehicles.

4.3. Distributed Control

Distributed control indicates that the distributed units is connected to each other by the communication line. The control principle is different from central control is that the central unit does not exist and through dedicated digital communication line can easily achieve local controller communicate among themselves , as shown in Fig. 8(c). the system can maintain full functionality, when the failure of some communication links occurs, it is regarded as the main advantage of this approach [21]. Therefore, the distributed control can well get over the single point of failure. The functionalities that can be achieved by centralized control can also be achieved by this approach and can represent in the Digital-Communication-line-based coordination control window of Figure4. However, the parallel controllers have a mutual impact on each other, which degrades the transient performance of the system. Therefore, in [22] a cascade control structure, which employs power sharing control as an inner loop and employs bus voltage control as an outer loop, is proposed to alleviate the aforementioned mutual control effect.

All in all, it can draw such a conclusion that compared to the centralized control the distributed control can also achieve information awareness. Therefore, the control objectives of the system, such as the sharing of output current, restoration of voltage, efficiency enhancement of the overall system, SoC balancing of the ESS, and others can also be easily improve and achieve. So it's possible to say that, distributed control with greater advantages can offer much wider functionalities than decentralized control. However, one coin has two sides, the distributed control also has its main limitations which are complexity of performance analysis and non-ideal environments characterized caused by communication time delays and measurement errors of the sensor.

5. Conclusion And Future Direction

Micro-grid scale will be even greater in the coming years and its extended functionalities will increase too. All areas of the system will become more difficult, especially, the control areas. In this paper, we have reviewed the control strategy in dc MG to ensure the system work well. Through the above analysis we can know that local control of converters plays an important role not only in achieving to regulate voltage and current of the system, but also in realizing coordinated control strategies. There are three coordinated control strategies depending on communication between distributed units within the dc MG to be used make it smart, they are decentralized, centralized, and distributed control. The detail analysis is presented in above. However, the control of dc MGs will continue to evolve rapidly in next years to make the system more efficient and stable. The dc MGs contain linear and nonlinear parts, so the dynamic characteristics of the dc MGs need new versions of DBS control, PLS control, and adaptive droop decentralized control. These control strategies will be further studied in the future.

Acknowledgment

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