The Journal of Engineering

The 14th IET International Conference on AC and DC Power Transmission (ACDC 2018)

eISSN 2051-3305
Received on 22nd August 2018
Accepted on 19th September 2018
E-First on 18th December 2018
doi: 10.1049/joe.2018.8419
www.ietdl.org

Multi-level bus voltage compensation of droop control with enhanced load-sharing capability for DC microgrid

Sucheng Liu[1] ✉, Zhongpeng Li[1], Wenjie Liu[2], Xiaodong Liu[1]
[1]School of Electrical and Information Engineering, Anhui University of Technology, Ma'anshan, People's Republic of China
[2]Information Engineering School, Nanchang University, Nanchang, People's Republic of China
✉ *E-mail: liusucheng@gmail.com*

Abstract: In DC microgrid, droop control is an essential part of local primary level in hierarchical control to perform load-sharing and plug-and-play function. The main problem with droop control is that better load sharing is achieved at the cost of higher bus voltage drop, which could even be worse when cable resistance is considered. To solve this problem, a multi-level bus voltage compensation of droop control (MLBVC-DC) for DC microgrid with enhanced load-sharing capability is proposed. With high enough droop gain to ensure load-sharing accuracy, the produced bus voltage drop will be compensated with multi-level feedforward to the reference bus voltage of DC microgrid according to different load regions. Also, the problem with the piecewise droop at load current setting points is solved by hysteretic control and Control Area Network (CAN) communication. Simulation and experimental results verify the proposed MLBVC-DC strategy.

1 Introduction

In last decades, various microgrid (MG) structures have emerged as feasible solutions for integrating distributed generations (DGs) [1]. Amongst them, MG with direct-current bus (DC-MG) has been paid increasingly more attention recently thanks to its prominent advantages, such as simpler control schemes due to absence of frequency and reactive power control, higher efficiency and power quality, and lower cost [2, 3], over alternative-current MG (AC-MG). Fig. 1 shows a typical structure of PV-dominated DC bus microgrid, where the AC utility grid can be connected or disconnected to decide the DC-MG whether in grid-connected mode or islanding mode. The PV and energy storage system (ESS) units in parallel can be operating with local droop control for sharing load power to maintain the bus voltage.

Like hierarchical control paradigm in utility grid and AC-MGs, DC-MG also adopts three-level hierarchical control, that is, primary, secondary, and tertiary levels, where the droop control is widely used in primary level to perform load sharing locally and plug-and-play function [4–6]. However, the main problem with conventional droop control (CDC) is that better load sharing can only be achieved at cost of higher bus voltage drop, which could even be worse when cable resistance is considered. To improve the load-sharing performance, a compensation method to overcome input voltage variation of the DC–DC converter using the detailed unequal line parameters are proposed in [7]. Although no additional communication is needed, the main drawback is the requirement of full knowledge of line parameters in the grid. Adaptive droop control strategy has been presented to achieve better current sharing at heavy load using larger droop gains and less bus voltage drop at light load using smaller droop gains [8, 9]. Similarly, the idea of adaptive droop control method is introduced to balance the state-of-charge (SoC) of each ESS unit [10]. To deal with the trade-off between load sharing and voltage regulation, a secondary control usually has to be imposed to eliminate the bus voltage error caused by primary droop control that for load sharing. A supervisory control [11] is proposed to enhance the performance of droop control by adjusting the droop gain from command in the upper layer controller. In [12–16], various distributed compensation structures with low bandwidth communication are presented. The voltage and current information are shared with each other modules to resolve the negative effect of transmission line. But the multi-loop (more than two control loops) design makes the outer loop compensation a complicated task.

This paper proposes a multi-level bus voltage compensation of droop control (MLBVC-DC) for DC-MG. With a high enough droop gain to improve load-sharing capability, the bus voltage drop can be compensated by the proposed MLBVC-DC strategy via multi-level feedforward to the reference voltage with respect to partitioned load regions. In this case, both the load sharing and bus voltage regulation can be achieved at primary level in hierarchical control of DC-MG. The rest of the paper is organised as follows. The MLBVC-DC strategy is proposed in part 2, simulation and experimental results are provided to verify the proposed MLBVC-DC strategy in part 3. Part 4 finally draws conclusion of the work.

2 Proposed MLBVC-DC strategy

Beginning with basic droop function in DC-MG, the equivalent reduced circuit model of DC-MG with two equal size DG units is

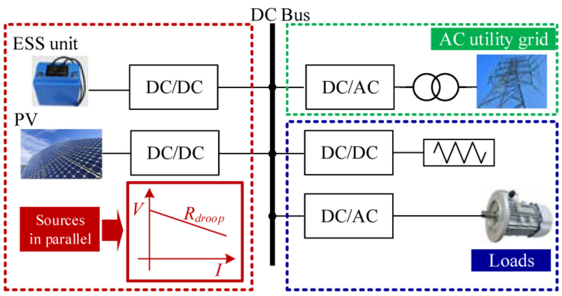


Fig. 1 *Typical structure of PV-dominated DC Bus microgrid*

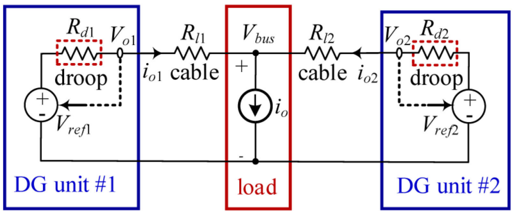


Fig. 2 *Reduced circuit model of DC-MG with two droop controlled DG units*

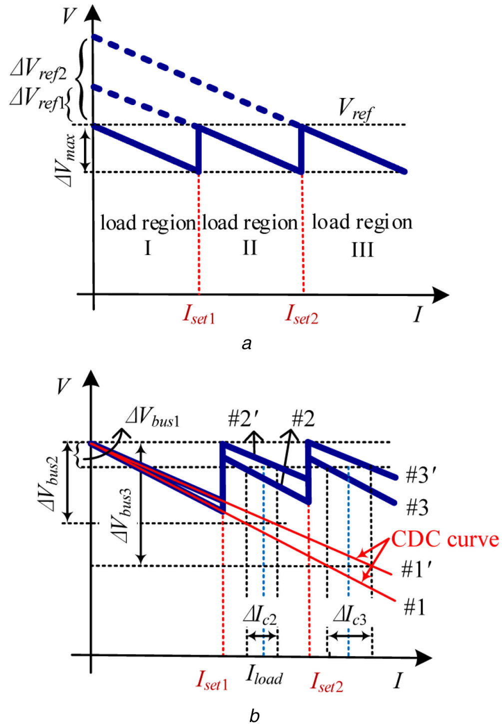


Fig. 3 *Proposed MLBVC-DC strategy and its comparison with conventional droop control (CDC)*
(a) Droop curve of the MLBVC-DC, ***(b)*** Comparison with CDC curve

shown in Fig. 2. According to Kirchhoff's voltage law (KVL), the bus voltage can be expressed as:

$$V_{\text{bus}} = V_{\text{refj}} - i_{\text{oj}}(R_{\text{dj}} + R_{\text{lj}}) \tag{1}$$

where i_{oj}, R_{dj}, R_{lj} and V_{refj} are the output current, the droop gain (i.e. virtual resistance), the cable resistance, and the reference voltage of the j-th (where $j = 1$ or 2) DG unit, respectively.

The ratio of output current of DG unit #1 to that of #2 can be derived as

$$\frac{i_{o1}}{i_{o2}} = \frac{R_{d2} + R_{l2}}{R_{d1} + R_{l1}} \tag{2}$$

It is clear from (2) that ideal load sharing for the two DG units meets with $i_{o1} = i_{o2}$, which implies that two conditions have to be satisfied: (i) $R_{\text{dj}} \gg R_{\text{lj}}$, to fully overcome the negative effect of cable resistances on load sharing, and (ii) $R_{d1} = R_{d2}$, which suggests equal droop gain for the two DG units. However, the side effect of sufficiently large droop gains (condition (1)) is that high bus voltage drop will be produced from (1).

This problem can be addressed with the proposed MLBVC-DC strategy whose droop curve is illustrated in Fig. 3*a*, accompanied by its comparison with CDC curve in Fig. 3*b*. In Fig. 3*a*, the full load range is divided into three load regions, that is, load region I, II, and III, respectively. With droop control, the bus voltage drops with the increase of load current. By MLBVC-DC, two-level feedforward to the reference bus voltage will compensate the voltage drops according to the corresponding load regions. In other words, the reference of bus voltage will be increased in two steps when the DC-MG works through the full load range. Fig. 3*b* shows the comparison of MLBVC-DC with CDC curve, especially in heavier load regions II and III. In load region II, the output current of each DG units is within the range between I_{set1} and I_{set2}, the droop characteristics of the two MLBVC-DC controlled DG units are of #2' and #2 sub-curves, parallel with those of the two CDC curves labelled as #1′ and #1 respectively. In this load range, the load-sharing difference between MLBVC-DC controlled DG units is ΔI_{c2}, which is same as that of CDC controlled ones because the droop gains are exactly same. However, the bus voltage drop of the DC-MG with MLBVC-DC is ΔV_{bus1} which is much smaller than ΔV_{bus2} with CDC. Similarly, in load range III above I_{set2}, the droop characteristics of the two MLBVC-DC controlled DG units are of #3' and #3 sub-curves, still compared with #1′ and #1 of CDC. In that load range, the bus voltage deviation of the DC-MG with MLBVC-DC is also ΔV_{bus1} which is again much smaller than ΔV_{bus3} with CDC although the load-sharing differences are still same as ΔI_{c3}. As a result, by multi-level bus compensation, the droop curve shifts up and down according to the partitioned load regions and the bus voltage drop can be substantially reduced.

In designing the MLBVC-DC, the load range setting point I_{seti} is calculated as

$$I_{\text{seti}} \le \frac{\Delta V_{\max}}{R_d} \times i \tag{3}$$

where i indicates the current setting point for the ith load region of DC-MG, $\Delta V_{\max}$ is the allowable maximal bus voltage deviation and normally ± 5% of the DC bus voltage as in Fig. 3*a*, and R_d the high enough droop gain to ensure load-sharing accuracy.

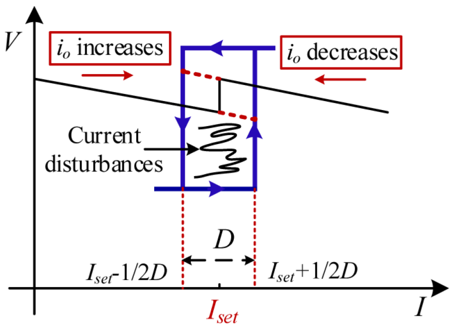


Fig. 4 *Hysteresis control functions around the load current setting point*

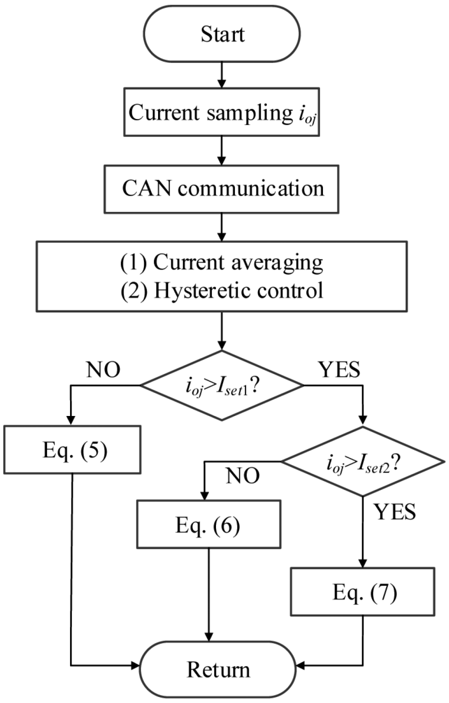


Fig. 5 *Flow chart for control algorithm of MLBVC-DC*

Furthermore, the voltage compensation $\Delta V_{\text{ref}i}$ to the bus reference will be determined by

$$\Delta V_{\text{ref}i} = \frac{I_{\text{set}1} + I_{\text{set}2}}{2} \times R_d \times i \tag{4}$$

where i equals 1 indicating the load region II and i equals 2 indicating the load region III.

By MLBVC-DC strategy, the bus voltage of DC-MG operating in the three load regions can be expressed as

$$V_{\text{oj}} = V_{\text{ref}} - i_{\text{oj}} R_{\text{dj}}, (i_{\text{oj}} < i_{\text{set}1}) \tag{5}$$

$$V_{\text{oj}} = V_{\text{ref}} - i_{\text{oj}} R_{\text{dj}} + \Delta V_{\text{ref}1}, (i_{\text{set}1} < i_{\text{oj}} < i_{\text{set}2}) \tag{6}$$

$$V_{\text{oj}} = V_{\text{ref}} - i_{\text{oj}} R_{\text{dj}} + \Delta V_{\text{ref}2}, (i_{\text{oj}} > i_{\text{set}2}) \tag{7}$$

It is straightforward to code the MLBVC-DC strategy in digital controller from (5) to (7). But, the main problem with MLBVC-DC strategy is that the piecewise nature of the droop curve may cause malfunction around current setting points. Specifically, if with two DG units of MLBVC-DC, those two piecewise droop curves cannot run in exactly same phase, the output currents of the DG units will thus deviate about the setting points. In that case, the droop curve of one DG unit will shift up into load region II, but the droop curve of the other one DG unit may still remain within load region I.

To deal with this problem, the control area network (CAN) communication is first employed to share the current information between each droop-controlled DG units and acquire the average current as the signal to implement the different load region. By doing so, the consistency of the load current sharing can be ensured. In the proposed control scheme, only output current value of each DG unit is shared, which only requires transmission of 2-byte data by each DG unit. Total data transmitted over the communication channel are $2 \times n$ bytes, where n is the number of DG units. Hence, the CAN communication scheme is capable of managing such small data packets. Second, the unwanted repetitive switching between adjacent piecewise droop sub-curves around load current setting points is to be resolved by hysteresis control (HC). As shown in Fig. 4, with HC algorithm added, the influence of the average current disturbances at the load current setting points can be eliminated. Meanwhile, the compensation of bus voltage reference is achieved with reasonable design of hysteresis loop width D. In order to effectively suppress the current disturbance and compensate the bus voltage, the hysteresis loop width D is selected as 0.1 times of the rated output current. In this regard, the load current setting points become $I_{\text{set}} + 1/2D$ and $I_{\text{set}} - 1/2D$ when the current increases or decreases with HC scheme.

Table 1 Circuit parameters for DC micro grid system

Item	Symbol	Value	Unit
reference voltage	V_{ref}	24	V
line resistance	R_{l1}/R_{l2}	0.05/0.1	Ω
droop gain	R_d	0.5	–
current setting point	I_{set1}/I_{set2}	2/4	A
reference compensation	$\Delta V_{ref1}/\Delta V_{ref2}$	1.5/3.0	V

Based on the above description of the MLBVC-DC strategy, the flow chart of the whole control algorithm is deduced as Fig. 5, which will guide one on coding the control strategy in digital controller-based implementations, such as DSP or FPGA. The main procedures of the control algorithm are explained as follows. Starting with DG units' output current sampling, and the sampled current will be gathered via CAN communication. By imposing HC and current averaging function, the consistency of the average current is maintained and the load-sharing error caused by current disturbances at load current setting points also suppressed. Then, the corresponding droop sub-curves will be selected to run with the decision tree based on (5)–(7). In the end, the control algorithm returns with next cycle execution.

3 Simulation and experimental results

3.1 Simulation results

To verify the performance of the proposed MLBVC-DC strategy, the DC-MG model with two DC DG units is preliminarily simulated. Each DG unit is interfaced with a buck-type DC-DC power converter. The system parameters are listed in Table 1.

3.1.1 Current sharing for continuous load: First of all, in order to test the current sharing performance at those current setting points, the load current changes continuously from 1 to 13 A to make each DG unit work through full load range. Figs. 6*a* and *b* show comparison of current sharing at the load current setting

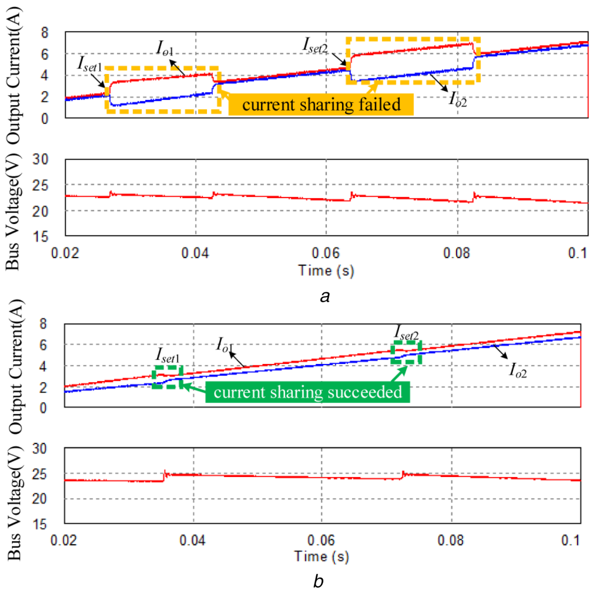


Fig. 6 *Current sharing performance for continuous load*
(a) CAN communication is not activated, ***(b)*** CAN communication is activated

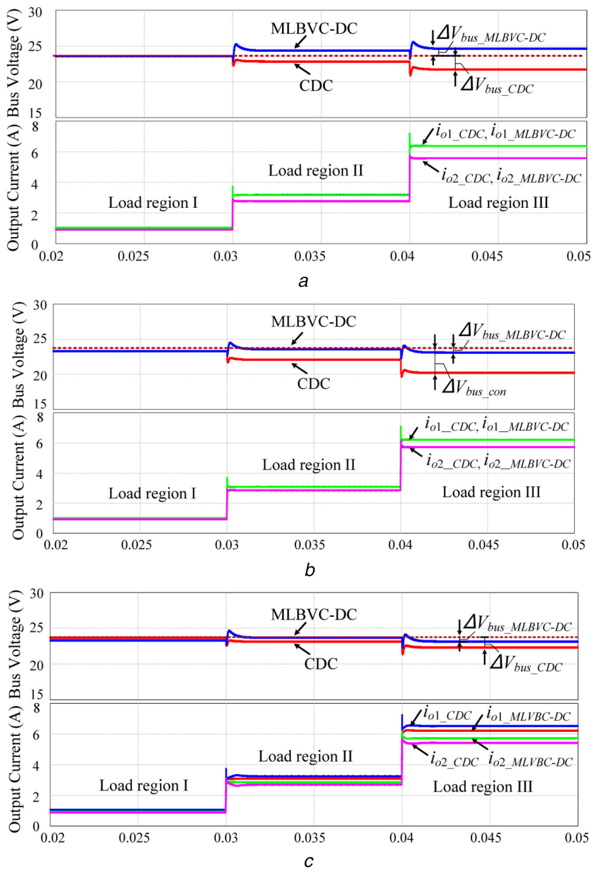


Fig. 7 *Comparison of simulation results between proposed MLBVC-DC and CDC*
(a) Both MLBVC-DC and CDC are with same droop $R_d = 0.3$, ***(b)*** Both MLBVC-DC and CDC are with same droop $R_d = 0.5$, ***(c)*** MLBVC-DC with droop gain $R_d = 0.5$ and CDC $R_d = 0.3$

points with CAN communication between without of it. In Fig. 6*a* where the CAN communication is not activated, the output currents I_{o1} and I_{o2} of the two DG units diverge when working through those two current setting points I_{set1} and I_{set2}. In contrast, the current sharing succeeds at the two current setting points when CAN communication is activated. Besides, the bus voltage of the DC-MG with CAN communication is less disturbed than that of without communication due to current distributions. Therefore, with CAN communication and HC, the DC-MG with MLBVC-DC strategy performs well during continuous load conditions.

3.1.2 Dynamic response to load steps: Based on the simulation for continuous load, dynamic response to load steps for the DC-MG model is tested further. The load current starts with $I_{Load} = 2$ A in load region I as in Fig. 3. At $t = 0.03$ s, the load current steps up to $I_{Load} = 6$ A where indicates the DG units enter into load region II. After that, at $t = 0.04$ s, the load current steps up further to $I_{Load} = 12$ A which says the DG units works within load region III.

For comparing the performance of the proposed MLBVC-DC strategy with CDC, three scenarios were simulated, that is, both MLBVC-DC and CDC are with same droop $R_d = 0.3$, both MLBVC-DC and CDC are with same droop $R_d = 0.5$, and MLBVC-DC with droop gain $R_d = 0.5$ and CDC $R_d = 0.3$, as shown in Figs. 7*a–c,* respectively. With same droop gain for both MLBVC-DC and CDC in Figs. 7*a* and *b*, the current sharing for both two schemes are also the same throughout whole load region, and better sharing can be achieved with higher droop gain, but the voltage drop of MLBVC-DC is always smaller than that of CDC in heavier load regions II and III, that is, $\Delta V_{bus\_MLBVC\text{-}DC} < \Delta V_{bus\_CDC}$, thanks to multi-level compensation for the bus voltage. In this regard, CDC usually uses smaller droop gain like Fig. 7*c*, to sacrifice any load-sharing accuracy for bus voltage regulation. The MLBVC-DC strategy, in contrast, does not has such constraint, both current sharing accuracy and voltage regulation can be achieved.

Moreover, a detailed comparison between CDC and MLBVC-DC on bus voltage error is shown in Fig. 8. With the MLBVC-DC method, the output voltage error is always kept with the limit less than $\pm 5\%$. For CDC, however, the bus voltage error will be exceeding the limit with the increase of the load current above load region I. Therefore, the proposed MLBVC-DC strategy improves bus voltage significantly without sacrificing the current sharing performance, especially at heavier load conditions of the DC-MG.

3.1.3 Experimental results: In addition to simulations, experimental results are provided as well to further verify the proposed MLBVC-DC strategy on a scaled-down laboratory DC-MG prototype whose schematic control diagram is depicted in Fig. 9, and Fig. 10 shows photo of the laboratory prototype. The main parameters are same as listed in Table 1 for the simulation model. The two DG units are both interfaced with buck-type DC-DC power converter in voltage mode control, where the multi-level feedforward compensation in outer voltage loop is added to the control reference of the DC bus voltage.

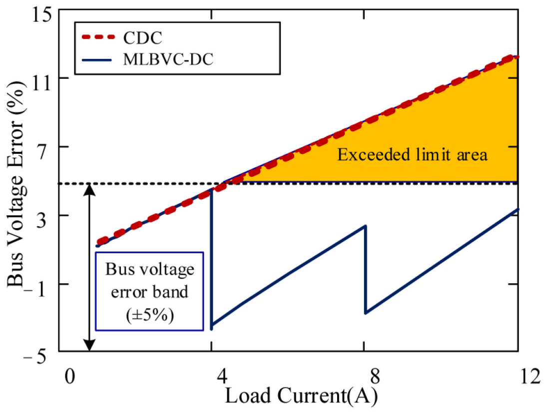


Fig. 8 *Comparison between proposed MLBVC-DC and conventional droop control (CDC) on bus voltage error*

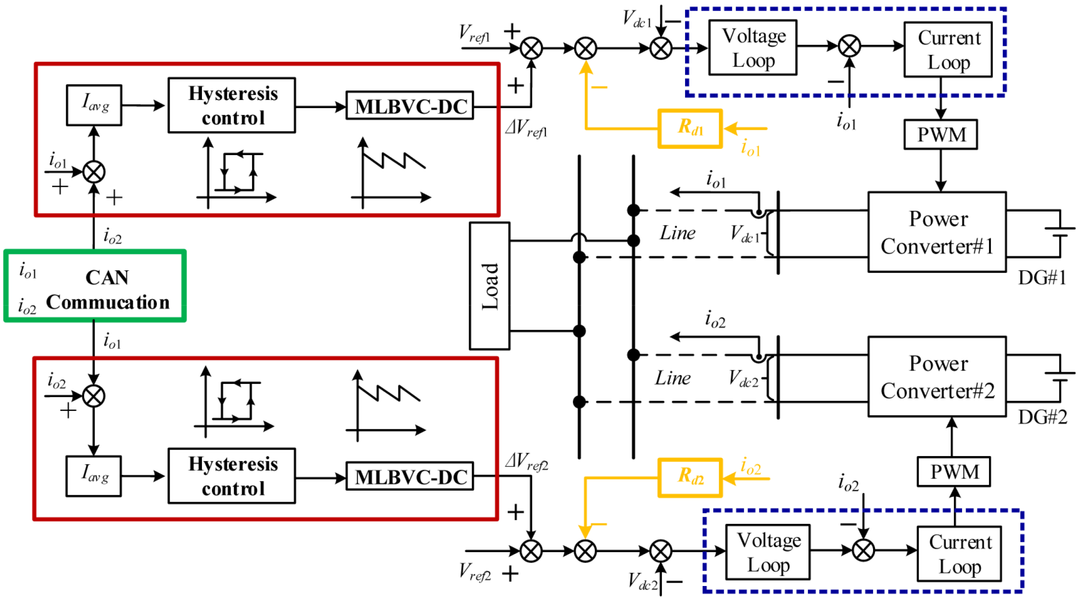


Fig. 9 *Schematic for implementing the DC-MG with MLBVC-DC strategy*

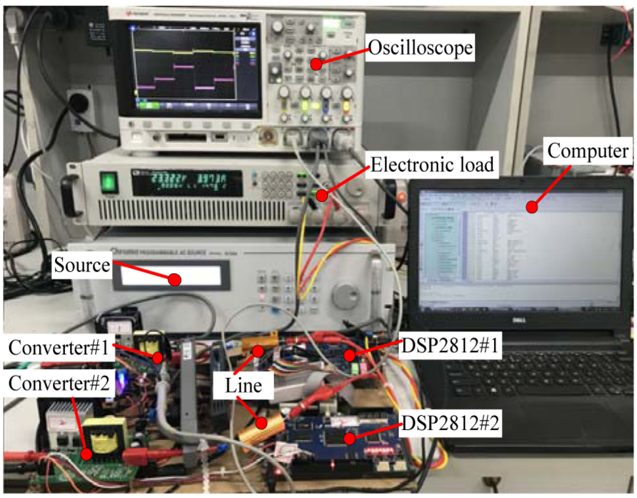
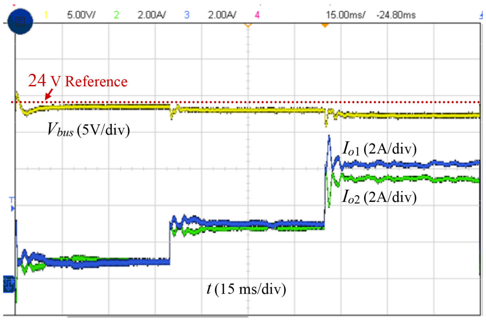


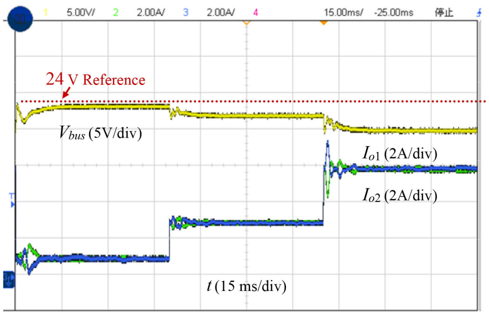
Fig. 10 *Photo of the DC-MG laboratory prototype*

Again, the DC-MG of CDC with different droop gain for the purpose of clear comparison is tested and the results are shown in Fig. 11. Figs. 11*a* and *b* show the CDC testing results with droop gains are given by $R_d = 0.3$ and $R_d = 0.5$, respectively. From these two results, one can find that the larger droop gain, the better current sharing, but the higher bus voltage drop at same time, and vice versa. For this reason, a trade-off must be made between the load sharing and the output voltage regulation performance with CDC method.

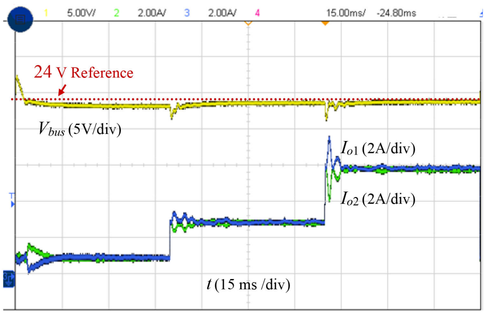
In contrast, the measured result for MLBVC-DC strategy is shown in Fig. 11*c* where it uses a high enough droop gain with $R_d = 0.5$ that is far larger than the cable resistance to overcome the negative effect on load sharing and thus current sharing accuracy is guaranteed first, and meanwhile multi-level feedforward to the reference voltage compensates the bus voltage drop. As a result, not only the load-sharing accuracy but also the bus voltage of the MLBVC-DC-controlled DC-MG are superior to those of the CDC-controlled one.



a



b



c

Fig. 11 *Comparison of measured waveforms between conventional droop control (CDC) versus proposed MLBVC-DC strategy*
(a) CDC with droop gain $R_d = 0.3$, ***(b)*** CDC with droop gain $R_d = 0.5$, ***(c)*** MLBVC-DC with droop gain $R_d = 0.5$

4 Conclusion

This paper proposes MLBVC-DC strategy by which the droop gain can be high enough to enhance the current sharing accuracy, and meanwhile the multi-level voltage compensation added to the bus reference to improve the bus voltage drop caused by *V-I* droop control. Based on the piecewise idea, the proposed MLBVC-DC strategy has the simple and flexible design fashion, and load adaptability has also been realised through the switching between sub-curves corresponding to the different load regions.

Moreover, optimal design of the droop control can be achieved even at primary level only in hierarchical control paradigm of DC-MG. In addition, the current sharing problem with setting points has been addressed by hysteresis control and CAN communications as well. Simulation and experimental results have validated the performance of the proposed MLBVC-DC strategy.

5 Acknowledgments

This work was supported by Natural Science Foundation of China under grant no. 51407003 and Anhui Provincial Science Foundation 1508085EQE97 and 1708085ME106.

6 References

[1] Elsayed, A.T., Mohamed, A.A., Mohammed, O.A.: 'DC microgrids and distribution systems: an overview', *Electr. Power Syst. Res*, 2015, **119**, pp. 407–417

[2] Strasser, T., Andrén, F., Kathan, J.: 'A review of architectures and concepts for intelligence in future electric energy systems', *IEEE Trans. Ind. Electron.*, 2015, **62**, (4), pp. 2424–2438

[3] Radwan, A.A.A., Mohamed, Y.A.R.I.: 'Linear active stabilization of converter-dominated dc microgrids', *IEEE trans. Smart Grid*, 2012, **3**, (1), pp. 203–216

[4] Guerrero, J.M., Vasquez, J.C., Matas, J., *et al.*: 'Hierarchical control of droop-controlled AC and DC microgrids – a general approach toward standardization', *IEEE Trans. Ind. Electron.*, 2011, **58**, (1), pp. 158–172

[5] Maulik, A., Das, D.: 'Optimal operation of droop-controlled islanded microgrids', *IEEE Trans. Sustain. Energy*, 2018, **9**, (3), pp. 1337–1348

[6] Hu, J., Duan, J., Ma, H., *et al.*: 'Distributed adaptive droop control for optimal power dispatch in DC-microgrid'. *IEEE Trans. Ind. Electron.*, 2018, **65**, (1), pp. 778–789

[7] Wang, J.: 'Parallel DC/DC converters system with a novel primary droop current sharing control', *IET Power Electron.*, 2012, **5**, (8), pp. 569–580

[8] Ganesh, R., Panda, G., Peesapati, R.: 'Hardware-in-loop implementation of an adaptive droop control strategy for effective load sharing in DC microgrid'. Proc. Int. Conf. Power Syst., New Delhi, India, March 2016, pp. 1–6

[9] Khorsandi, A., Ashourloo, M., Mokhtari, H.: 'An adaptive droop control method for low voltage DC microgrids'. Proc. Conf. Power Electronics, Drive Systems and Technologies, Tehran, Iran, February 2014, pp. 84–89

[10] Lu, X., Sun, K, Guerrero, J.M., *et al.*: 'State-of-charge balance using adaptive droop control for distributed energy storage systems in DC microgrid applications', *IEEE Trans. Ind. Electron.*, 2014, **61**, (6), pp. 2804–2815

[11] Dragicevic, T., Guerrero, J., Vasquez, J., *et al.*: 'Supervisory control of an adaptive-droop regulated DC microgrid with battery management capability', *IEEE Trans. Power Electron.*, 2014, **29**, (2), pp. 695–706

[12] Anand, S., Fernandes, B.G., Guerrero, M.: 'Distributed control to ensure proportional load sharing and improve voltage regulation in low-voltage dc microgrids', *IEEE Trans. Power Electron.*, 2013, **28**, (4), pp. 1900–1913

[13] Lu, X., Guerrero, J.M., Sun, K.: 'An improved droop control method for dc microgrids based on low bandwidth communication with dc bus voltage restoration and enhanced current sharing accuracy', *IEEE Trans. Power Electron.*, 2014, **29**, (4), pp. 1800–1812

[14] Yang, N., Paire, D., Gao, F.: 'Compensation of droop control using common load condition in DC microgrids to improve voltage regulation and load sharing', *Int J. Electr. Power Energy Syst.*, 2015, **64**, pp. 752–760

[15] Prajof, P, Goyal, Y, Agarwal, V.: 'A novel communication based average voltage regulation scheme for a droop controlled DC microgrid', *IEEE Trans. Smart Grid*, 2017, **99**, Early access

[16] Wang, P., Lu, X., Yang, X., *et al.*: 'An improved distributed secondary control method for dc microgrids with enhanced dynamic current sharing performance', *IEEE Trans. Power Electron.*, 2016, **31**, (9), pp. 6658–6673