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Power Sharing and Voltage Deviation Restriction for Multi-Bus DC Microgrids

Handong Bai, Zhancheng Liu, Hongwei Zhang

***Abstract*— Power sharing and voltage regulation are fundamental but conflict control objectives of DC microgrids. This paper presents a distributed control strategy to achieve adjustment of the control objectives from accurate power sharing to accurate voltage regulation. At the same time, the bus voltage of critical node is regulated to reach the rated value of the DC microgrid. Based on this control strategy, steady state characteristics of the closed-loop system are analyzed. For a given DC microgrid, the proposed control method is verified experimentally.**

I. Introduction

Replacing traditional fossil energy with renewable energy is the most effective and direct way to solve the current energy crisis [1]. But this substitution has also resulted in significant changes in both the structure and dynamics of power systems.

In order to integrate various renewable energys, such as photovoltaic and wind power, and energy storage units, such as batteries and ultra-capacitors, into distributed power grids, the concept of microgrid is proposed [2]. Microgrid is a locally controllable system on the distribution or sub-transmission level composed of multiple distributed generations (DGs), energy storage units and loads.

Since most renewable generations have direct current (DC) characteristics [3], DC microgrid as an effective and reliable integration of DGs is attracting an increasing attention in both power and control communities in recent years [4]–[7]. In order to maintain normal operation of DC microgrids, two fundamental control objectives are generally taken into consideration, i.e., load power sharing [8] and voltage regulation [9]. Load power sharing refers to reasonably allocate the load power among DGs. Voltage regulation aims to guarantee the bus voltages within a admissible range around their rated value. To attain these objectives, a distributed two-layer control structure is usually adopted in DC microgrids as shown in Fig. 1. Therein, the droop control, which is a cooperative control method without communication, is

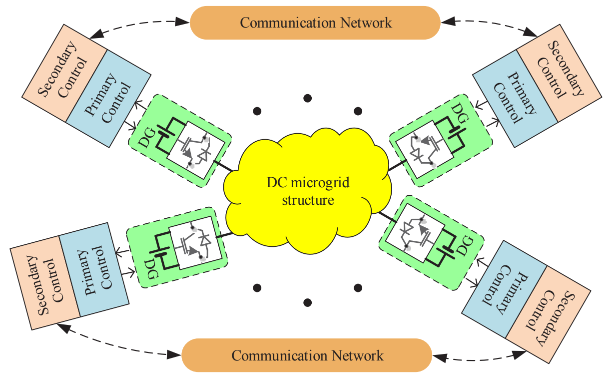

Fig. 1: distributed DC microgrid system

commonly employed in the primary control layer [7], [10]. The distributed secondary control can improve the accuracy of power sharing and voltage regulation, and enhance the reliability and scalability of the DC microgrid systems [5], [11], [12].

In multi-bus DC microgrids, if the impedances of power lines between buses are nonnegligible, accurate voltage regulation of buses and accurate power sharing among DGs cannot be achieved simultaneously. In other words, voltage regulation and power sharing are conflicting objectives [5], [13]. Accordingly, most existing control methods replace accurate voltage regulation with average voltage regulation among buses [6], [12], [14]–[17]. However, an obvious disadvantage of these control strategies is that voltage deviations of buses from the rated value cannot be controlled, which may cause abnormal operations or even damage of loads if the voltage deviations exceed the allowable range [5].

In addition to power sharing, some literature also focuses on voltage deviation restriction of buses [5], [13], [18]. In [13], a compromised control strategy including current sharing and containment control for bus voltages is proposed. In [18], an optimal control method achieves the control objective adjustment from accurate current sharing to accurate voltage regulation. In [5], the authors illustrate the coupling mechanism between current sharing and voltage regulation, and thereby propose a distributed control method to achieve voltage deviation restriction and degree adjustment of current sharing.

In multi-bus DC microgrids, current sharing is a feasible approximation of power sharing for small voltage deviations of buses. However, there is no doubt that compared to current sharing objective, it is more reasonable for control objectives

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to focus on power sharing while restricting steady state voltage deviations. Due to the nonlinear relationship between power and voltage, it is quite challenging to consider both power sharing and voltage deviation restriction. To our best knowledge, this issue has not been studied in literature.

In this paper, we focus on the control objectives of power sharing and voltage deviation restriction for multi-bus DC microgrids, and propose a distributed control method to achieve adjustable objective from accurate power sharing to accurate voltage regulation. In addition, a prototype of DC microgrid is set up to illustrated the effectiveness of the proposed control method.

II. Preliminaries

A. Notations and graph theory

The notation 0 denotes zero scalar, vector or matrix with appropriate dimensions. Let $\mathbf{1}_N = [1, \cdots, 1]^T \in \mathbb{R}^N$. A diagonal matrix is denoted as $diag(g_1, g_2, \cdots, g_n)$ with $g_i \in \mathbb{R}$ being the i-th diagonal entry.

The communication network of a DC microgrid is modeled as a graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{v_1, \cdots, v_N\}$ denotes the set of nodes, i.e., DGs or buses, and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ denotes the set of edges, i.e., communication links. The topology of a graph $\mathcal{G}$ is captured by its adjacency matrix $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N \times N}$, where a_{ij} is the weight of edge (v_j, v_i), and $a_{ij} > 0$ if $(v_j, v_i) \in \mathcal{E}$; otherwise $a_{ij} = 0$. When $a_{ij} = a_{ji}, \forall i, j$, the graph is undirected; otherwise, it is directed. A graph with adjacency matrix $\mathcal{A}$ is denoted as $\mathcal{G}(\mathcal{A})$. The Laplacian matrix $\mathcal{L} = [l_{ij}] \in \mathbb{R}^{N \times N}$ of $\mathcal{G}$ is defined as $l_{ii} = \sum_{j=1}^{N} a_{ij}$ and $l_{ij} = -a_{ij}$ if $i \neq j$ [19].

B. DC microgrid modeling

For a general multi-bus DC microgrids formed by $N > 1$ DGs, each DG is connected to a DC bus by a converter. If assuming each DG is equipped with a fast responsible energy storage unit with sufficient capacity, the output voltage of the converter can keep consistent with the control signal, and will not be saturated. Under this assumption, it is reasonable to ignore the nonlinear characteristics of DGs in the modeling process. Therefore, combining DG and the associated converter can be modeled as a controlled voltage source [20]. Consiquensly, we model DGs as follows.

$$\mathbf{V} = \mathbf{U}, \tag{1}$$

where $\mathbf{U} = [u_1, \cdots, u_N]^{\mathrm{T}}$ denotes the control signals of DGs and $\mathbf{V} = [V_1, \cdots, V_N]^{\mathrm{T}}$ denotes the output voltages of the associated converters.

For DC microgrid system is mostly low with low voltage level, the power lines in DC microgrids are usually modeled by pure resistants [21]. In this paper, the power line between buses i and j is represented by R_{ij} with associated admittance $Y_{ij} = \frac{1}{R_{ij}}$. Moreover, the admittance matrix is denoted by $\mathbf{Y} = [Y_{ij}] \in \mathbb{R}^{N \times N}$, where $Y_{ij} = 0$, if bus i and bus j are not directly connected, and $Y_{ii} = \Sigma_{j \neq i} Y_{ij}$. Then, the electrical network of the DC microgrid can be modeled as

$$\mathbf{P} = diag\left(\mathbf{V}\right)\mathbf{I} = diag\left(\mathbf{V}\right)\left(\mathbf{Y} + \mathbf{Y}_L\right)\mathbf{V} \tag{2}$$

where $\mathbf{P} = [P_1, \cdots, P_N]^T$ and $\mathbf{I} = [I_1, \cdots, I_N]^T$ denote the injective power and current of DGs, respectively; $\mathbf{Y}_L = diag(R_{L_1}, \cdots, R_{L_N})^{-1}$ denotes the impedances of loads.

Remark 1: Assume the Kron-reduction has been carried out for the DC microgrid.

C. Droop Control

For the ith DG, $\forall i \in \{1, \cdots, N\}$, the voltage droop control is as follows,

$$u_i = V_i^* - r_i I_i, \quad \forall i \in \{1, \cdots, N\}, \tag{3}$$

where V_i^*, u_i, r_i and I_i denote output voltage reference, voltage set point, droop coefficient (also called virtual resistance [22]) and output current of the ith DG, respectively. The voltage set point u_i is used to control the ith DG. Substituting (3) into (1), the droop control is rewritten in compact form as

$$\mathbf{V} = \mathbf{V}^* - \Lambda diag\left(\mathbf{V}\right)^{-1}\mathbf{P}, \tag{4}$$

where $\Lambda = [r_1, \cdots, r_N]^T$, and $\mathbf{V}^* = [V_1^*, \cdots, V_N^*]^T$.

According to the analysis above, a multi-bus DC microgrid with droop control can be described by (2) and (4).

D. Accurate power sharing

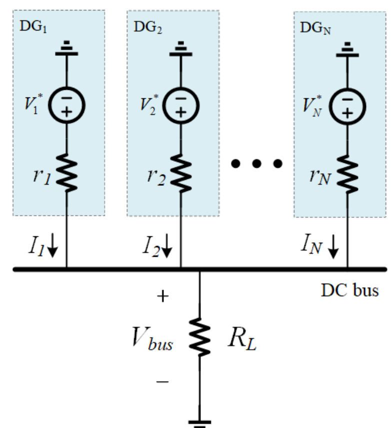


Fig. 2: A single-bus DC microgrid

For a single-bus DC microgrid shown in Fig. 2, all DGs are connected to the same DC bus, and thereby the impedances of the power lines between DGs are negligible. If voltage droop control is employed for each DG to achieve cooperative behavior among DGs, then voltage set points of DGs are identical with the bus voltage, i.e. $V_i = V_{bus}, i \in \{1, \cdots, N\}$. Letting $V_i^* = V_{rat}, i \in \{1, \cdots, N\}$, the following identity is obtained at steady state.

$$\frac{P_i}{P_j} = \frac{r_j}{r_i}, \quad \forall i, j \in \{1, \cdots, N\} \tag{5}$$

Moreover, we set the virtual resistance as $r_i = \alpha \frac{1}{P_i^*}$, where $\alpha \in \mathbb{R}_+$ is constant, and P_i^* is the power capacity of DG i. Consequently, accurate power sharing of single-bus DC microgrid is achieved, i.e.,

$$\frac{P_i}{P_i^*} = \frac{P_j}{P_j^*}, \quad \forall i, j \in \{1, \cdots, N\}. \tag{6}$$

For a multi-bus DC microgrid, the concept of accurate power sharing is similarly defined.

Definition 1 (Accurate power sharing): In a multi-bus DC microgrid described by (2) and (4), accurate power sharing is achieved among DGs, if

$$\frac{P_1}{P_1^*} = \frac{P_2}{P_2^*} = \cdots = \frac{P_N}{P_N^*}. \tag{7}$$

In a multi-bus DC microgrid, if the impedances of power lines between buses are nonnegligible, the impedances of power lines will deteriorate the accuracy of power sharing. In order to achieve accurate power sharing of multi-bus DC microgrids, a secondary control level is generally used to compensate the droop control [12], [16], [23].

E. Problem formulation

In addition to power sharing among DGs, for a multi-bus DC microgrid, another important control objective is voltage regulation among DC buses. In order to operate loads normally, the bus voltages need to be maintained into an admissible range around the rated value. However, the objective of voltage regulation has conflicts with accurate power sharing. In other words, when load power is shared accurately among DGs, the bus voltages cannot be regulated generally in an intended way. In order to formulate the interested problem, we define accurate voltage regulation at first.

Definition 2 (Accurate voltage regulation): In a DC microgrid described by (2) and (4), accurate voltage regulation is attained among DC buses, if

$$V_1 = V_2 = \cdots = V_N = V_{rat}, \tag{8}$$

where V_{rat} denotes the rated voltage of the DC microgrid.

In general, for a multi-bus DC microgrid, since both accurate power sharing and accurate voltage regulation cannot be achieved simultaneously, an alternative is to take average voltage regulation among DC buses instead of accurate voltage regulation. Following this scheme, an obvious drawback is that the voltage deviations of buses from the rated value cannot be governed. If the voltage deviations exceed the admissible maximum, e.g. 5% [12], abnormal operation or even damage may occur for critical loads. Therefore, this paper aims to solve the following problem.

Problem 1: For a DC microgrid described by (2) and (4), design a distributed control method that enables continuous adjustment from accurate power sharing to accurate voltage regulation.

III. A Method Considering Voltage Regulation and Power Sharing

In this section, a novel distributed cooperative control method is proposed to achieve continuous adjustment from accurate power sharing to accurate voltage regulation.

A. A Distributed Cooperative Control

We design a distributed secondary control law for V_i^* in (3) as follows, and the corresponding block diagram is shown in Fig 3.

$$\dot{V}_i^* = \sum_{j=1}^{N} a_{ij}\left(\frac{P_j}{P_j^b} - \frac{P_i}{P_i^b}\right) + g_i\left(V_{rat} - V_i\right), \tag{9a}$$

$$P_i^b = \theta P_i^* + (1-\theta)\frac{V_{rat}^2}{R_{L_i}} \quad i \in \{1, \cdots, N\}. \tag{9b}$$

where a_{ij} are the entries of the adjacency matrix $\mathcal{A}$ of the communication graph $\mathcal{G}(\mathcal{A})$, and g_i denotes the weight of the edge from V_{rat} to the ith node, with $g_i > 0$, if node i is the critical node; otherwise $g_i = 0$. Parameter $\theta \in [0, 1]$ is a trade-off factor to adjust the accuracy of power sharing and voltage regulation. When $\theta = 1$, accurate power sharing is achieved; When $\theta = 0$, accurate voltage regulation is attained; When $\theta \in (0, 1)$, the DC microgrid stayes a compromised state between accurate power sharing and accurate voltage regulation. It is generally impossible to

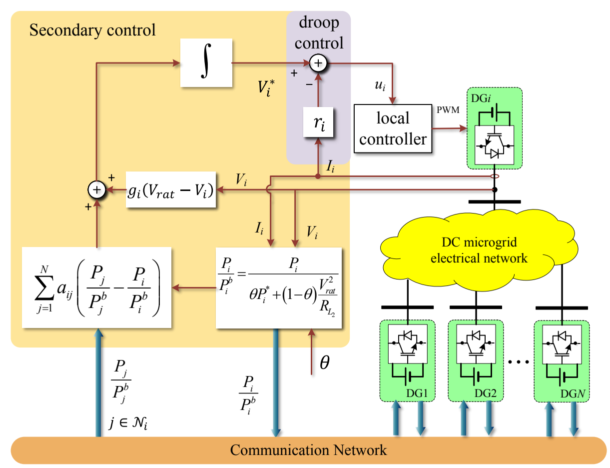


Fig. 3: Control block diagram of the DC microgrid: controller representation (9)

regulate the bus voltages of multiple different nodes to an identical rated value, when load power is shared in a fixed proposition. Thus, we needd the following assumption.

Assumption 1: In (9a), $g_i > 0$ for only one $i \in \{1, \cdots, N\}$ and $g_j = 0$ for all $j \neq i$. Moreover, the communication graph $\mathcal{G}(\mathcal{A})$ is undirected and connected.

B. Steady state analysis

Under the control of (9), the steady state of the DC microgrid is characterized by the following theorem.

Theorem 1: Consider the DC microgrid described by (2) and (4), which is governed by (9). Then, the steady state satisfies the following conditions.

(i) For a given θ, power is shared among all DGs in the following proportion, i.e.,

$$\frac{P_1}{P_1^b} = \frac{P_2}{P_2^b} = \cdots = \frac{P_N}{P_N^b} = \beta(\theta),$$

where $\beta(\theta)$ is a function of θ satisfying the following equation.

$$diag\left(\mathbf{P}^b\right)\beta\mathbf{1}_N = diag\left(\hat{\mathbf{V}}\right)\left(\mathbf{Y}+\mathbf{Y}_L\right)\hat{\mathbf{V}},$$

and $\mathbf{G}\hat{\mathbf{V}} = V_{rat}\mathbf{G}\mathbf{1}_N$.

(ii) When $\theta = 1$, accurate power sharing is achieved, i.e.,

$$\frac{P_1}{P_1^*} = \frac{P_2}{P_2^*} = \cdots = \frac{P_N}{P_N^*},$$

while the voltage of critical bus reaches the rated value, i.e., $V_i = V_{rat}$, when $g_i \neq 0$.

(iii) When $\theta = 0$, accurate voltage regulation is attained, i.e.,

$$V_1 = V_2 = \cdots = V_N = V_{rat}.$$

Proof: Part(i).
Rewrite (9a) in a compact form as

$$\dot{\mathbf{V}}^* = -\mathcal{L}diag\left(\mathbf{P}^b\right)^{-1}\mathbf{P} + \mathbf{G}\left(V_{rat}\mathbf{1}_N - \mathbf{V}\right), \quad (10)$$

where $\mathcal{L}$ is the Laplacian matrix of $\mathcal{G}(\mathcal{A})$; $\mathbf{P}^b = [P_1^b, \cdots, P_N^b]^T$, $\mathbf{P} = [p_1, \cdots, P_N]^T$, and $\mathbf{G} = diag(g_1, \cdots, g_N)$. In steady state, since the left-hand side of (9a) equals 0, i.e., $\dot{\mathbf{V}}^* = 0$, we have that

$$-\mathcal{L}diag\left(\mathbf{P}^b\right)^{-1}\mathbf{P} + \mathbf{G}\left(V_{rat}\mathbf{1}_N - \hat{\mathbf{V}}\right) = 0,$$

where $\hat{\mathbf{V}}$ denotes the steady state bus voltage. According to the consensus theory of multi-agent system [19] and considering only one nonzero entry in $\mathbf{G}$, we have

$$diag\left(\mathbf{P}^b\right)^{-1}\mathbf{P} = \beta(\theta)\mathbf{1}_N, \quad (11)$$

and $V_i = V_{rat}$, when $g_i \neq 0$. Substituting (11) into (2) yields

$$diag\left(\mathbf{P}^b\right)\beta(\theta)\mathbf{1}_N = diag\left(\hat{\mathbf{V}}\right)\left(\mathbf{Y}+\mathbf{Y}_L\right)\hat{\mathbf{V}},$$

and $\mathbf{G}\hat{\mathbf{V}} = V_{rat}\mathbf{G}\mathbf{1}_N$.

Part (ii).
When $\theta = 1$, control law (9) is

$$\dot{V}_i^* = \sum_{j=1}^{N} a_{ij}\left(\frac{P_j}{P_j^*} - \frac{P_i}{P_i^*}\right) + g_i\left(V_{rat} - V_i\right).$$

It is trivial to show that

$$\frac{P_1}{P_1^*} = \frac{P_2}{P_2^*} = \cdots = \frac{P_N}{P_N^*},$$

and $V_i = V_{rat}$, when $g_i \neq 0$.

Part (iii).
Substituting $\theta = 0$ into (11) yields

$$\mathbf{P} = V_{rat}^2\mathbf{Y}_L\beta(0)\mathbf{1}_N = diag(\hat{\mathbf{V}})(\mathbf{Y}+\mathbf{Y}_L)\hat{\mathbf{V}}.$$

This implies that $diag(\hat{\mathbf{V}})\mathbf{Y}\hat{\mathbf{V}} = 0$. Since the bus voltage of the critical node reaches the rated value at steady state, we derive that

$$\hat{\mathbf{V}} = V_{rat}\mathbf{1}_N.$$

This completes the proof. ∎

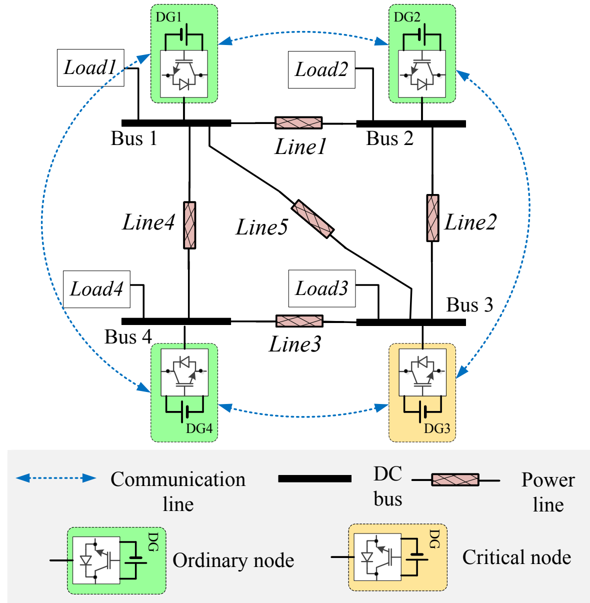


Fig. 4: DC microgrid with 4 buses

IV. Experimental Results

Consider a DC microgrid consisting of 4 DGs (see Fig. 4). Let DG 3 be the critical node, which means that the bus voltage V_3 will be regulated to the rated value in steady state. The communication network among the DGs is shown by blue dashed lines. For simplicity, we let the weight of each communication link be 1. However, note that same results hold for general link weights. The parameters of DGs, loads and power lines are listed in Table I. Let $V_{rat} = 48V$.

TABLE I: Parameters of DGs, loads and power lines

DGs (W)	loads (Ω)	power lines (Ω)
$P_1^* = 100$	$R_{L_1} = 50$	$R_1 = 5.8$
$P_2^* = 200$	$R_{L_2} = 45$	$R_2 = 6.3$
$P_3^* = 200$	$R_{L_3} = 30$	$R_3 = 5.0$
$P_4^* = 100$	$R_{L_4} = 40$	$R_4 = 5.3$
		$R_5 = 5.2$

According to the DC microgrid shown in Fig. 4, a DC microgrid prototype is developed (see Fig. 5), in which each DG is presented by a programmable voltage source. The parameters of DGs, loads and power lines of this DC microgrid prototype are identical with those listed in Table I. The rated voltage of the DC microgrid prototype is set to $48V$. For each DG, the droop control (3) and the proposed secondary control (9) of each DG are realized in a DSP TMS320F28335 control board. The communication network among the secondary controllers of DGs is implemented using Controller Area Network (CAN) with a data rate of $500kb/s$.

This experiment consider three cases, namely $\theta = 1$, $\theta = 0$ and $\theta = 0.5$. For the first 10 seconds, only the local droop controller (3) is applied to each DG. During $t \in [10, 20]s$,

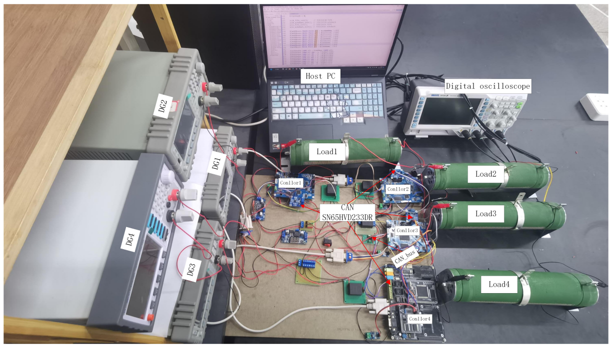


Fig. 5: DC microgrid prototype

the distributed secondary controller (9) is activated and node 3 is set to be the critical node.

Case I: $\theta = 1$

As shown in Fig. 6(c), before the secondary control is activated, only the droop control is enabled, and thereby accurate power sharing is not achieved. After the secondary control is activated, the output powers of all DGs gradually reach accurate sharing, i.e., $P_1 : P_2 : P_3 : P_4 = 1 : 2 : 2 : 1$ (see Fig. 6(b) and 6(c)). The bus voltage of the critical node V_3 gradually reaches the rated value $48V$ (see Fig. 6(a)).

Case II: $\theta = 0$

When $\theta = 0$, after the secondary control is enabled, all bus voltage V_i reach accurate voltage regulation (see Fig. 7(a)). However, the output powers of the DGs are no longer accurately shared (see Fig. 7(b) and 7(c)).

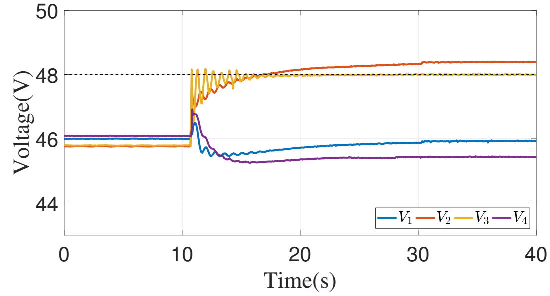
Case III: $\theta = 0.5$

In this case, after enabling the secondary controller, the voltage of the critical node is still regulated to the rated value $48V$. From the power sharing point of view, Case III (see Fig. 8(c)) is better than Case II (see Fig. 7(c)), and worse than Case I (see Fig. 6(c)). On the contrary, from voltage regulation point of view, Case III (see Fig. 8(a)) is better than Case I (see Fig. 6(a)), and worse than Case II (see Fig. 7(a)).

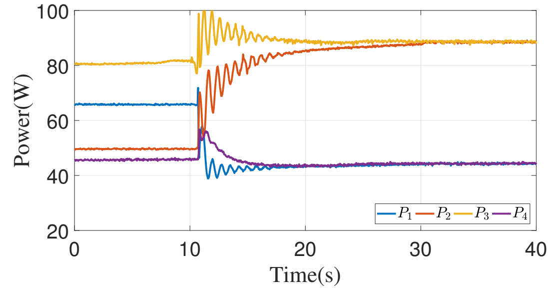
It can be seen that above experimental results illustrate Theorem 1.

V. Conclusion

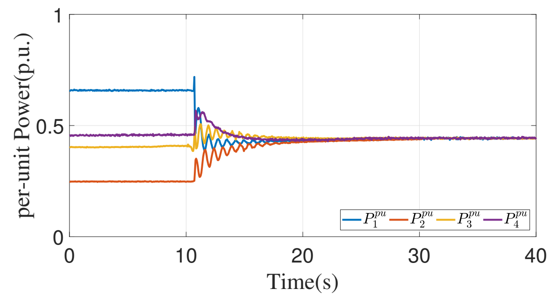
In this paper, a distributed control method is proposed which can realize the adjustment of control objectives from accurate voltage regulation to accurate power sharing, and can precisely adjust the bus voltage of the critical node. In addition, a DC microgrid prototype is developed based on DSP TMS320F28335 controllers. Finally, for a given DC microgrid topology, the algorithm proposed in this paper is verified on the experimental platform, and the effectiveness of the proposed method is illustrated by the experimental results.



(a) the bus voltages



(b) the power



(c) the per-unit power

Fig. 6: The experimental results of Case I ($\theta = 1$)

References

[1] H. Lund, "Renewable energy strategies for sustainable development," *Energy*, vol. 32, no. 6, pp. 912–919, 2007.

[2] R. H. Lasseter, "Microgrids," *IEEE Power Engineering Society Winter Meeting*, vol. 1, pp. 305–308, 2002.

[3] A. T. Elsayed, A. A. Mohamed, and O. A. Mohammed, "DC microgrids and distribution systems: An overview," *Electric Power Systems Research*, vol. 119, pp. 407–417, 2015.

[4] H. Zhang, F. L. Lewis, and A. Das, "Optimal design for synchronization of cooperative systems state feedback, observer and output feedback," *IEEE Transactions on Automatic Control*, vol. 56, no. 8, pp. 1948–1952, 2011.

[5] H. Bai, H. Zhang, H. Cai, and J. Schiffer, "Voltage regulation and current sharing for multi-bus DC microgrids: a compromised design approach," *Automatica*, vol. 142, p. 110340, 2022.

[6] C. De Persis, E. R. Weitenberg, and F. Dörfler, "A power consensus algorithm for DC microgrids," *Automatica*, vol. 89, pp. 364–375, 2018.

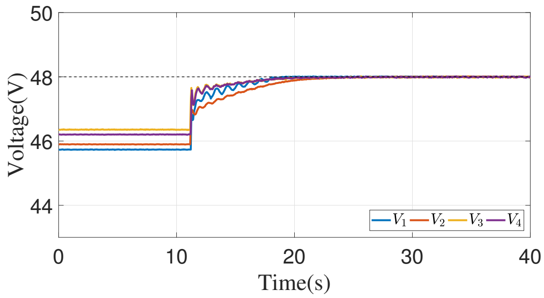
[7] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC microgrids - Part I: A review of control strategies and stabilization techniques," *IEEE Transactions on Power Electronics*, vol. 31, no. 7, pp. 4876–4891, 2015.

[8] P. Karlsson and J. Svensson, "DC bus voltage control for a distributed power system," *IEEE Transactions on Power Electronics*, vol. 18, no. 6, pp. 1405–1412, 2003.

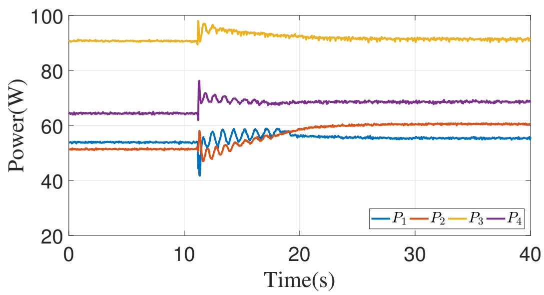
[9] Y. Ito, Z. Yang, and H. Akagi, "DC microgrid based distribution power generation system," in *Proc. of the 4th International Power Electronics and Motion Control Conference*, 2004, pp. 1740–1745.

[10] J. M. Guerrero, J. C. Vasquez, J. Matas, L. Vicuna, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids - A general approach toward standardization," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, 2011.

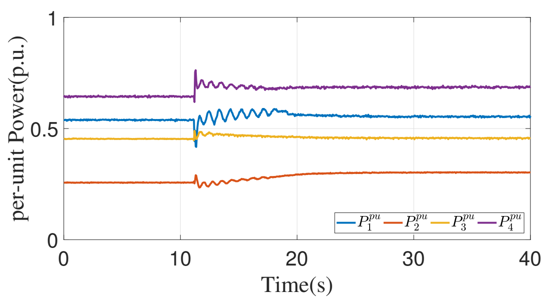
[11] R. Han, M. Tucci, A. Martinelli, J. M. Guerrero, and G. Ferrari-Trecate, "Stability analysis of primary plug-and-play and secondary



(a) the bus voltages

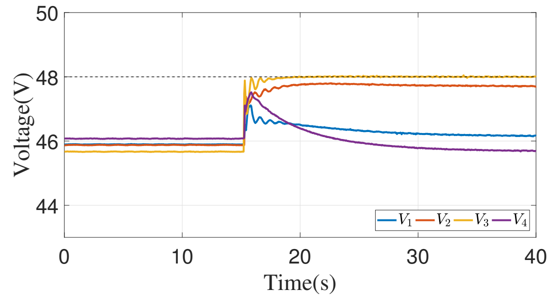


(b) the power

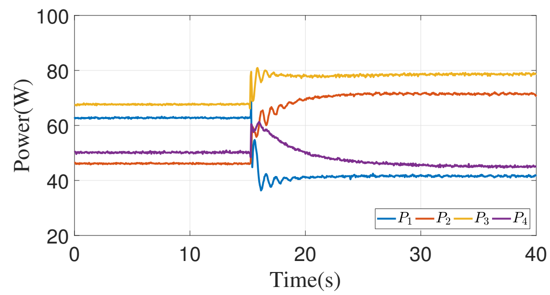


(c) the per-unit power

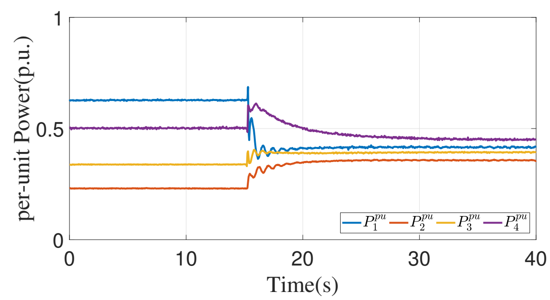
Fig. 7: The experimental results of Case II ($\theta = 0$)



(a) the bus voltages



(b) the power



(c) the per-unit power

Fig. 8: The experimental results of Case III ($\theta = 0.5$)

leader-based controllers for DC microgrid clusters," *IEEE Transactions on Power Systems*, vol. 34, no. 3, pp. 1780–1800, 2019.

[12] V. Nasirian, S. Moayedi, A. Davoudi, and F. L. Lewis, "Distributed cooperative control of DC microgrids," *IEEE Transactions on Power Electronics*, vol. 30, no. 4, pp. 2288–2303, 2015.

[13] R. Han, H. Wang, Z. Jin, L. Meng, and J. M. Guerrero, "Compromised controller design for current sharing and voltage regulation in DC microgrid," *IEEE Transactions on Power Electronics*, vol. 34, no. 8, pp. 8045–8061, 2019.

[14] M. Cucuzzella, S. Trip, C. De Persis, X. Cheng, A. Ferrara, and A. van der Schaft, "A robust consensus algorithm for current sharing and voltage regulation in DC microgrids," *IEEE Transactions on Control Systems Technology*, vol. 27, no. 4, pp. 1583–1595, 2018.

[15] S. Trip, M. Cucuzzella, X. Cheng, and J. Scherpen, "Distributed averaging control for voltage regulation and current sharing in DC microgrids," *IEEE Control Systems Letters*, vol. 3, no. 1, pp. 174–179, 2019.

[16] P. Nahata, M. S. Turan, and G. Ferrari-Trecate, "Consensus-based current sharing and voltage balancing in DC microgrids with exponential loads," *IEEE Transactions on Control Systems Technology*, vol. 30, no. 4, pp. 1668–1680, 2022.

[17] M. Tucci, L. Meng, J. M. Guerrero, and G. F. Trecate, "Stable current sharing and voltage balancing in DC microgrids: A consensus-based secondary control layer," *Automatica*, vol. 95, pp. 1–13, 2018.

[18] L. Ding, Q. Han, L. Wang, and E. Sindi, "Distributed cooperative optimal control of DC microgrids with communication delays," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 9, pp. 3924–3935, 2018.

[19] F. L. Lewis, H. Zhang, K. Hengster-Movric, and A. Das, *Cooperative Control of Multi-Agent Systems: Optimal and Adaptive Design Approaches*. London: Springer, 2014.

[20] J. Schiffer, D. Zonetti, R. Ortega, A. M. Stankovic, T. Sezi, and J. Raisch, "A survey on modeling of microgrids: From fundamental physics to phasors and voltage sources," *Automatica*, vol. 74, pp. 135–150, 2016.

[21] J. Beerten and R. Belmans, "Analysis of power sharing and voltage deviations in droop-controlled DC grids," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4588–4597, 2013.

[22] X. Lu, J. M. Guerrero, K. Sun, and J. C. Vasquez, "An improved droop control method for DC microgrids based on low bandwidth communication with DC bus voltage restoration and enhanced current sharing accuracy," *IEEE Transactions on Power Electronics*, vol. 29, no. 4, pp. 1800–1812, 2013.

[23] Z. Liu, M. Su, Y. Sun, H. Han, X. Hou, and J. M. Guerrero, "Stability analysis of DC microgrids with constant power load under distributed control methods," *Automatica*, vol. 90, pp. 62–72, 2018.