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Voltage regulation and current sharing for multi-bus DC microgrids ⋆

Handong Bai *, **Hongwei Zhang** *, **Chaoyong Li** **

* *School of Electrical Engineering, Southwest Jiaotong University, Chengdu, Sichuan, 611756, China (e-mail: hdbai@my.swjtu.edu.cn;hwzhang@swjtu.edu.cn)*
** *College of Electrical Engineering, Zhejiang University, Hangzhou, Zhejiang, 310027, China (e-mail: chaoyong@zju.edu.cn)*

Abstract: It is well known that accurate voltage regulation and current sharing are conflicting control objectives for DC microgrids. By taking electrical network into consideration, this paper analyzes the relation between voltage regulation and current sharing. Based on this relationship, a novel control scheme, which simultaneously considers both voltage regulation and current distribution, is proposed. It significantly simplifies the design complexity and is able to adjust the degree of compromise between accurate voltage consensus and accurate current sharing.

Keywords: current sharing; DC microgrid; voltage regulation; multi-agent system

1. INTRODUCTION

Replacing traditional fossil energy with distributed renewable energy is an effective way to deal with environmental pollution (Lasseter, 2002). Distributed renewable energy sources, such as photovoltaic and fuel cells, batteries and ultra-capacitors, usually have DC characteristics (Justo et al., 2013; Elsayed et al., 2015). The integration of distributed energy sources by DC microgrids can improve efficiency, reduce the number of power converters and economic costs. Recently, research on DC microgrids has attracted increasing attentions in related scientific communities (Maknouninejad et al., 2014; Nasirian et al., 2015; Liu et al., 2018).

In order to guarantee stability of DC microgrids and coordination among multiple distributed generations (DGs), the control systems of DC microgrids usually have hierarchical scheme, and two main control objectives are voltage regulation (Karlsson and Svensson, 2003) and load sharing (Ito et al., 2004). According to the hierarchical structure of the control system (Guerrero et al., 2011; Bidram and Davoudi, 2012), the primary control layer mostly adopts the droop control method to realize coordination of DGs without communication; and the secondary control layer is used to improve power quality of the microgrid, such as improving the accuracy of current sharing among DGs and stabilizing bus voltages. Secondary control schemes of microgrids are usually in a distributed manner (Simpson-Porco et al., 2015; Liu et al., 2018), where each converter has an independent coordinate controller, and a sparse communication network is constructed to exchange information between these controllers. Each of them controls the output voltage of the corresponding converter through the information of the local DG and and its neighbors, and achieves the above-mentioned control objectives.

It is well known that in DC microgrids, accurate voltage regulation and accurate current sharing are two conflicting objectives (Han et al., 2019; Tucci et al., 2018). In Han et al. (2019), a containment control method is proposed to achieve a compromise between the two control objectives, but the proposed method can not adjust the degree of the accuracy of current sharing and voltage regulation for different application scenarios. In Nasirian et al. (2015), a distributed control strategy was proposed to achieve accurate current sharing, and average voltage regulation of DGs. Similar approaches about average voltage regulation are also proposed by Tucci et al. (2018); Chen et al. (2018). In Fan et al. (2020), a discrete-time event-triggered scheme is developed for both average voltage regulation and accurate current sharing. But the main drawback of this sort of average voltage regulation method is that it fails to regulate the voltage of individual node.

In most existing works, the relationship between the two control objectives is ignored. In fact, linear relationship does exist between voltage and current of constant virtual impedances produced by droop control in DC micrigrids, resulting a strong coupling between voltage regulation and current sharing. In this paper, the relationship between these two control objectives is analyzed. When the accurate current sharing is achieved, the dynamics of node voltages is clarified. Based on this relationship, a novel control scheme considering both voltage regulation and current distribution is proposed, which is able to adjust the degree of compromise between accurate voltage consensus and accurate current sharing.

The rest of this paper is organized as follows. Some background on graph theory and microgrids are given in Section 2. Section 3 analyzes an existing distributed controller of accurate current sharing. Section 4 proposes a

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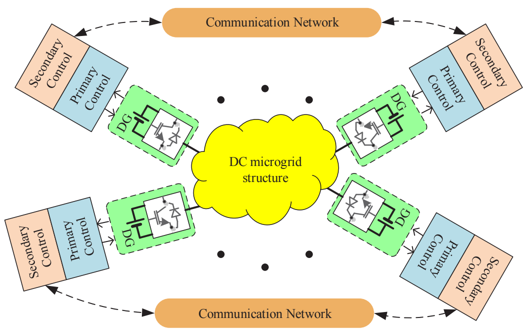

Fig. 1. Schematic of microgrid control architecture

novel control scheme design taking both voltage consensus and current sharing into consideration. The performance of the proposed control scheme is illustrated by case studies in Section 5. Section 6 concludes this paper.

2. PRELIMINARIES

2.1 Notations

The notations used throughout this paper is rather standard. A matrix $A \in \mathbb{R}^{n\times n}$ is positive definite or positive semidefinite, if $x^T Ax > 0$ or $x^T Ax \geq 0$ for all vectors $x \neq 0$. Denote the diagonal matrix as $diag(g_1, g_2, \cdots, g_n)$ with g_i being the ith diagonal entry. An matrix $A = [a_{ij}] \in \mathbb{R}^{n\times n}$ is said to be nonnegative, denoted by $A \geq 0$, if $a_{ij} \geq 0$. Furthermore, for $B \in \mathbb{R}^{n\times n}$, $B \geq A$ means $A - B \geq 0$. By $\mathcal{M}$, we denote the class of all matrices $A = [a_{ij}] \in \mathbb{R}^{n\times n}$ such that $a_{ij} \leq 0$ for all $i \neq j$, and $a_{ii} \geq 0$. Meanwhile, the inverses of matrices of $\mathcal{M}$ exist and are nonnegative (Siljak, 1978).

2.2 Graph Theory

A DC microgrid includes N DGs is illustrated in Fig. 1. In a DC microgrid, all DGs and the corresponding communication network can be treated as a multi-agent system. The communication network can be modelled as a graph $\mathcal{G} = (\mathcal{V}, \varepsilon)$, where $\mathcal{V} = \{1, \cdots, N\}$ denotes the set of nodes and $\varepsilon \subseteq \mathcal{V} \times \mathcal{V}$ denotes the set of edges. DG can be considered as node of the graph. If node i can receive the information from node j, there exists an edge (v_j, v_i) from node j to node i, and node j is a neighbor of node i. Matrix $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N\times N}$ denotes the adjacency matrix of the communication graph $\mathcal{G}$, where a_{ij} is the weight of edge (v_j, v_i), and $a_{ij} > 0$ if $(v_j, v_i) \in \varepsilon$, otherwise $a_{ij} = 0$. 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 $i \neq j$.

2.3 Electrical network of DC microgrids

In DC microgrids, each distributed energy resource is connected to DC bus by a power converter. Assume each random distributed energy resource is equipped with a fast responsible energy storage unit with sufficient capacity, then the output voltage of the converter can keep consistent with the control signal, and the output voltage will not be saturated. Under this condition, the nonlinear characteristics of DGs can be negligible in the modeling

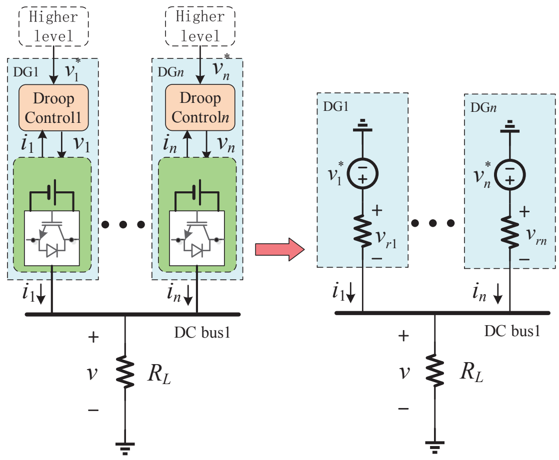

Fig. 2. Single bus DC microgrid

process, and both DG and associated converter can be modeled as a controlled voltage source (Schiffer et al., 2016; Coelho et al., 2002). Thus, DGs can be modeled by

$$\mathbf{V} = \mathbf{u}^V \tag{1}$$

where $\mathbf{V} = [V_1, \cdots, V_N]^{\mathrm{T}} \in \mathbb{R}^N$ is the output voltage vector of converters, and $\mathbf{u}^V = [u_1, \cdots, u_N]^{\mathrm{T}} \in \mathbb{R}^N$ is the control vector for the converter of DGs.

In addition, due to low voltage level of DC microgrids, the impedance of transmission lines in the system are dominantly resistant, therefore transmission lines can be modeled by resistances in DC microgrids (Beerten and Belmans, 2013). Moreover, constant impedance load is mainly considered in this paper.

Considering that the feeder cables are short when the DGs and loads are connected to the same bus, the DC microgrid model studied in this paper does not consider the impedance of feeders. For the transmission lines between buses, the impedances are nonnegligible because of the long distance. The electrical network of a DC microgrid can be described by the following nodal voltage equation (Kundur, 1994)

$$\mathbf{I} = \mathbf{Y}\mathbf{V} \tag{2}$$

where $\mathbf{I} = [i_1, \cdots, i_N]^{\mathrm{T}} \in \mathbb{R}^N$ denotes the current vector injected into DC buses; $\mathbf{Y} = [y_{ij}], \mathbf{Y} \in \mathbb{R}^{N\times N}$ denotes the admittance matrix of DC network; and $\mathbf{V} = [v_1, \cdots, v_N]^{\mathrm{T}} \in \mathbb{R}^N$ denotes the voltage vector of DC buses.

2.4 Conventional Droop Control

Consider a DC microgrid including N DGs. The voltage droop control of the ith DG is

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

where V_i^*, u_i, r_i and I_i denote output voltage reference, voltage set point, droop coefficient and output current of the ith DG, respectively. Then, the voltage set point u_i is used to control the ith DG. According to (1), the output voltage of DGs can be expressed as

$$V_i = V_i^* - V_{r_i}, \quad \forall i \in \{1, \cdots, N\}, \tag{4}$$

where $V_{r_i} = r_i I_i, \forall i \in \{1, \cdots, N\}$ denotes the voltage drop over r_i as a virtual resistance.

Figure 2 shows a single bus DC microgrid including multiple DGs and a load. Voltage droop control method is employed for each DG to achieve cooperative behavior among DGs. Then, let the voltage reference of each DG be a rated value, e.g. $V_1^* = V_2^* = \cdots = V_N^* = V_{rated}$. Since all of DGs are connected to the common bus in parallel, then voltage set points of DGs are identical with the bus voltage, e.g. $V_i = V$, $\forall i \in \{1, \cdots, N\}$. Thereby, we can obtain

$$V_{r_1} = V_{r_2} = \cdots = V_{r_N}. \tag{5}$$

Moreover, the virtual resistances are chosen to be in proportion to the reciprocal of the output current rating of DG, such as,

$$r_i = \alpha \frac{1}{I_i^*}, \quad \forall i \in \{1, \cdots, N\}, \tag{6}$$

where α is a positive constant, and I_i^* is the output current rating of the ith DG. For any two different DGs, the following equation holds.

$$\frac{I_i}{I_k} = \frac{r_k}{r_i} = \frac{I_i^*}{I_k^*}, \quad \forall i \neq k. \tag{7}$$

We can see that, for a single bus DC microgrid, all DGs share the current of loads proportionally according to the ratio of virtual resistances under the droop control strategy. Meanwhile, if currents are accurately allocated among DGs, all voltage drops over virtual resistances will be identical.

3. ANALYSIS OF A DISTRIBUTED CURRENT SHARING CONTROL LAW

For multi-bus DC microgrids under conventional droop control, the accurate current sharing will be deteriorated by uncertain resistances between buses. To improve the accuracy, an established way is to employ distributed co-operative control strategies based on consensus algorithm to compensate droop control (Maknouninejad et al., 2014). In this method, each DG is treated as a node, and a sparse communication network connects all the nodes. The communication network is assumed to contain a spanning tree (**?**), and all the DGs can exchange state information with their neighbors. And then, in secondary control level of each DG, voltage reference of droop control is generated and passed to the droop controller.

In Maknouninejad et al. (2014), a secondary control law is designed as follows

$$\dot{V}_i^* = \sum_{j=1}^{N} a_{ij} \left(\frac{I_j}{I_j^*} - \frac{I_i}{I_i^*} \right), \quad \forall i \in \{1, \cdots, N\}. \tag{8}$$

According to Maknouninejad et al. (2014), when the system reaches steady state, proportional current sharing is achieved, i.e.,

$$\frac{I_j}{I_j^*} = \frac{I_i}{I_i^*}, \ \forall i \neq j \tag{9}$$

It is well known that voltage and current of a resistance are linearly related. Then, it is natural to raise the question that for the DC microgrids with accurate current sharing as in (9), what is the relationship of each DG's output voltage?

Considering the fact that

$$I_i = (V_i^* - V_i)/r_i, \quad \forall i \in \{1, \cdots, N\},$$

we can rewrite (8) as

$$\dot{V}_i^* = \sum_{j=1}^{n_i} a_{ij} \left(\frac{V_j^* - V_j}{r_j I_j^*} - \frac{V_i^* - V_i}{r_i I_i^*} \right)$$

Since virtual resistance is determined by (6), accordingly, we have

$$\dot{V}_i^* = \sum_{j=1}^{N} \frac{a_{ij}}{\alpha} \left(V_{r_j} - V_{r_i} \right) \tag{10}$$

where $V_{r_i} = V_i^* - V_i$ and $V_{r_j} = V_j^* - V_j$ are voltage drops over virtual resistance r_i and r_j, respectively.

System (10) can be further put into a compact form,

$$\dot{\mathbf{V}}^* = -\frac{1}{\alpha} \mathcal{L} \mathbf{V}_r, \tag{11}$$

where $\mathbf{V}_r$ represents the voltage drop over the virtual resistances. The droop control law (4) can be rewritten as

$$\mathbf{V}^* = \mathbf{V}_r + \mathbf{V}, \tag{12}$$

Considering the nonsingularity of the admittance matrix $\mathbf{Y}$, (2) can be transformed as

$$\mathbf{V} = \mathbf{Y}^{-1} \mathbf{I}. \tag{13}$$

In addition, the volt-ampere characteristic of the virtual resistance is

$$\mathbf{I} = \frac{1}{\alpha} \mathbf{\Lambda}^{-1} \mathbf{V}_r, \tag{14}$$

where $\mathbf{\Lambda} = diag\left(I_1^{*-1}, \cdots, I_N^{*-1} \right)$.

Then, considering (11) (12) (13) (14), a straightforward computation yields

$$(\alpha \mathbf{E} + \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1}) \dot{\mathbf{V}}_r = -\mathcal{L} \mathbf{V}_r,$$

where $\mathbf{E}$ is the identity matrix. Since the matrix $(\alpha \mathbf{E} + \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1})$ is nonsingular, we have

$$\dot{\mathbf{V}}_r = \mathbf{A}_c \mathbf{V}_r, \tag{15}$$

where

$$\mathbf{A}_c = -\left(\alpha \mathbf{E} + \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1} \right)^{-1} \mathcal{L}.$$

Once we have (15), we are ready to analyze the relationship of each DG's output voltages under control law (8).

Theorem 1. Consider a multi-bus DC microgrid under current sharing control law (8). The steady state of the voltages of virtual resistances will be equal, i.e.,

$$V_{r_1} = V_{r_2} = \cdots = V_{r_N}.$$

Moreover, if the voltage reference of any DG is given, then all the voltage references of the rest DGs are determined accordingly. And there exists voltage deviation between voltage references of two different DGs, which equals to the corresponding bus voltage difference, i.e., $V_i^* - V_j^* = V_{ij}, \forall i \neq j$. □

The proof is omitted due to space limitation.

The above result implies that, for multi-bus DC microgrid, under the constraint of accurate current sharing among DGs, if any one node voltage is fixed at a nominal value, the rest node voltages are determined accordingly around the nominal value. It is impossible to arbitrarily regulate all bus voltages, which obviously breaks accurate current sharing.

4. A METHOD CONSIDERING BOTH VOLTAGE REGULATION AND CURRENT SHARING

In some scenarios, distributed control law needs to be designed, which not only guarantees current sharing, but also makes all bus voltages within their normal operating ranges.

Since voltage regulation and current sharing are inherently conflicting, in order to regulate all bus voltages in a reasonable neighborhood around the rated value, the only choice is to sacrifice the accurate current sharing performance. In other words, we have to make a tradeoff between the two control objectives about current sharing and voltage regulation.

Inspired by the current sharing control law (8), we design a new control law as follows

$$\dot{V}_i^* = \sum_{j=1}^{N} a_{ij} \left\{ \theta \left(\frac{I_j}{I_j^*} - \frac{I_i}{I_i^*} \right) + \frac{1-\theta}{\alpha} \left(V_j^* - V_i^* \right) \right\} + g_i \left(V_{rated}^* - V_i^* \right), \tag{16}$$

where V_{rated}^* is the rating of the voltage reference for the key node, and g_i denotes the weight of the edge from leader to follower i, with $g_i > 0$ if node i can directly access V_{rated}^* or $g_i = 0$, otherwise; $\theta \in [0, 1]$ is a trade-off factor reflecting the degree of current sharing and voltage regulation among DGs. If accurate current sharing is desired, regardless of voltage regulation, we can set $\theta = 1$; on the contrary, if voltage consensus is of central importance, set $\theta = 0$; Otherwise, by picking $\theta \in (0, 1)$, both current sharing and voltage consensus will be taken into consideration simultaneously, and weights of these two control objectives can be easily adjusted.

Substituting $I_i = (V_i^* - V_i)/r_i, \forall i \in \{1, \cdots, N\}$ into (16), we have

$$\dot{V}_i^* = \sum_{j=1}^{N} \frac{a_{ij}}{\alpha} \left(V_j^* - V_i^* - \theta V_{ji} \right) + g_i \left(V_{rated}^* - V_i^* \right). \tag{17}$$

Obviously, (17) shows that θ has direct impacts on the deviation V_{ji} of voltage references. As θ approaches 1, the higher degree of accuracy of current sharing and the lower degree of voltage consensus can be achieved; And as θ approaches 0, the opposite conclusion can be drawn.

In order to analyze the stability of closed-loop system, we will first establish the dynamics of the closed-loop system of DC microgrid with the distributed secondary controller (16).

Define $\mathbf{V}_{\frac{r}{\theta}} = \left[V_{\frac{r}{\theta}1}, \cdots, V_{\frac{r}{\theta}N} \right]^T \in \mathbb{R}^N$.

$$\mathbf{V}_{\frac{r}{\theta}} = \mathbf{V}^* - \theta \mathbf{V},$$

where $V_{\frac{r}{\theta}i} = V_i^* - \theta V_i$.

Considering (12) (13) (14), we have

$$\mathbf{V}_{\frac{r}{\theta}} = \left(\mathbf{E} + \frac{1-\theta}{\alpha} \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1} \right) \mathbf{V}_r,$$

$$\mathbf{V}^* = \left(\mathbf{E} + \frac{1}{\alpha} \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1} \right) \mathbf{V}_r.$$

According to the knowledge of $\mathbf{Y}$ and $\mathbf{\Lambda}$, we know that if $\theta \in [0, 1]$, matrix $\left(\mathbf{E} + (1-\theta)/\alpha \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1} \right)$ is nonsingular. Thus,

$$\mathbf{V}^* = \mathbf{M} \mathbf{V}_{\frac{r}{\theta}}, \tag{18}$$

where

$$\mathbf{M} = \left(\mathbf{E} + \frac{1}{\alpha} \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1} \right) \left(\mathbf{E} + \frac{1-\theta}{\alpha} \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1} \right)^{-1}.$$

According to Fiedler and Prak (1962), we can show that $\mathbf{E} + \frac{1}{\alpha} \mathbf{Y}^{-1} \mathbf{\Lambda}^{-1} \geq \mathbf{E}$, and $\mathbf{M}$ is nonsingular and each row sum is no less than 1.

The controller (17) can be rewritten as

$$\dot{\mathbf{V}}^* = -\frac{\mathcal{L}}{\alpha} \mathbf{V}_{\frac{r}{\theta}} + \mathbf{G} \left(\underline{\mathbf{V}_{rated}^*}_N - \mathbf{V}^* \right). \tag{19}$$

Substituting (18) into (19), the dynamics of the close-loop system can then be obtained as

$$\dot{\mathbf{V}}_{\frac{r}{\theta}} = \mathbf{A}_d \mathbf{V}_{\frac{r}{\theta}} + \mathbf{B}_d \underline{\mathbf{V}_{rated}^*}_N, \tag{20}$$

where

$$\begin{cases} \mathbf{A}_d = -\mathbf{M}^{-1} \left(\dfrac{\mathcal{L}}{\alpha} + \mathbf{G} \mathbf{M} \right) \\ \mathbf{B}_d = \mathbf{M}^{-1} \mathbf{G} \end{cases}$$

Since $\theta \in [0, 1]$, $\mathbf{V}_{\frac{r}{\theta}}$ represents a weighted voltage drop larger than the real ones over virtual resistances.

For the stability of closed-loop system, we have the following theorem.

Theorem 2. Let $\theta \in [0, 1]$. System of the DC microgrid under control law (16) is stable. Moreover, the virtual voltages $V_{\frac{r}{\theta}i}$ will achieve consensus, i.e., as $t \to \infty$,

$$V_{\frac{r}{\theta}1} = V_{\frac{r}{\theta}2} = \cdots = V_{\frac{r}{\theta}N}.$$

The proof is omitted due to space limitation.

5. SIMULATION RESULTS

We consider a DC microgrid including 6 DGs, as shown in Fig. 3. DC buses are interconnected by transmission lines $r_{ij}, \forall i, j \in \{1, 2, 3, 4, 5, 6\}$.

The communication network among DGs is shown in Fig. 3, in which blue dashed lines describe communication links. The communication network can be expressed by the adjacency matrix $\mathcal{A}$ as

$$\mathcal{A} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

Let the output current ratings of DGs be

$$\mathbf{I}^* = [40, 40, 40, 20, 20, 20]^{\mathrm{T}},$$

and $\alpha = 50$. Then, the values of virtual resistances can be obtained,

$$\mathbf{R}_{virtual} = [r_i] = [1.25, 1.25, 1.25, 2.5, 2.5, 2.5]^{\mathrm{T}}.$$

The parameters of loads and transmission lines are listed in Table 1.

The simulation consists of three cases to test the dynamics of the system when the controller (16) is set to be $\theta = 1, \theta = 0$ and $\theta = 0.5$, respectively. In these three cases, before $0.5s$, only droop control was used, and distributed secondary controller was disabled. The reference voltage of

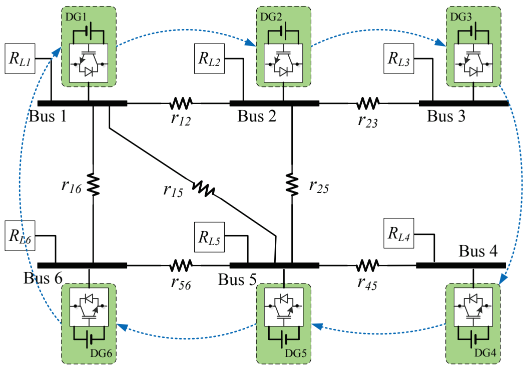

Fig. 3. DC microgrid with 6 buses

all DGs was set to $400V$. At $0.5s$, the distributed secondary controller is enabled. The three examples have parameters $\theta = 1, \theta = 0, \theta = 0.5$, and $g_3 = 1$ and $g_i = 0, i \neq 3$. Only DG3 can access the information of the rated voltage $423V$.

5.1 *Case I: Accurate current sharing* ($\theta = 1$)

In this case, accurate current sharing should be achieved. As can be seen from Fig. 4(c), when only the droop control is connected, the output currents are not inversely proportional to the virtual resistance. That means that accurate current sharing is not achieved. After $0.5s$, due to the role of distributed secondary controller, the output current of DGs gradually realizes the accurate distribution. The output currents of DG1-3 tend to be identical, and the output currents of DG4-6 also reach consensus. Meanwhile, the output current of DG1-3 is twice of the output current of DG4-6. As can be seen from Fig. 4(a), the output voltage V_3^* of DG3 gradually reaches the rated value of $423V$, and the current is accurately allocated. In addition, we can see from Fig. 4(b) that the voltage drop of virtual impedance is inconsistent when only droop control is in effect, which is due to the influence of transmission line impedance. After accessing the distributed secondary controller, the voltage drop of virtual impedance tends to be the same, which shows that the secondary controller eliminates the influence of transmission line impedance and achieves accurate current sharing.

5.2 *Case II: Accurate voltage regulation* ($\theta = 0$)

In this case, θ is set to zero, and hence accurate voltage regulation is achieved. As can be seen from Fig. 4(d), when time approaches $4s$, the voltage references of DGs are close to $423V$, which realizes the consensus of the voltage references. As can be seen from the Fig. 4(f), when the consensus of the voltage references is achieved, the output currents of DGs are not shared proportionally, and the current sharing is worse than that when only droop control

Table 1. loads and transmission lines

R_{L1}	40Ω	r_{12}	1Ω
R_{L2}	20Ω	r_{15}	1.5Ω
R_{L3}	28Ω	r_{16}	1Ω
R_{L4}	35Ω	r_{23}	2Ω
R_{L5}	25Ω	r_{25}	1Ω
R_{L6}	28Ω	r_{45}	2Ω
		r_{56}	1Ω

is involved. Meanwhile, it can be seen from Fig. 4(e) that after accessing the secondary controller, the voltage drops of virtual resistances of DGs are more inconsistent than that before $0.5s$. By comparing the above results with time, it can be seen that the accurate current sharing and voltage consensus are conflicting. When the accurate current sharing is realized, there must be a deviation between the voltage of each node. On the contrary, the output current of each DG cannot be accurately shared if the voltage of each node reaches consensus.

5.3 *Case III: A compromise between current sharing and voltage regulation* ($\theta = 0.5$)

According to the analysis of Section 4, when the system reaches steady state, the microgrid system will be in a compromised situation between accurate current sharing and voltage consensus. The output current can be roughly recognized as the same, and voltages of nodes achieve more consensus than that of Case I. The above conclusions are illustrated by Figs. 4(g), 4(h), and 4(i).

6. CONCLUSION

This paper studied the mechanism of interaction between accurate current sharing and voltage regulation in DC microgrids. The stability of the closed-loop system under accurate current sharing secondary controller was analyzed. According to the relationship between current sharing and voltage regulation, a novel control method was proposed which takes into account the degree of accuracy of current sharing and voltage consensus simultaneously.

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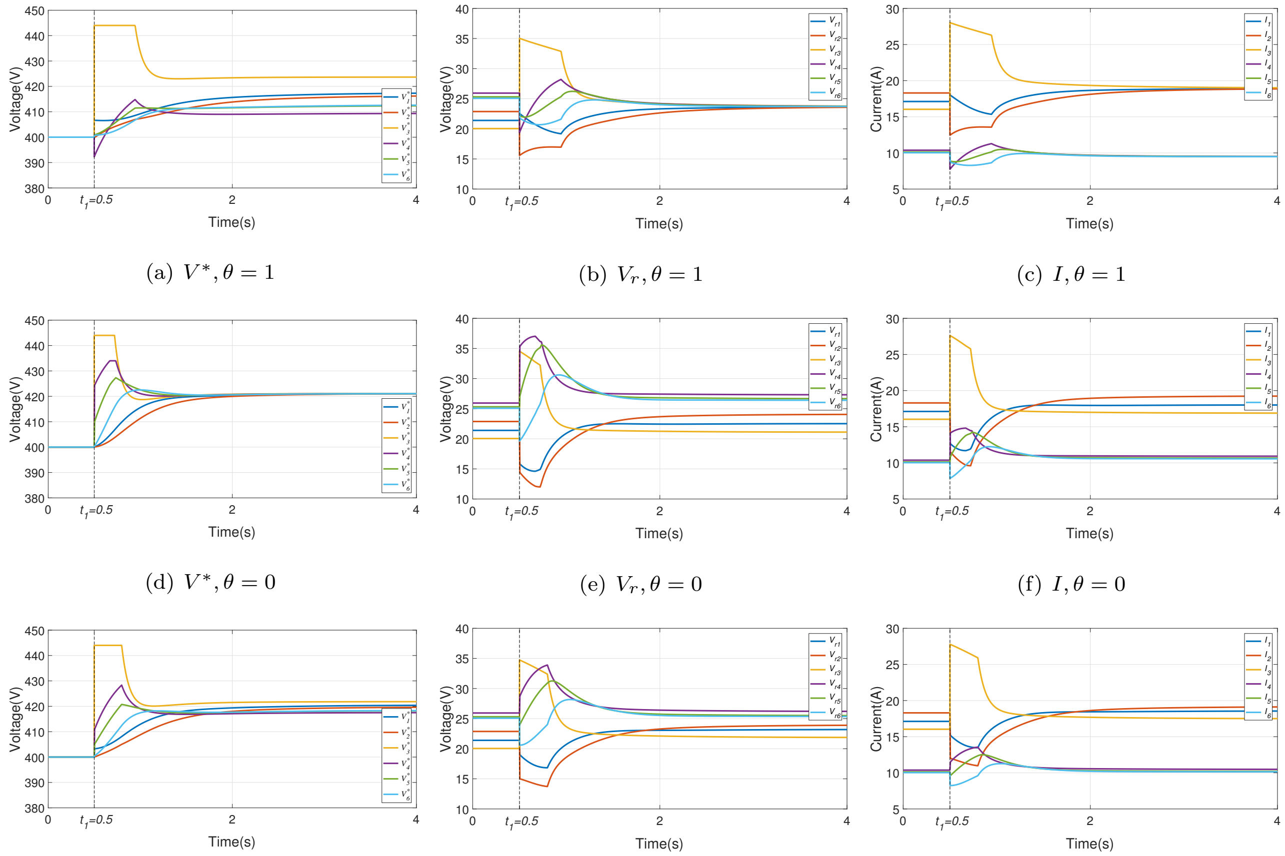

(a) $V^*, \theta = 1$ (b) $V_r, \theta = 1$ (c) $I, \theta = 1$

(d) $V^*, \theta = 0$ (e) $V_r, \theta = 0$ (f) $I, \theta = 0$

(g) $V^*, \theta = 0.5$ (h) $V_r, \theta = 0.5$ (i) $I, \theta = 0.5$

Fig. 4. The results of closed-loop system with distributed secondary control

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