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A Decentralized Control Method for DC Microgrids With Improved Current Sharing Accuracy

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Abstract: A decentralized control method that deals with current sharing issues in dc Microgrids (MGs) is proposed in this paper. The traditional I-V (current versus voltage) droop control method which coordinates the Distributed Generators (DGs) in dc MGs is improved by introducing an additional intermediate variable into the control method. This intermediate variable is inserted between current and voltage variables to reduce their interlocking dependence, which directly produces an output current sharing performance that is less relied on the line resistance between DGs and the common dc bus. Meanwhile, a voltage stabilizer is complementary developed to maintain a constant output voltage magnitude during steady state. In contrast with previously proposed methods, the main contribution of the proposed method is that improved current sharing accuracy is realized without using communication links, central controller and additional sensors for line resistance measurements. A detailed simple mathematical model including the effect of the line resistance is derived for analysis of the stability of the proposed controller. The feasibility and effectiveness of the proposed control strategy are validated by experimental results from a dc MG prototype.

1. Introduction

The concept of microgrids has been introduced in order to provide optimal and reliable operation to power systems by integrating and utilizing distributed energy resources (DERs) [1]. According to the voltage type of the common bus, MGs can be distinguished as ac and dc MGs [2, 3]. Although goals are specific to each type of MG, when natively dc loads are connected, the dc MGs have become popular recently thanks to its own advantages [4,5]. Dc MGs can achieve higher efficiency by eliminating redundant power conversion stages traditionally used when distributed generations (DGs) such as PV modules and batteries are linked through the same bus voltage level along the MG. Furthermore, since reactive power and skin effect are not present, dc MGs offer higher power quality than MGs inserted into ac power systems [6]. Consequently, the operation of dc MGs and their coordinated control system has an increasing practical value.

For the purpose of maintaining a high quality and reliable electrical power system, the coordinated control system which governs the DGs is a key element for both ac and dc MGs. The main objective of a coordinated control system is to prevent overstressing of any energy source

and properly distribute the total power load to each DG in proportion to their rated powers [7, 8]. To realize this, the so called droop control which employs own electrical parameters such as common bus frequency or voltage as global indicator is widely applied in MG systems. The reasons why droop control becomes widely accepted is that it has an inherent decentralized characteristic. An important characteristic of the droop control governing DGs is that coordinated operations are provided only with local information measurements. In addition, droop control improves the reliability while offering expandability with "plug-and-play" interfacing [9–12]. The droop control applied in dc MGs is usually I-V droop which can be modeled as a dc voltage source in series with virtual impedance [13]. Common bus voltage as global indicator is the key information which is supposed to be the same at each point along the droop-based dc MG. However, the existence of line resistances makes the assumption untenable and results in poor droop control performance on current sharing.

To enhance the accuracy of current sharing, several types of solutions have been proposed. In general, there are three basic methods to overcome the effect of line resistance on current sharing accuracy. The first method is based on the signal injection technique [14,15]. This approach can reduce the current sharing error by introducing the concept of "frequency" into dc system. Here, the difference of frequency among DGs will cause a circulating small real power, according to which DG output voltage is adjusted, until the load current is shared properly. However, this approach increases the control system complexity and decreases the quality of the output voltage and current. The second method estimates the line resistance, which is then applied to set a virtual impedance to compensate voltage drops across the line resistance. In [16, 17], the estimation strategy is dependent on the information during grid-connected mode, this means MG can run in islanded mode only if it operates in grid-connected mode in advance. The voltage of common point is utilized in [18, 19] to simplify the estimation process; however, it may be impractical to obtain the information of common point when DGs are distributed with long feeders [20, 21]. Resembling the control hierarchy of the traditional ac grid, the third method uses hierarchical structure consisting of three levels: primary, secondary, and tertiary control. In this hierarchical method, communication links are employed for accurate load current sharing. The primary control is usually designed with classic droop control to locally adjust the output voltage. To restore electrical parameters to their reference values, a secondary control is introduced. Conventionally, the secondary control is implemented in a centralized manner [22, 23], which relies on an MG central controller sending compensation control messages to the DG local controller. Recently, secondary control has been embedded into the DG local controller in a distributed way, which employs low bandwidth communication to exchange information with other DGs to tune the droop curve [24, 25]. Moreover, a sparse communication network is spanned across the MGs that enables limited messages passing among DGs, each DG only exchange data with its neighbors [26–28]. In addition, economical operation and power flow optimization are taken considerations into the tertiary control. Despite communication links are useful for accuracy of current sharing, it may cause new issues such as risk for lower reliability, scalability limitations and possible cost increments.

Responding to the concerns risen above, a decentralized improved current sharing control is proposed in this paper. In order to avoid the line resistance effect, the method introduces an intermediate variable, change rate of the output voltage $\dot{V}$, into the droop curve instead of V to improve current sharing accuracy. Moreover, a complementary voltage stabilizer is developed to maintain the output voltage at steady state. The detailed model of the proposed control method is derived, and the stability of the system is analyzed. The feasibility and effectiveness of the proposed control method are validated by experimental results from a dc MG prototype. The advantages of the

proposed approach include: 1) it does not require a central controller and communication links; 2) it does not need the information of the common point and line resistance; 3) decentralized characteristics are kept: plug-and-play functions and reliable operation can be easily achieved.

The rest of the work is outlined as follows. In Section 2, an overview of the typical structure of a dc MG is presented along with an explanation of how line resistance influences the traditional I-V droop performance on current sharing. Section 3 introduces the operation principle of the proposed control method and analyzes the stability of the control system under different parameters variation. Experimental results obtained for verifying the control effectiveness and theoretical quantification are presented in Section 4, before concluding the findings in Section 5.

2. DC MG Structure and Control

2.1. DC MG Structure

Fig. 1 shows a typical dc MG system structure, in which distributed energy resources (DERs) such as photovoltaic (PV) modules, wind turbines and energy storage system (ESS) are decentralized connected to a common dc bus using interfacing converters. Also, there is continuous interaction among DERs, the ac utility grid and loads. In that case, the control of these converters is a key issue in the proper operation of the MG, especially in the load current sharing between different DGs.

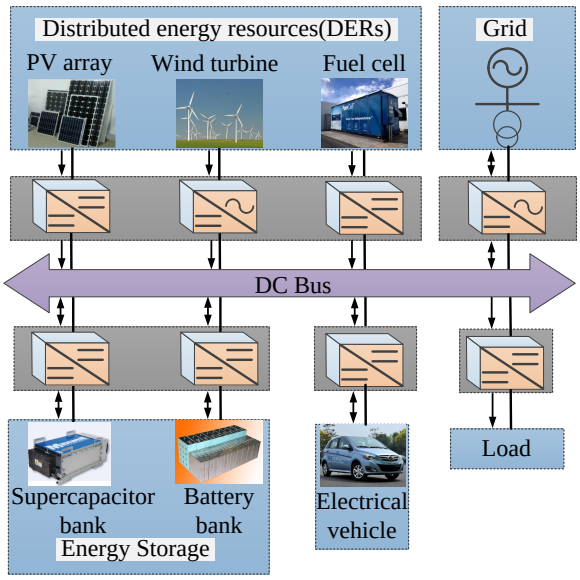


Fig. 1. *Typical structure of dc MG system.*

2.2. Traditional Load Current Sharing Control in dc MG

Load current sharing control in dc microgrids can traditionally be realized by I-V droop mechanism, which is expressed as

$$u_{\mathrm{dc}} = u_{\mathrm{dc}}^{*} - R_d i_{\mathrm{dc}}, \tag{1}$$

where u_{dc} is the converter dc output voltage, u_{dc}^{*} is the reference value of the dc output voltage,

$i_{\rm dc}$ is the dc output current and R_d is the droop gain. DG based on traditional droop control can be regarded as series combination of a dc voltage source $u^*_{\rm dc}$ and a virtual resistance R_d. A simplified dc MG with n DGs is shown in Fig. 2 [29], where $R_{{\rm line}i}(i = 1, 2, , n)$ represents the line resistance of i_{th} DG connected to the dc bus common point.

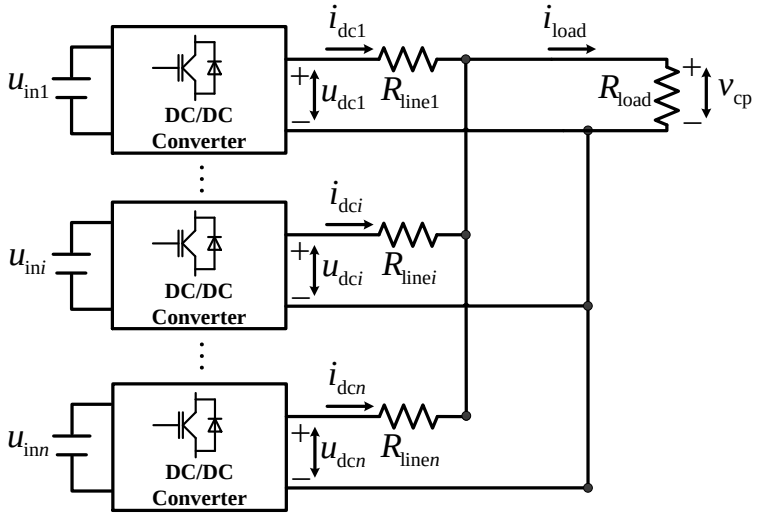


Fig. 2. *Simplified dc MG model with n DGs.*

By applying Kirchoffs voltage law (KVL) in Fig. 2, the expression for the converter output current of each converter can be given as:

$$i_{{\rm dc}i} = \frac{u_{{\rm dc}i} - v_{\rm cp}}{R_{{\rm line}i}}, \quad \forall i \in \{1, 2, \cdots, n\}. \tag{2}$$

Further, the relationship among output current of each DGs with I-V droop controller can be derived from (1) and (2) as:

$$\frac{i_{{\rm dc}i}}{i_{{\rm dc}j}} = \frac{R_{dj}}{R_{di}} + \frac{R_{{\rm line}j} - \dfrac{R_{dj}}{R_{di} \cdot R_{{\rm line}i}}}{R_{di} + R_{{\rm line}i}}, \tag{3}$$

where $i, j \in \{1, 2, \cdots, n\}$, and $i \neq j$.

In ideal conditions, load current is inversely proportional shared according to the virtual resistance of each converter when $R_{{\rm line}i}$ is assumed equal to zero. However, the assumption above is not practical for a large scale systems. Taking line resistance into account, the local output voltage of each converter is not exactly the same, and then the current sharing accuracy is degraded according to (3). The mechanism of current sharing error production can be illustrated in detail in Fig. 3, where the solid line represents the I-V droop curve, and the dotted lines show the relationship between voltage and current of the transmission line. Assuming the DGs are working in parallel with the same rated capacity, so the virtual resistances are the same and solid lines overlap each other. Due to mismatching of line resistances, the intersections of the I-V droop and the two dotted lines will separate to fulfill the relationship in (2) respectively, which results in current sharing error $\Delta i_{\rm dc}$.

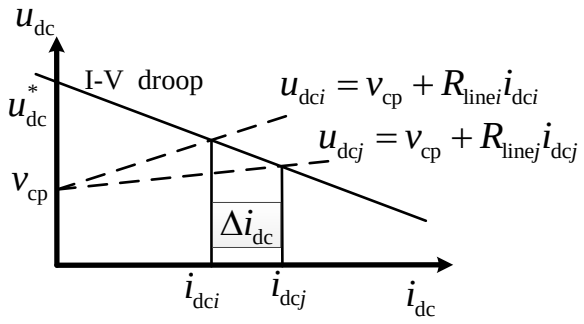


Fig. 3. *Relationship between traditional I-V curve and the transmitted voltages and currents.*

3. Operation Principle of The Proposed Control Method

In the traditional I-V droop control, the dc bus voltage plays an important role as a global indicator in decentralized control system of dc MGs. However, due to the line resistance, the output voltage of each DG can hardly be identical, which influences the performance of I-V droop on current sharing. To avoid the effect of the line resistance, this paper introduces an intermediate variable $\dot{V}$, change rate of the output voltage, to replace V in the traditional droop relationship. The proposed control method for current sharing is explained in this section.

3.1. Proposed Improved Droop Control Method

The proposed controller is expressed as (4), where m_{droop} is droop gain, $\dot{u}_{\rm dc}^*$ is the reference value of $\dot{u}_{\rm dc}$ which is usually set to $0V/s$, and $i_{\rm dc}^*$ is the reference value of $i_{\rm dc}$ when $\dot{u}_{\rm dc} = \dot{u}_{\rm dc}^*$.

$$\begin{cases} \dot{u}_{\rm dc} = \dot{u}_{\rm dc}^* - m_{droop}(i_{\rm dc}^* - i_{\rm dc}) \\ u_{\rm dc} = u_{\rm dc}^* + \int \dot{u}_{\rm dc} dt \end{cases} . \tag{4}$$

The block diagram of (4) is shown in Fig. 4. Considering that all DGs have the same acceptable output voltage change rate value which belongs to the operational region $[-\dot{u}_{\rm dc-max}, +\dot{u}_{\rm dc-max}]$, therefore the negative and positive maximum acceptable value correspond to the situacion when the output current equals to the rated value I_R and zero respectively. Thus, the droop gain m_{droop} and initial condition of $i_{\rm dc}^*$ can be expressed as follows:

$$m_{droop} = -\frac{2\dot{u}_{\rm dc-max}}{I_R} \tag{5}$$

$$i_{\rm dc}^*(0) = \frac{I_R}{2}. \tag{6}$$

On the other side, the differential form of nodal voltage equation at the common point can be derived from Fig. 2.

$$\dot{v}_{\rm cp}\left(\frac{1}{R_{\rm load}} + \sum_{i=1}^{n}\frac{1}{R_{{\rm line}i}}\right) = \sum_{i=1}^{n}\frac{\dot{u}_{{\rm dc}i}}{R_{{\rm line}i}}. \tag{7}$$

Considering the situation when all $\dot{u}_{\rm dc}$ of each DG is the same, since the $R_{\rm load}$ is much larger than line resistances [29], (8) can be derived from (7). Substituting (8) into the differential form

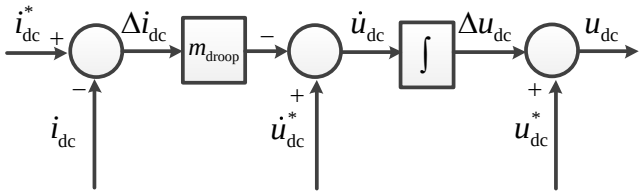


Fig. 4. *Block diagram of proposed droop controller.*

of expression (2) , the relationship among change rate of output current can be expressed as (9), which indicates that output current of each DG will keep unchanged when each $\dot{u}_{\mathrm{dc}}$ is the same. Here, this situation is defined as steady state I.

$$\dot{u}_{\mathrm{dc}1} = \dot{u}_{\mathrm{dc}2} = \cdots = \dot{u}_{\mathrm{dc}n} = \dot{v}_{\mathrm{cp}} \tag{8}$$

$$\dot{i}_{\mathrm{dc}1} = \dot{i}_{\mathrm{dc}2} = \cdots = \dot{i}_{\mathrm{dc}n} = 0. \tag{9}$$

Substituting (8) into the proposed controller (4), the relationship among each DG's output current at steady state I can be obtained, which shows that the load current is shared by each DG proportionally to their rated current I_R.

$$\frac{i_{\mathrm{dc}1}}{I_{R1}} = \frac{i_{\mathrm{dc}2}}{I_{R2}} = \cdots = \frac{i_{\mathrm{dc}n}}{I_{Rn}}. \tag{10}$$

Figure 5 illustrates the operation of the proposed method when two DGs are considered as per Fig. 2. Assuming the system is already steady before t_0 and load current is shared between $\mathrm{DG}_i(i_{\mathrm{dc}i}(t_0))$ and $\mathrm{DG}_j(i_{\mathrm{dc}j}(t_0))$, and load is located closer to DG_j. As load current increases at a certain moment, the output current of $\mathrm{DG}_j(i_{\mathrm{dc}j}(t_1))$ increases more drastically than $\mathrm{DG}_i(i_{\mathrm{dc}i}(t_1))$ to pick up the load because of $R_{\mathrm{line}i} > R_{\mathrm{line}j}$. According to the proposed droop curve, the relationship between the change rate of output voltage can be expressed as $\dot{u}_{\mathrm{dc}j}(t_1) < \dot{u}_{\mathrm{dc}i}(t_1)$, which means the output voltage of DG_j decreases more quickly than DG_i, and the load current flows from DG_j to DG_i gradually in this process. Eventually, $\dot{u}_{\mathrm{dc}i}(t_1)$ and $\dot{u}_{\mathrm{dc}j}(t_1)$ become the same and output current of each DGs keeps unchanged, the system arrives at steady state I.

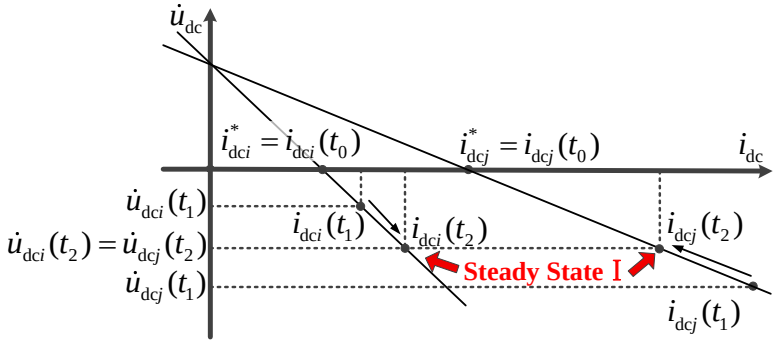


Fig. 5. *Principle of proposed droop controller.*

3.2. Complementary Voltage Stabilizer

As shown in Fig. 5, the change rate of output voltage of each DG is the same ($\dot{u}_{\mathrm{dc}i}(t_2) = \dot{u}_{\mathrm{dc}j}(t_2)$) at steady state I, however, they do not equal to zero which results in output voltage still varying. Therefore, a complementary voltage stabilizer is proposed to keep output voltage unchanged.

In this subsection, a voltage stabilizer is designed by adopting a first-order differential equation which can be expressed as (11). In this equation, $(\dot{u}^*_{\mathrm{dc}} - \dot{u}_{\mathrm{dc}})$ is a quantity which is subject to exponential decay and τ stands for the associated exponential decay time constant. It is worth mentioning that the exponential decay time constant τ of all DGs should be identical to make sure $\dot{u}_{\mathrm{dc}}$ of each DG keeps at the same pace in decay process.

$$\tau \frac{d}{dt}(\dot{u}^*_{\mathrm{dc}} - \dot{u}_{\mathrm{dc}}) + (\dot{u}^*_{\mathrm{dc}} - \dot{u}_{\mathrm{dc}}) = 0. \tag{11}$$

Substituting (11) into (4), the variation of (11) can be expressed as:

$$\tau \frac{d(\dot{u}^*_{\mathrm{dc}} - \dot{u}_{\mathrm{dc}})}{dt} = -(\dot{u}^*_{\mathrm{dc}} - \dot{u}_{\mathrm{dc}}) = \tau m_{droop} \frac{d}{dt}(i^*_{\mathrm{dc}} - i_{\mathrm{dc}}). \tag{12}$$

In the whole decay process, as aforementioned discussion, all DGs dynamics of $\dot{u}_{\mathrm{dc}}$ are the same so that output currents keep constant. Therefore, by simplifying and transforming the expression in (12), the voltage stabilizer controller can be obtained as:

$$\Delta i^*_{\mathrm{dc}} = \int \frac{\dot{u}^*_{\mathrm{dc}} - \dot{u}_{\mathrm{dc}}}{-\tau m_{droop}} dt. \tag{13}$$

The control block diagram of voltage stabilizer is shown in Fig. 6, and the operation of voltage stabilizer is illustrated in Fig. 7. At t_2 moment, system arrives at steady state I, but change rate of output voltage of each DG does not equal to zero. According to (13), the voltage stabilizer will shift the proposed droop curve by generating an increment of i^*_{dc} which will force $\dot{u}_{\mathrm{dc}}$ towards to zero. At t_3 moment, change rate of output voltage becomes zero $\dot{u}_{\mathrm{dc}}(t_3) = 0$ and output voltage maintains stable, the system arrives at steady state II.

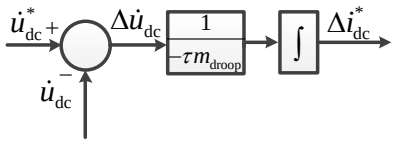


Fig. 6. *Block diagram of voltage stabilizer.*

3.3. Analysis of the Proposed Current Sharing Control System

As analyzed above, the proposed current sharing control system consists of two parts. The first part is droop controller in which an intermediate variable is introduced to reduce the line resistance effect on current sharing accuracy. The second part is the complementary voltage stabilizer which pushes change rate of output voltage towards zero by shifting the proposed droop curve. The overall control block diagram is shown in Fig. 8, where voltage stabilizer and proposed droop controller can be seen as outer loop controller and inner loop controller respectively, and reference of current reference value i^*_{dc} is the interface between the two control loops.

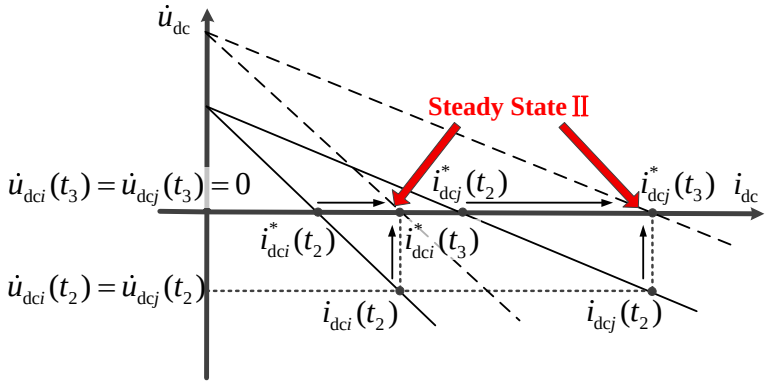


Fig. 7. *Principle of voltage stabilizer.*

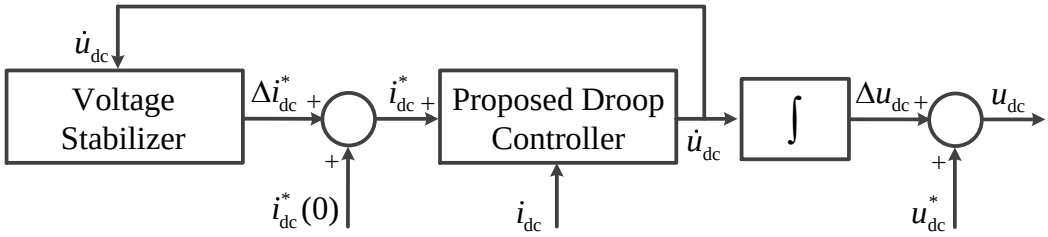


Fig. 8. *Overall control block diagram of proposed current sharing control.*

Theoretically, the proposed control system can achieve the current sharing perfectly if the time constant of the outer loop (τ) is enough longer than the one associated with the inner loop. But in practical application, selecting value of τ need to consider the output voltage deviation. For that reason, the following procedure is developed to define the limits of τ. Here, equations (4), (13) and Fig.8 are used to express the output voltage deviation as:

$$\Delta u_{\mathrm{dc}}(s) = K_{\mathrm{DC}} \cdot G_{\mathrm{d}}(S) \cdot (i_{\mathrm{dc}}(s) - i^*_{\mathrm{dc}}(0)) \tag{14}$$

where $K_{\mathrm{DC}} = \tau m_{droop}, G_{\mathrm{d}}(S) = \dfrac{1}{\tau s + 1}$.

Equation (14) shows that deviation of output voltage results from the current difference going through a low pass filter $G_{\mathrm{d}}(S)$ and dc gain K_{DC}. The longer exponential decay time constant τ is, the more accurate current sharing can be achieved, but on the other hand, the larger voltage deviation happens. To guarantee that the voltage deviation does not exceed its maximum acceptable value , the value of the exponential decay time constant should be limited according to 5, 6 and 14.

$$\tau \leq \frac{\Delta u_{\mathrm{dc-max}}}{\dot{u}_{\mathrm{dc-max}}}. \tag{15}$$

In order to have a better evaluation of the proposed control method, system stability is analyzed for the case of a dc MG with DG_i and DG_j. The detailed model of control diagram for i_{th} DG is shown in Fig.9.

From Fig.9, the output voltage of each DG can be derived as:

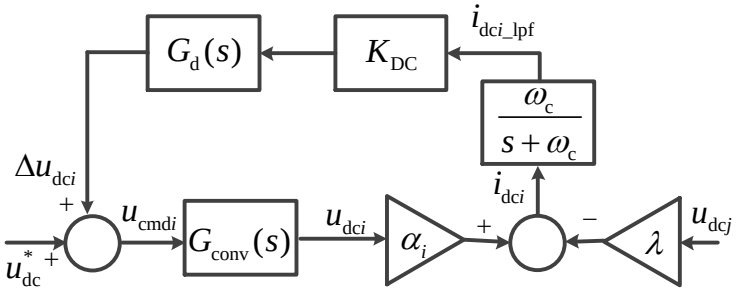


Fig. 9. *Detailed model of control diagram for stability analysis.*

$$\begin{cases} u_{\mathrm{dc}i}(s) = G_{\mathrm{conv}}(s)[\dot{u}_{\mathrm{dc}}^* + K_{\mathrm{DC}}G_{\mathrm{d}}(S)\dfrac{\omega_{\mathrm{c}}}{s+\omega_{\mathrm{c}}}(\alpha_i u_{\mathrm{dc}i} - \lambda u_{\mathrm{dc}j})] \\ u_{\mathrm{dc}j}(s) = G_{\mathrm{conv}}(s)[u_{\mathrm{dc}}^* + K_{\mathrm{DC}}G_{\mathrm{d}}(S)\dfrac{\omega_{\mathrm{c}}}{s+\omega_{\mathrm{c}}}(\alpha_j u_{\mathrm{dc}j} - \lambda u_{\mathrm{dc}i})] \end{cases} \tag{16}$$

where ω_{c} is the cutting frequency of the low pass filter for output current, the voltage loop $G_{\mathrm{conv}}(s) \approx 1$ [30], and system configuration parameters α_1 ,α_2 and λ are expressed as:

$$\begin{cases} \alpha_i = \dfrac{R_{\mathrm{line}j} + R_{\mathrm{load}}}{R_{\mathrm{line}i} \cdot R_{\mathrm{line}j} + R_{\mathrm{line}i} \cdot R_{\mathrm{load}} + R_{\mathrm{line}j} \cdot R_{\mathrm{load}}} \\ \alpha_j = \dfrac{R_{\mathrm{line}i} + R_{\mathrm{load}}}{R_{\mathrm{line}i} \cdot R_{\mathrm{line}j} + R_{\mathrm{line}i} \cdot R_{\mathrm{load}} + R_{\mathrm{line}j} \cdot R_{\mathrm{load}}} \\ \lambda = \dfrac{R_{\mathrm{load}}}{R_{\mathrm{line}i} \cdot R_{\mathrm{line}j} + R_{\mathrm{line}i} \cdot R_{\mathrm{load}} + R_{\mathrm{line}j} \cdot R_{\mathrm{load}}} \end{cases} . \tag{17}$$

By combining 14, 16 and 17, the system characteristic equation can be obtained as:

$$As^4 + Bs^3 + Cs^2 + Ds + E = 0 \tag{18}$$

where

$$\begin{cases} A = \tau^2 \\ B = (2\tau + 2\tau^2\omega_{\mathrm{c}}) \\ C = [1 + 4\tau\omega_{\mathrm{c}} + \tau^2\omega_{\mathrm{c}}^2 - (\alpha_1 + \alpha_2)(\tau^2\omega_{\mathrm{c}}m_{droop})] \\ D = [2\omega_{\mathrm{c}} + 2\omega_{\mathrm{c}}^2\tau - (\alpha_1 + \alpha_2)(\tau\omega_{\mathrm{c}}m_{droop})(\tau\omega_{\mathrm{c}} + 1)] \\ E = [\omega_{\mathrm{c}}^2 - (\alpha_1 + \alpha_2)(\tau^2\omega_{\mathrm{c}}m_{droop}) + (\tau\omega_{\mathrm{c}}m_{droop})(\alpha_1\alpha_2 - \lambda^2)] \end{cases} . \tag{19}$$

The stability of the closed-loop can be tested by analyzing the location of the dominant closed-loop of (19) while varying the exponential decay time constant τ, the proposed droop gain m_{droop} and cutting frequency ω_{c}. The detailed parameters are listed in Table 1. The root locus diagrams with different exponential decay time constant, droop gain and cutting frequency are shown in Fig.10(a), (b), (c) respectively. From Fig.10 (a), (b), (c), it is indicated that system stability can be ensured because all the poles are located on the left half plane.

Table 1 System parameters used in stability analysis

Item	Value	Unit
R_{load}	30	Ω
$R_{\text{line}i}$	2.9	Ω
$R_{\text{line}j}$	1.4	Ω
m_{droop}	-1∼-100	$V/Asec$
τ	0.5∼10	sec^{-1}
ω_{c}	10∼200	rad/sec

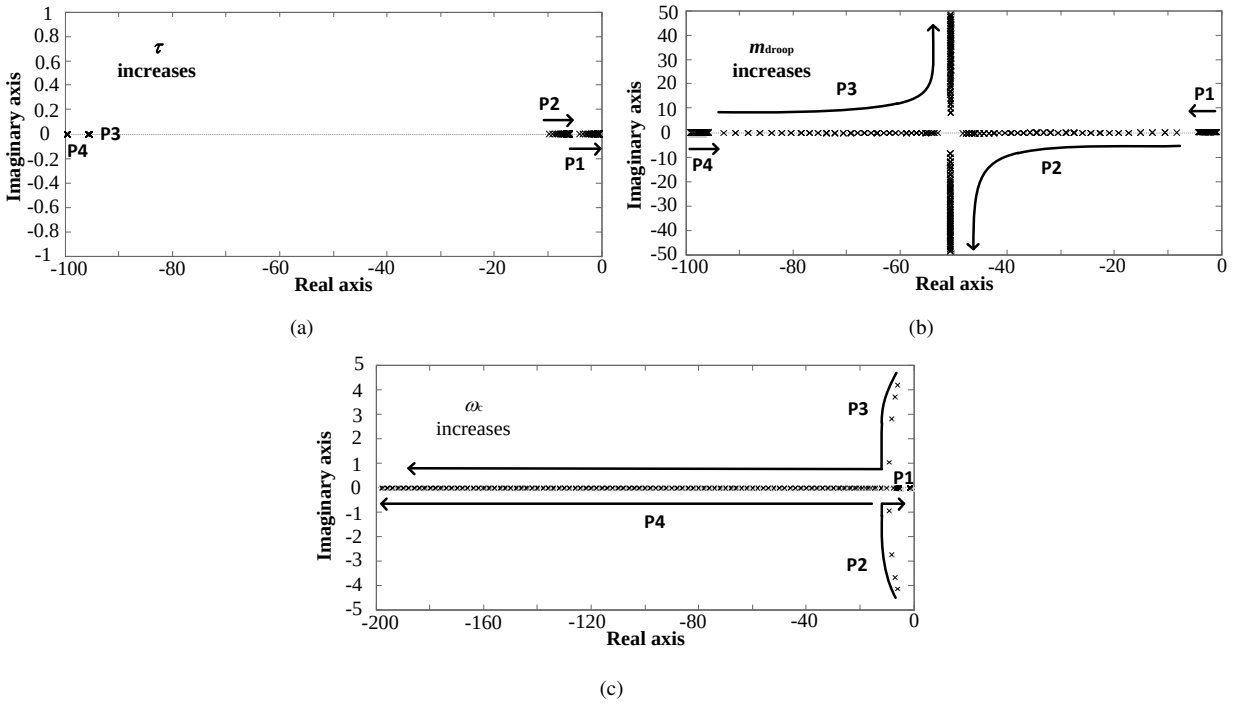


Fig. 10. *Root locus diagrams of proposed control with variations of different parameters.*

4. Experimental Validation

The proposed current sharing method is realized using Matlab/Simunlink. To control in real time, the simulation model is compiled using dSPACE 1104. A laboratory prototype as shown in Fig.11 is developed to validate the proposed control system. The system parameters are shown in Table 2.

Figure 12(a), (b), (c), (d) show the experimental results of output current i_{dc}, change rate of voltage $\dot{u}_{\text{dc}}$, output voltage u_{dc} and current reference value i^*_{dc} respectively. For convenient comparison and analysis, traditional control is used before $T = 10s$, and after $T = 10s$ proposed control is adopted instead.

1. 0∼10s
   As analysis in 2.2, line resistance has negative impact on current sharing performance of traditional droop control.

2. 10∼12s
   As analysis in 3.1, due to $R_{\text{line2}} < R_{\text{line1}}$ much more load current is allocated to DG_2 (shown in Fig. 12(a)), whose change rate of output voltage is more negative than DG_1 according

Table 2 System experiment parameters

Item	Value	Unit
$u^*_{\rm dc}$	150	V
$R_{\rm load}$	30∼45	Ω
$R_{\rm line1}$	2.9	Ω
$R_{\rm line2}$	1.4	Ω
R_d	5	Ω
m_{droop}	-8	$V/Asec$
τ	3	sec^{-1}
$\omega_{\rm c}$	126	rad/sec

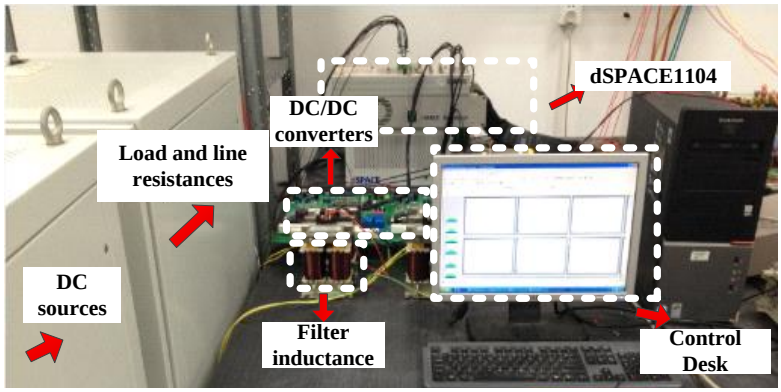


Fig. 11. *Laboratory prototype.*

to the proposed droop curve Fig. 12(b), so the output voltage of DG_2 will decrease faster Fig. 12(c) and load current flows from DG_2 to DG_1 which helps improve the accuracy of current sharing. At $T = 12s$ the change rate of output voltages become the same and output currents keep unchanged, system arrives at steady state I.

3. 12∼16s
   As analysis in 3.2, the proposed droop curve shifts to the right since the current references of two DGs increased Fig. 12(d), and the change rates of the output voltage decay at same pace Fig. 12(b). At $T = 16s$ the change rates of output voltage become zero and output voltages keep unchanged, system arrives at steady state II. It is worth mentioning that the output currents keep unchanged Fig. 12(a) in the whole voltage stabilizer process.

In traditional control, the error of sharing $\Delta I_{err}\%$ is 28.6% due to line resistance, where the current sharing error can be defined as:

$$\Delta I_{err}\% = \frac{|i_{\rm dc1} - i_{\rm dc2}|}{(i_{\rm dc1} + i_{\rm dc2})}. \tag{20}$$

As explained before, an intermediate variable $\dot{V}$ is introduced to avoid line resistance effect which improves the accuracy to 10.3%. As analysis in 3.3, load current cannot be shared perfectly because of selection limit of τ in practical.

Fig.13(a), (b), (c), (d) show the experimental results during load switching with proposed control. At $T = 10s$ load switching happens, much more load current is allocated to DG_2 Fig.13(a), whose change rate of output voltage is more negative than DG_1 according to the proposed droop

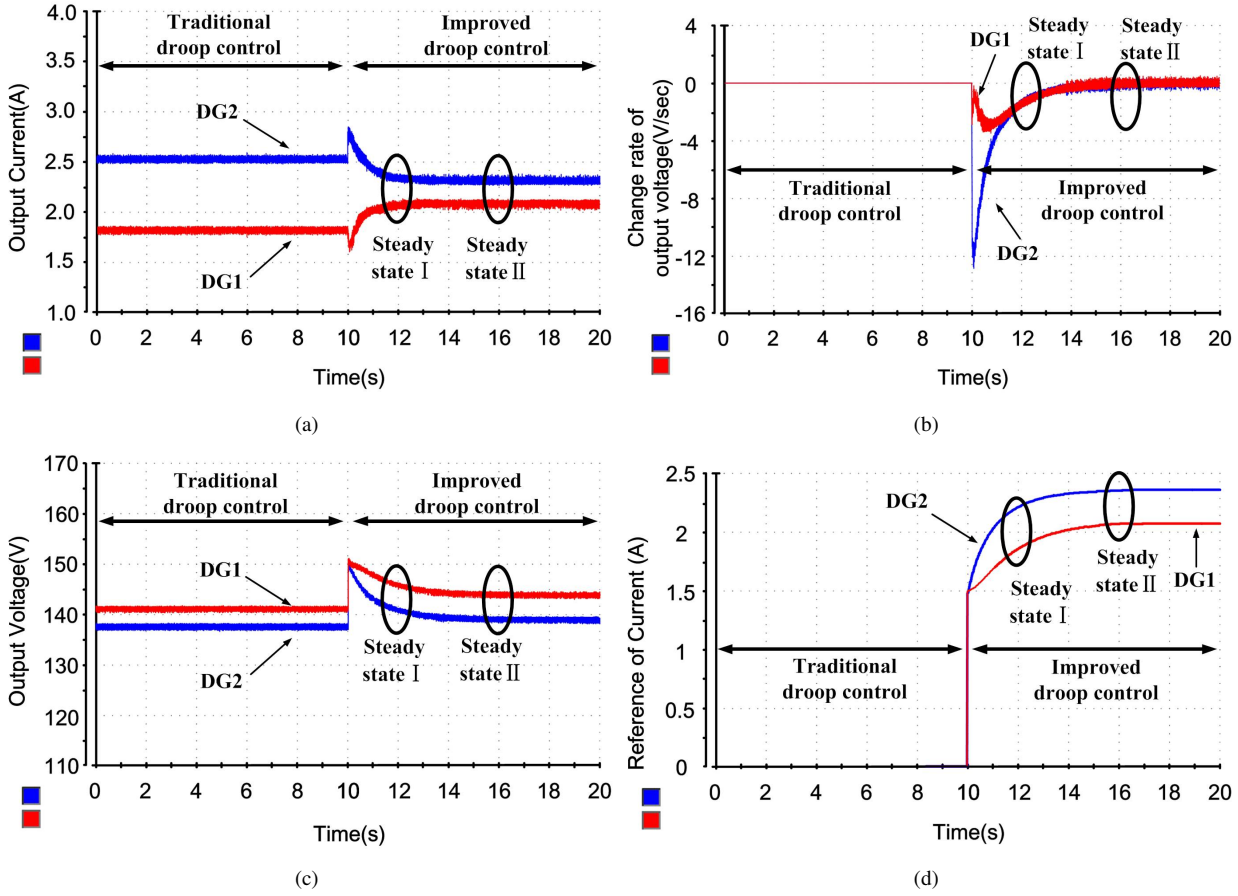


Fig. 12. Comparison of experimental results between traditional droop control and improved droop control.

curve Fig.13(b), so the output voltage of DG_2 will decrease faster Fig.13(c) and load current flows from DG_2 to DG_1. At $T = 12s$ the change rate of output voltages become the same and output currents keep unchanged, system arrives at steady state I. Current references of two DGs increased Fig.13(d), and the change rates of the output voltage decay at same pace Fig.13(b). At $T = 16s$ the output voltage change rates become zero and output voltages keep unchanged while system arrives at steady state II. As shown in Fig.13, the proposed control performs fast current sharing and stable operation.

5. Conclusion

A decentralized control method with improved current sharing accuracy applied in dc MGs has been presented and analysed in this paper. The change rate of the dc output voltage, as intermediate variable between output voltage and output current, was employed to avoid their interlocking dependence caused by line resistance. One of the main advantages of the proposed control method is that it does not require additional sensors to approximate the line resistance value, which is straightforward to implement as well as gives improved performance on the current sharing accuracy over the traditional droop voltage control. Alongside the advantages of communication links and dedicated central controller are not needed, the proposed controller keeps the decentralized characteristics such as reliability, expandability and plug-and-play capabilities. The performance

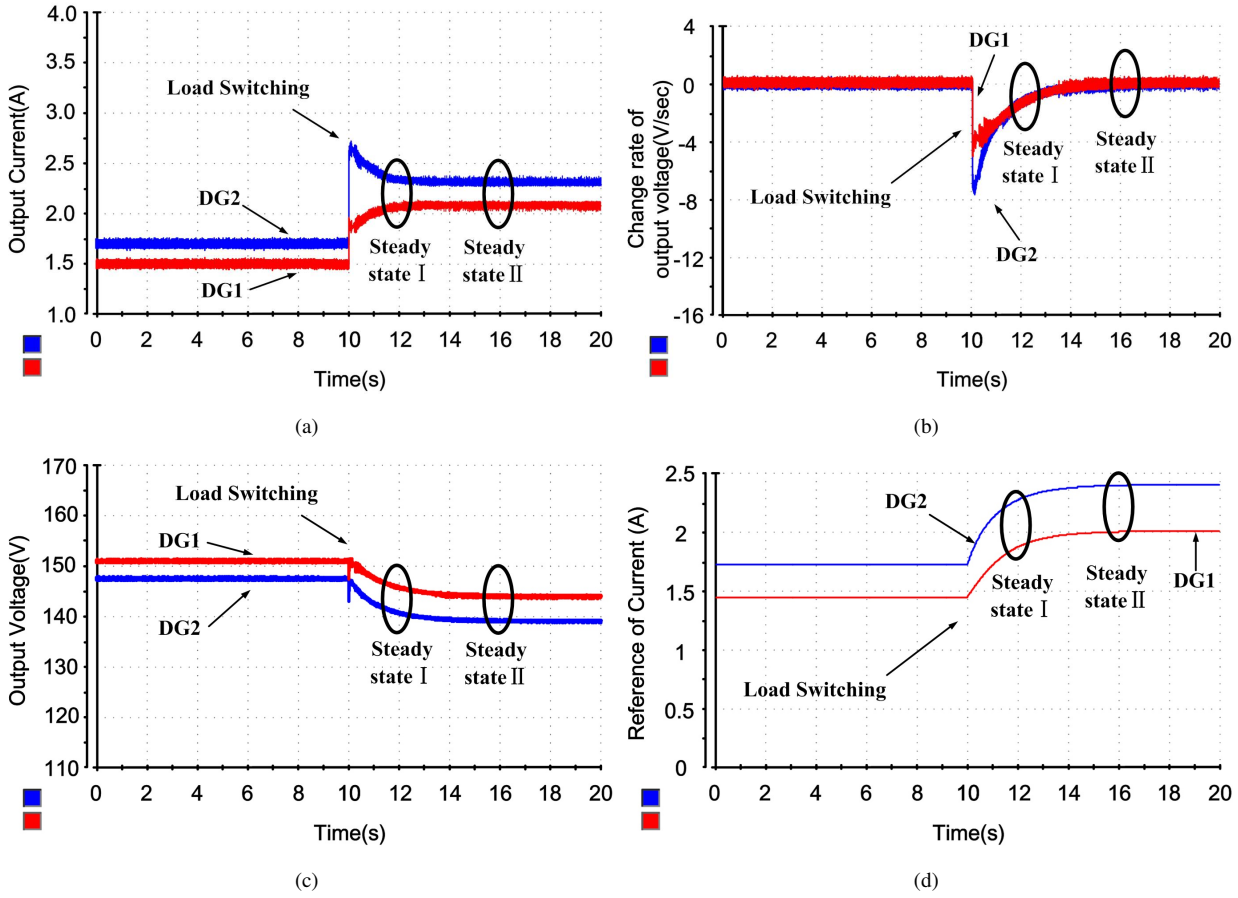


Fig. 13. *Experimental results during load switching with proposed control.*

of the proposed control method considering line resistance variations and the filter dynamics was investigated by eigenvalue analysis. The analysis verifies the fast dynamic response and small-signal stability of the method. In addition, experimental results clearly showed that implementation of the proposed controller behaves accurately and fast during load changes.

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