Nonlinear Control Analysis of Sensors Effect and Line Resistance for Current Sharing and Voltage Regulation in DC Microgrids

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***Abstract-* This paper proposes a new nonlinear droop control to improve voltage regulation and current-sharing among paralleled DC-DC converters in the DC-Microgrid (DCMG) in the Smart Homes (SHs). Line impedances can degrade the performance of the conventional droop methods in the current sharing among parallel DC-DC converters in the DC-Microgrids in the SHs. Moreover, sensing errors of the voltage and current in the DCMG can influence the current-sharing among parallel converters. The novel nonlinear proposed method improves voltage regulation and current sharing among the DC-DC converters by considering the effect of line impedance and sensing errors, which is an important issue in practical applications. The suggested method can guarantee the desire current-sharing from light-load to the heavy-load conditions in a stand-alone DCMG. Finally, theoretical analysis and Hardware-in-the-loop (HIL) experimental results are validated the effectiveness and applicability of the proposed control approach for different scenarios.**

***Index Terms-* nonlinear droop, current sharing, voltage regulation, DC-DC converter, smart home.**

I. INTRODUCTION

In the past decade, DC-Microgrids (DCMGs) have gained more attention due to the advantages such as simple control, higher efficiency, absence of harmonic and reactive power issues, and easy compatibility between sources and DC loads [1]. Moreover, utilizing renewable energy sources (RESs) and energy storage systems (ESSs) with integrating the DC-DC converters in the islanded DCMG provide more reliability, power quality, efficiency, and reduce the environmental concerns [2], [3].

In the islanded DCMG, RESs and ESSs are connected to the DC bus and loads through the related DC-DC converters. Moreover, in order to improve the reliability of the DCMG and to increase the injected power to the loads, DC-DC converters are paralleled in the stand-alone DCMGs [4], [5]. However, paralleling DC-DC converters in the DCMGs introduce current sharing issues. Current sharing among paralleled DC-DC converters in the DCMG is affected by the line resistance and sensor errors [6].

Droop control has been mainly used in the islanded DCMG to improve current sharing among parallel converters [7]. The main advantage of the droop control is its ability to provide current sharing among parallel DC-DC converters without communication links; Therefore, reliable performance of the DCMG can be obtained [8]. However, line resistance and sensors can degrade the performance of the droop control in the practical applications.

Up to now, several control strategies have been proposed to improve current sharing and voltage regulation in the DCMGs. In [9], a gain scheduling approach is suggested to provide suitable gain of the droop control based on the loading condition. This method improves the current sharing among parallel DC-DC converters. But, the use of gain scheduling method is limited to the proportional controllers. In [10], a piecewise linear droop control is proposed to improve current sharing in the DCMGs. In this method, the droop range split into the segments, which select larger droop gains when the DC load exceeds a pre-defined threshold. This method eliminates the current sharing errors caused by the sensors with proper droop gain. However, discontinues droop trajectories may lead to transients and oscillations in the DC-DC converters when the droop method is switched between different modes.

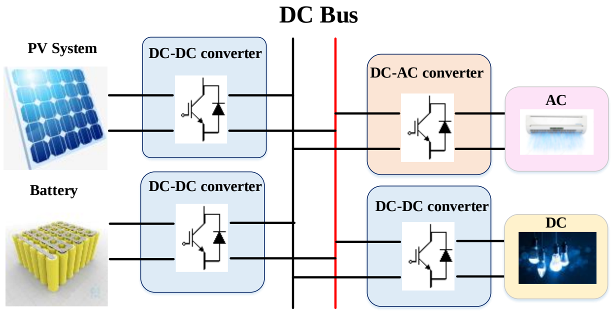


Fig. 1. Illustration of the typical DC-Microgrid.

To achieve a desired current sharing in the DCMGs, the authors in [11] proposed an adaptive droop control based on the superimposed frequency. In this method, the superimposed small AC voltage degrades the power quality of the system with oscillations in the voltage and current of the paralleled converters. In [12], an adaptive droop control strategy is suggested, which adaptively changes the droop gains to improve current sharing among paralleled DC-DC converters. In order to enhance the transient current sharing among the parallel converters in the DCMGs, reference [13] proposed an adaptive droop control based on the state of charge (SOC) of the ESSs in the DCMG. However, in these methods, the effect of the line impedance and sensors is not considered.

Besides, the linear droop control methods, nonlinear droop control strategies are proposed in several works [14]. A nonlinear droop control method is proposed in [15] and the performance of different droop trajectories is compared with the linear droop. Moreover, in [16], a nonlinear droop control is proposed to achieve current sharing and voltage restoration. These studies are concluded that the nonlinear droop control has better performance than linear droop control. But, they are limited to two-source system. Also, the performance of the DC-DC converters in all loading condition from light-load to heavy-load did not considered. Moreover, due to the dual control loops in the controller, these methods suffer from low dynamic response in the dynamic loading conditions [17].

In this paper, a novel nonlinear droop control is proposed to enhance voltage regulation and improve the current sharing among parallel DC-DC converters in the DCMGs. The effect of the line impedances and sensors in the paralleled DC-DC converters are considered. In the suggested strategy, the voltage regulation and current sharing among the paralleled DC-DC converters in the DCMGs are improved by adjusting the droop gains based on the local measuring of the output voltage and output current of each DC-DC converter. Moreover, accurate current sharing among paralleled converters is achieved in all loading conditions from light-load to heavy-load. The proposed method guarantees the voltage regulation of the DCMG in the acceptable range.

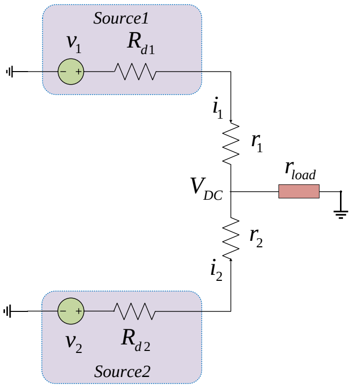


Fig. 2. Equivalent circuit of two parallel DC-DC converter.

The outline of this paper is as follows: In Section II the current sharing in the DCMG is discussed. Section III presents the proposed nonlinear droop control. Experimental results are shown in Section IV. Conclusions are drawn in Section V.

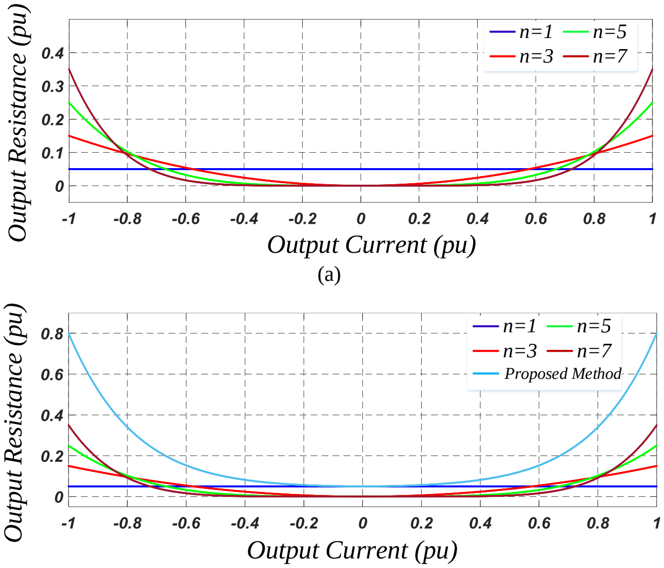
II. CURRENT SHARING IN DROOP CONTROL

A typical DCMG structure, which is used in several applications such as smart homes, All-electric ships, and electric aircraft is shown in Fig. 1. The considered DCMG contains several paralleled DC-DC converters, which connect the renewable energy sources (RERs) and energy storage systems (ESSs) to the DC bus and loads. In the droop control, current sharing and voltage regulation are influenced by the line resistance and sensing error. This section discussed these effects in details.

A. *Line resistance*

In order to deliver the power to the loads in a DCMG in the SHs, several parallel sources are connected to the DC bus through cables. Due to the distance between sources and loads, the cables have different length in the DCMG; thus, have different equivalent resistance. Therefore, different length of the cable in the DCMG leads to unequal resistance, which is degraded the current sharing among parallel DC-DC converters. As shown in Fig. 2, two parallel source are considered, which are connected to the DC load. In the equivalent circuit, r_1 and r_2 are the line resistance between each source to load terminal, respectively. Also, v_1 and v_2 are the output voltage of the source1 and source2, respectively. r_{load} is the equivalent resistance of the DC loads. In addition, the droop resistance of the source1 and source2 are R_{d1} an R_{d2}, respectively. The droop equation can be expressed as follows:

$$v_i = v_{ref} - R_{di} \cdot i_i \tag{1}$$



(a)

(b)

Fig. 3. (a) Droop gains based on the output current for different values of n. (b) Different droop gain based on the proposed approach for n=1,3,5,7.

where v_{ref} is the reference voltage and v_i is the output voltage of the i^{th} source. Moreover, R_{di} and i_i are the droop resistance and current of the i^{th} source, respectively. In the droop control method, the droop resistance can be defined as:

$$R_{di} = \frac{\Delta v}{i_{\max}} \tag{2}$$

where Δv is the acceptable voltage deviation from the reference voltage and $i_{\max}$ is the maximum output current of the source, respectively.

As depicted in Fig 2, the total resistance from the sources to the DC load can be written as follows:

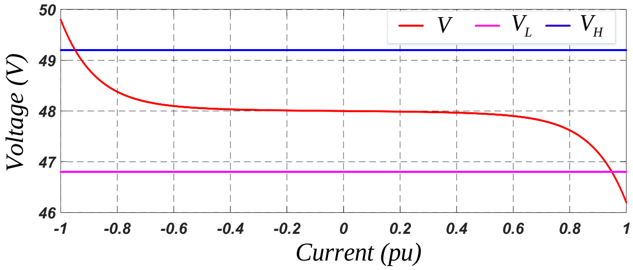


Fig. 4. Deviation of voltage from no-load to full-load condition.

$$r_1' = R_{d1} + r_1 \tag{3}$$

$$r_2' = R_{d2} + r_2 \tag{4}$$

By applying Kirchhoff's laws to the equivalent circuit in Fig. 2, the current of the source1 and source2 can be obtained as follows:

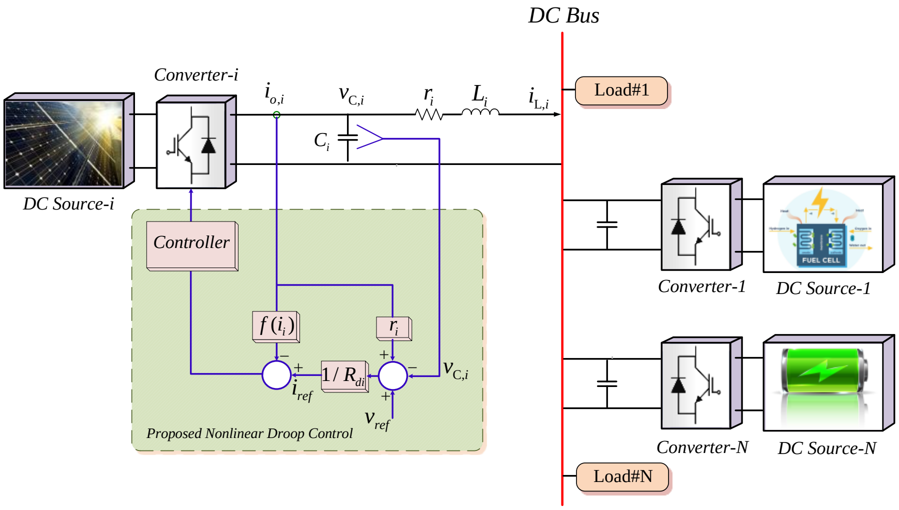


Fig. 5. Overall control diagram of the proposed method in the DCMG.

	Parameters	value
Electrical parameters	DC bus voltage	400
	Converter Inductance	$1000\mu H$
	DC Bus Capacitance	$2200\mu F$
	Line Resistance for DCMG1	0.6Ω
	Line Resistance for DCMG2	0.5Ω
	Line Resistance for DCMG3	0.3Ω
	Line Resistance for DCMG4	1.1Ω
Droop control parameters	k_p	5
	k_i	45
	k_1	0.2

TABLE I EXPERIMENTAL PARAMETERS

$$i_1 = \frac{r_{load}(v_1 - v_2) + v_1 \cdot r_2'}{r_1' \cdot r_2' + r_{load} \cdot r_1' + r_{load} \cdot r_2'} \tag{5}$$

$$i_2 = \frac{r_{load}(v_2 - v_1) + v_2 \cdot r_1'}{r_1' \cdot r_2' + r_{load} \cdot r_1' + r_{load} \cdot r_2'} \tag{6}$$

The difference between the current of the two paralleled DC-DC converter in the DCMG is given by:

$$i_1 - i_2 = \frac{2(v_1 - v_2)}{r_1' + r_2' + \frac{r_1' \cdot r_2'}{r_{load}}} + \frac{v_1 \cdot r_2' - v_2 \cdot r_1'}{r_1' \cdot r_2' + r_1' \cdot r_{load} + r_2' \cdot r_{load}} \tag{7}$$

And the load current can be presented as:

$$\begin{cases} V_{DC} = v_1 - i_1 r_1' = v_2 - i_2 r_1' \\ i_{load} = i_1 + i_2 \end{cases} \tag{8}$$

Since the reference voltage of the two sources is the same, the current sharing can be obtained as:

$$\frac{i_1}{i_2} = \frac{R_{d2} + r_2}{R_{d1} + r_1} \tag{9}$$

Based on (9), the source with larger line resistance injects less current to the DC loads. Moreover, the droop control can improve the current sharing among the parallel DC-DC converters. Additionally, high droop gain provides better current sharing among the parallel sources. However, high droop gain increase the voltage deviation [18]. Therefore, in the droop control method, it is a trade-off between the voltage regulation and current sharing.

B. *Error of the sensors*

Sensing errors in the DCMGs can influence the current sharing among paralleled DC-DC converters. The inaccurate calibration of the sensors and temperature are two main factors that can affect the operation of the sensors in the DCMGs. For example, in the medium voltage DCMGs in the SHs, voltage drift is commonly observed. Moreover, a typical voltage sensor, have a static accuracy of around 1 % [19]. Also, the errors in the current sensors and analog-to-digital converters in the DCMG always exist and cannot be eliminated in the DC-DC converters circuit. If in the equivalent circuit in the Fig. 2, the line resistance of the source1 and source2 are the same and $v_1 = v_2$, the relationship between currents of the source can be written as follows:

$$\frac{i_1}{i_2} = \frac{R_{d2}}{R_{d1}} \tag{10}$$

Considering the error in the sensors yields $v_1 \neq v_2$, and it can be derived as:

$$i_1 = \frac{R_{d2}}{R_{d1}} i_2 + \frac{v_1 - v_2}{R_{d1}} \tag{11}$$

The second term is the current sharing error, which is produced with the voltage sensors. It should be noted that this error is related to the sensors and droop gain. This error stays constant with the variation in the current load.

In summary, the current sharing error among parallel converters in the DCMGs is the result of both line resistances and sensor errors. The error from the line resistances increases when the load increases and the error from the sensing error stays constant regardless of the current load. In the next section, the nonlinear droop control is proposed in details to improve current sharing in the DCMGs.

III. PROPOSED NONLINEAR DROOP CONTROL TECHNIQUE

In order to improve current sharing and voltage regulation in the DCMGs, an optimization of the droop resistance trajectory should be considered. Several droop curves can be derived from light-load to heavy-load operation of the DC-DC converters for a pre-defined voltage error. These curves can be obtained by the following equation:

$$v_i = v_{ref} - \alpha_i \cdot \left(i_i^n\right), n \in R^+ \tag{12}$$

where

$$\alpha_i = \frac{\Delta v}{\left(i_{i,\max}\right)^n} \tag{13}$$

Base on (12), the droop resistance expression can be derived as:

$$R_{di} = \frac{dv_i}{di_i} = n \cdot \alpha_i \cdot \left(i_i\right)^{n-1} \tag{14}$$

The droop curves are shown in Fig. 3 from no-load to heavy-load for different values of n. The current is considered from -1 to 1 for a symmetrical operation in the bidirectional DC-DC converters.

As can be seen in Fig. 3(a), for n=1, the droop gain is constant and it is the linear droop method. In the nonlinear methods, when $n > 1$ in the light-load conditions, the value of the droop gain is close to zero; and the value of the droop gain is higher than the linear droop method in the heavy-load conditions. From Fig. 3(a), it can be seen that the linear droop method has small droop resistance in the heavy-load condition, while the nonlinear droop methods have small droop resistance in the light-load condition. As mentioned before, high droop gain provides better current sharing among the parallel DC-DC converters.

To cope with these limitations of the conventional linear and nonlinear methods, and to achieve proper current sharing and voltage restoration in the DCMGs, a novel nonlinear droop control is proposed here. From (1), by reversing the output reference from the droop characteristic, the new droop control approach can be realized by increasing the current reference when the DC bus voltage decreases in the DCMGs as follows:

$$i_{ref,i} = \frac{v_{ref} - v_{Ci}}{R_{di}} \tag{15}$$

where $i_{ref,i}$ is the reference current, and v_{Ci} is the output voltage measured from the i^{th} DC-DC converter. By expanding (12), with respect to the linear droop gain, the general equation of the droop method can be expressed as:

$$v_i = v_{ref} - \alpha_1 \cdot i_i - \alpha_i \cdot i_i^n \tag{16}$$

It should be noted that to have a symmetrical characteristic for the bidirectional DC-DC converter, it is preferred to select the droop curves with odd values of n. Therefore, (16) can be rewritten as:

$$\alpha_1 \cdot i_i = v_{ref} - v_i - \alpha_i \cdot i_i^n \tag{17}$$

And finally, by substituting (17) into the (15) the proposed nonlinear droop control can be formulated as follows:

$$i_{ref,i} = \frac{v_{ref} - v_i}{\alpha_1} - \left(\frac{\alpha_i}{\alpha_1} \cdot i_i^n\right) \tag{18}$$

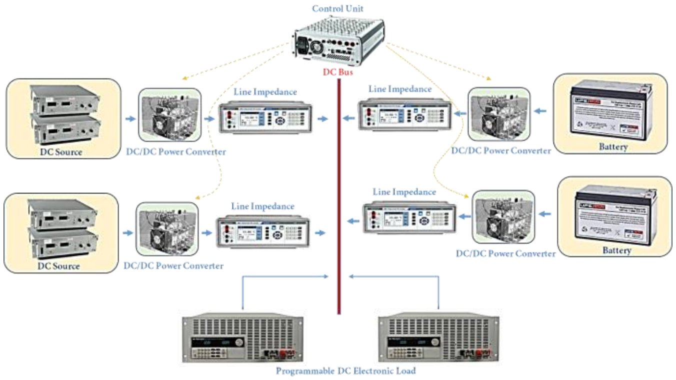


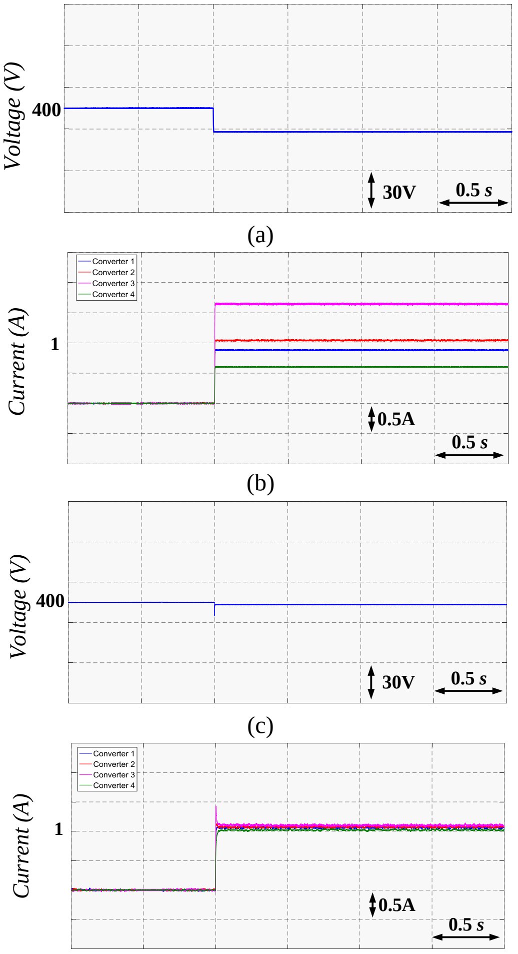
Fig. 6. Experimental setup.

where α_1 is the linear droop gain and α_i is defined in (13). As shown in Fig. 3(b), it can be concluded that the proposed droop method has the maximum available droop gain in all loading conditions from light-load to heavy-load. Therefore, the desired current sharing among paralleled DC-DC converter can be achieved with the suggested control method.

However, as depicted in Fig. 4, in the heavy-load condition the voltage deviation from the reference value is more than the expected deviation (i.e. $V_H = 410V$ and $V_L = 390V$) [20]. To eliminate this deviation, a voltage compensation method is proposed based on the line resistance. In this method, in order to improve the voltage regulation, a compensation term added to the reference voltage considering the line resistance. The modified droop method formulation can be obtained as follows:

$$i_{ref,i} = \frac{v_{ref} - v_i + \Delta v_i}{\alpha_1} - \left(\frac{\alpha_i}{\alpha_1} \cdot i_i^n\right) \tag{19}$$

where i_i and v_i are the output current and output voltage of the DC-DC converters in the DCMG in the SHs. The proposed method in (19), satisfies the voltage regulation in the acceptable range. In the proposed method only the local information is used and no communication infrastructure is needed. The overall diagram of the suggested control approach is shown in Fig. 5.



(a)

(b)

(c)

(d)

Fig. 7. Experimental results in the light loading condition; (a) DC bus voltage and (b) output currents of the DC-DC converters with the conventional droop control, (c) DC bus voltage and (d) output currents of the DC-DC converters with the proposed control scheme.

IV. EXPERIMENTAL RESULTS

To validate the effectiveness of the proposed control strategy, a DCMG consists of four parallel DC-DC converters is implemented in the SH. Table I shows the experimental parameters of the system. The experimental setup is shown in Fig. 6. The nominal voltage of the DCMG is $400V$ and the nominal output power of each DC-DC converter is considered to be $2.2kW$. Different scenarios are conducted to verify the applicability of the proposed method.

A. *Light-load condition*

Fig. 7 shows the experimental results for the light-load condition in the DCMG in the SH. In order to realize this condition, at $t = 1s$ a load of 1.6kW is applied in the DC bus. Figs. 7(a) and 7(b) show the performance of the conventional droop control method in the DCMG.

Fig. 7(a) shows the voltage of the DC bus, which drop below the acceptable range. From Fig. 7(b), it can be observed that the conventional droop control can't provide proper power sharing among paralleled DC-DC converters, which is maybe lead to over current situation in the DC-DC converters. Fig. 7(c) shows the voltage of the DC bus, which drop from 400 to 397 V. It can be concluded that with the proposed control scheme, the DC bus voltage has proper profile when the light load is connected to the DCMG. In this case, the voltage of the DCMG is remained in the acceptable range (i.e. $V_H = 410V$ and $V_L = 390V$).

From Fig. 7(d), it can be observed that for the light-load condition in the DCMG, the suggested nonlinear droop control method provides accurate current sharing among the parallel DC-DC converters with different line resistance.

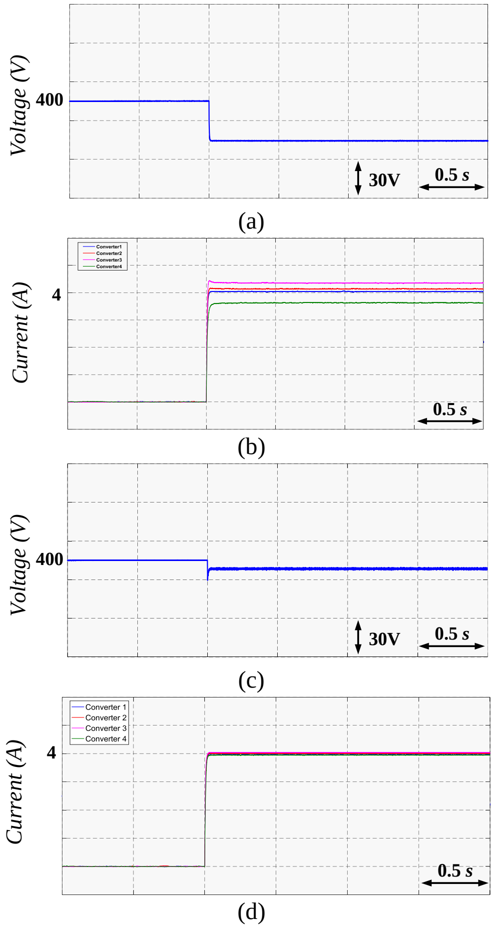


Fig. 8. Experimental results in the heavy loading condition; (a) DC bus voltage and (b) output currents of the DC-DC converters with the conventional droop control, (c) DC bus voltage and (d) output currents of the DC-DC converters with the proposed control method.

B. *Heavy-load condition*

This section illustrates the performance of the proposed method under heavy-load condition. Fig. 8 shows the experimental results for this case study. At $t = 1s$ a 6.3kW DC load is considered in the DC bus. As illustrated in Fig. 8(a), the voltage in the DC bus drop from 400 to 370 V and the DC-DC converters start contributing for the common load with conventional droop control method.

As depicted in Fig. 8(b), in the heavy-load condition, the conventional droop control method suffer from inaccurate current sharing among DC-DC converters in the DCMG. To improve the current sharing in this condition, the proposed nonlinear droop control is applied.

Fig. 8(c) shows the DC bus voltage in this case study. From Fig. 8(c), it can be seen that the DC bus voltage remains within the

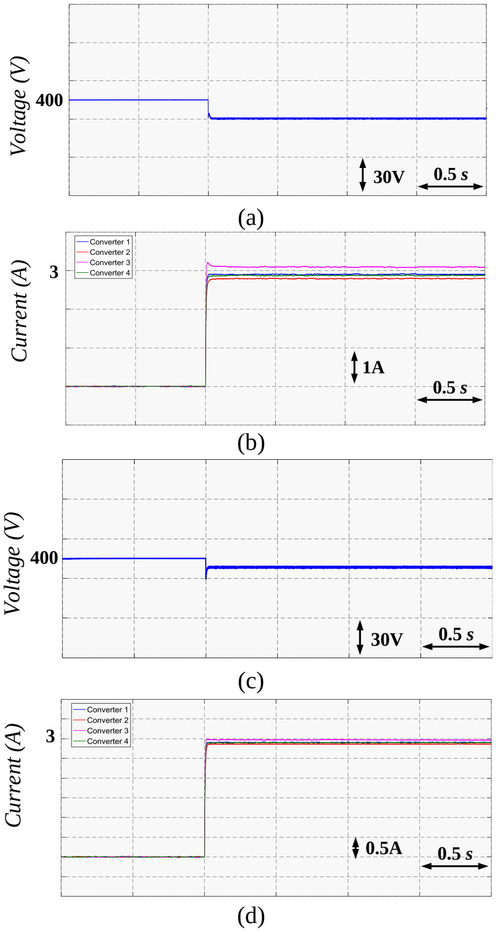


Fig. 9. Experimental results in the sensing errors condition; (a) DC bus voltage and (b) output currents of the DC-DC converters with the conventional droop control, (c) DC bus voltage and (d) output currents of the DC-DC converters with the proposed control approach.

acceptable range in heavy-load condition in the DCMG.

As illustrated in Fig. 8(d), with the proposed nonlinear droop control approach, the current sharing among the DC-DC converters is realized accurately with different line resistances. Therefore, the accuracy of the current sharing among paralleled DC-DC converters is enhanced compared to the Fig. 8(b).

C. Error of the sensors

To demonstrate the effectiveness of the nonlinear proposed method in the case of the sensor error, a DCMG consists of four DC-DC converter is considered. Among the converters, converter1 and converter 4 have sensor offset and equal line resistance. Moreover, source 2 and source 3 have different line resistance. Therefore, in source 1 and 4 the sensor error degrades the current sharing. While, in source 2 and 3 the inaccurate current sharing is caused by the line resistance. Fig. 9(a) and Fig. 9(b) show the performance of the conventional droop method. In addition, Fig. 9(c) and Fig. 9(d) show the experimental results for the proposed control scheme. The advantages of the proposed nonlinear droop method are proven by comparing the DC bus voltage deviation from the reference voltage and the current difference between the DC-DC converters in the DCMG in the SH. As illustrated in Fig. 9(a) and Fig. 9(c), the proposed control strategy has acceptable voltage deviation from the reference voltage. Moreover, by comparing Fig. 9(b) and Fig. 9(d), the suggested control method can eliminate the effect of the sensor drifts and line resistance effectively on the current sharing among DC-DC converters in the DCMG.

V. CONCLUSION

In this paper, a new nonlinear droop control method was proposed for paralleled DC-DC converters in the DCMG in the SHs. The suggested method significantly reduced the impact of the line resistance and sensor errors. Compared to the conventional droop control methods, the proposed scheme improved the voltage regulation and current sharing among paralleled DC-DC converters. Moreover, the proposed nonlinear droop strategy was provided desire current-sharing in all loading conditions from light-load to heavy-load. The hardware-in-the-loop (HIL) experimental results verified the effectiveness and applicability of the proposed control scheme during various loading conditions.

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