An Adaptive Power Distributed Control Method to Ensure Proportional Load Power Sharing in DC Microgrid Considering Equivalent Line Impedances

Duy-Hung Dam
School of Electrical Engineering
University of Ulsan, South Korea
damduyhung@gmail.com

Hong-Hee Lee
School of Electrical Engineering
University of Ulsan, South Korea
hhlee@mail.ulsan.ac.kr

***Abstract*— This paper proposed a distributed control method for dc microgrid to ensure the proportional load sharing by taking into account the different line impedance. In the proposed method, the operation point of each DG is effectively defined based on the power rating and the instantaneous power of the DG to achieve the proportional load power sharing. A low bandwidth communication is used to transmit the data required to determine the power reference for all DGs. In order to balance the power per unit requirement, the output voltage of each DG is controlled by a power controller to adjust the desired operating point. Therefore, all DGs can operate at the balanced operating point on the droop curve to ensure the proportional load power sharing. This paper also considers the load shedding to prevent the dc microgrid from operating under overload condition. The effectiveness of the proposed method is verified by simulation and experiment which are carried out with 2.8kW prototype dc microgrid.**

Keywords*— distributed control, dc microgrid, droop control, power sharing, line impedance

I. Introduction

In order to integrate different type of renewable energy sources and to supply power for a remote area, the concept of microgrid has been introduced as an efficient solution [1]. Microgrid is an aggregated entity to integrate distributed generators (DGs). Because the utility electrical grid generally relies on ac systems, many researchers have focused on the ac microgrids up to now. However, the renewable energy resources and loads such as the photovoltaic (PV) and the energy storage systems are dc coupled. When these kinds of dc sources and loads are integrated into the ac microgrid, it is inefficient in point of the power conversion and the system cost. Therefore, the dc microgrid has become interested in these days. The typical dc microgrid is shown in Fig. 1, where all of DGs and loads are connected to a common dc bus.

To control effectively the dc microgrid, some control methods have been presented based on the centralized, decentralized, distributed and hierarchical control algorithms [2]-[14]. These control methods aim to enhance the reliable operation and voltage regulation of dc microgrid. However, all DGs are parallel connected to the common dc bus, so the power sharing among DGs is an important task. The droop

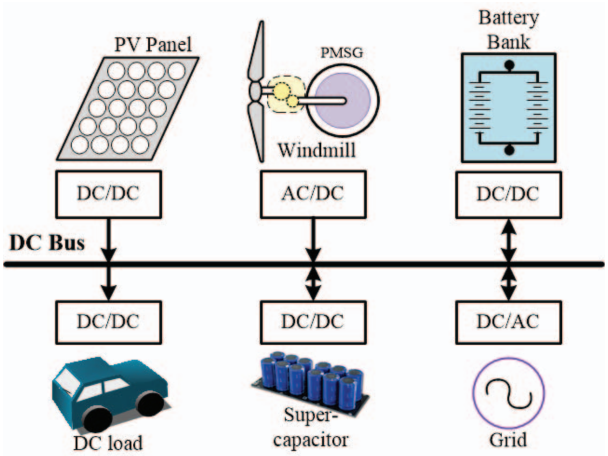

Fig. 1. Typical configuration of dc microgrid.

control method has been commonly used to share the loads and to regulate the dc bus voltage among the parallel DGs. However, the major drawback of the droop control method is the tradeoff between the dc bus voltage variation and the proportional load power sharing [11]. To overcome this drawback, the application of the communication interface has been taken into account by exchanging the information via communication to adjust the set-point for the droop control which can enhance both the voltage variation and the microgrid reliability. These communication-based droop control methods include the wireless/radio transmission techniques, the power line communication (PLC) [2], [8], and the low band-width methods [11], [13], [14]. Among these communication techniques, the PLC is popularly used in low voltage distribution network because it is available with the lowest cost compared with other methods. Pinomaa et al. [8] introduced a PLC based network architecture for the low voltage dc microgrid. However, the transmission of PLC under capacitive loads condition leads to a fault communication [13]. Another suitable technique for the communication in the dc microgrid is the controller area network (CAN) [11]. Because most of the digital signal processors/controller used to control the DGs in the microgrid usually include the CAN interface, the CAN solution is cost effective for the low bandwidth based distributed control in the microgrid.

To reduce the dc bus voltage variation and enhance the load power sharing, authors in [11], [13], [14] presented the low

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bandwidth based method for the dc microgrid. Anand et al. [11] used a high droop coefficient to reduce the difference of the load power sharing, and added a shifted voltage to regulate the voltage variation. In [13], Po-Hsu Huang et al. introduced a method to reduce the dc bus voltage variation by using an average voltage sharing control algorithm. However, these methods do not consider the line voltage variation due to the load variation, and are hard to achieve the current sharing accurately. To remove these problems, Xiaonan et al. [14] presented the low bandwidth based distributed control to transmit the information of voltage, current and current sharing ratio of each DG to achieve the accurate load power sharing and to improve dc bus voltage performance. Even though this study considers the line impedance for power sharing, the power sharing cannot be achieved when the load is changed because the line voltage drop due to the load variation is not considered; the variation of the line voltage drop leads to the inaccurate load power sharing.

In this paper, we propose an adaptive distributed control method to achieve the proportional power sharing and to improve the dc bus voltage variation by considering the equivalent line impedance concept which is related with the line voltage drop [15]. In order to implement the proposed method, a low bandwidth communication is used to collect the information of the power per unit of each DG. In addition, the load shedding control is also considered to prevent the dc microgrid from operating under overload condition. The effectiveness of the proposed control method is verified by the simulation and experiment.

II. Power Sharing under Loads Variation

For simple analysis, a dc microgrid which includes two DGs and two loads is considered as shown in Fig. 2. Fig. 3 shows the equivalent network circuit of the dc microgrid shown in Fig. 2. The droop controlled DG sources have the same voltage magnitude V_{dc} and their virtual impedances are r_{d1} and r_{d2}. In Fig. 3, r_{line1}, r_{line2} and r_{line3} are the line impedances, r_{load1} and r_{load2} are the load impedances. The equivalent load $\overline{r}_{load}$ and the equivalent line impedances r'_{line1}, r'_{line2} are obtained as following by applying the delta-star transformation:

$$\begin{aligned} r'_{line1} &= r_{line1} + \frac{r_{line2} r_{load1}}{r_{line2} + r_{load1} + r_{load2}} \\ r'_{line2} &= r_{line2} + \frac{r_{line2} r_{load2}}{r_{line2} + r_{load1} + r_{load2}} \\ \overline{r}_{load} &= \frac{r_{load1} r_{load2}}{r_{line2} + r_{load1} + r_{load2}} \end{aligned} \qquad (1)$$

By using (1), Fig. 3 is modified like Fig. 4, and the ratio of the output power of two DGs P^1 / P^2 can be derived as following:

$$\frac{P_1}{P_2} = \frac{(\overline{r}_{load} + r'_{line1})\, i_{out1}^2}{(\overline{r}_{load} + r'_{line2})\, i_{out2}^2} = \frac{V_{dc} i_{out1} - r_{d1} i_{out1}^2}{V_{dc} i_{out2} - r_{d2} i_{out2}} \qquad (2)$$

From (1) and (2), if the load is changed, the equivalent line impedance and the power sharing of DGs are also changed. Therefore, the load variation causes the power sharing to be disproportional.

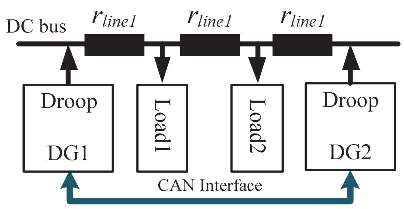

Fig. 2. Distributed dc microgrid.

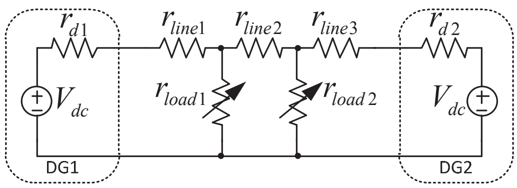

Fig. 3. Equivalent circuit of a dc microgrid with two DGs and two loads.

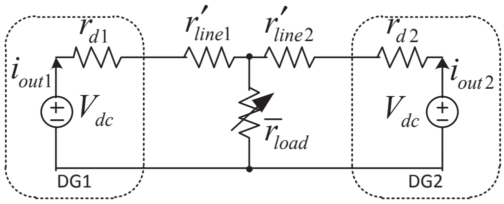

Fig. 4. Equivalent line impedance and equivalent load.

III. Proposed Distributed Control Method

As discussed in Section II, the difference of the equivalent line impedance in the microgrid results in the different power sharing when the conventional droop control is applied. In order to provide the load power in proportional to the DG output power, the operation point of DG should be adjusted according to the load variation. This paper introduces a distributed control method for the accurate proportional power sharing; the load power is supplied in proportional to the capacity of DG.

A. The Proposed Distributed Control

The proposed distributed control diagram is shown in Fig. 5, which contains five main parts: the measurement block, the droop control, the distributed controller, the voltage control loop, and the current control loop.

1) The measurement block: the output voltage and current of each DG are measured to control the DGs. The first-order lowpass filter is used to eliminate the noise in the output voltage and current with the reduced the phase delay.

2) Droop control: The droop controller determines the virtual voltage drop across the virtual impedance for each DG. The virtual voltage drop is decided by the droop coefficient K_d^i in Fig. 6. In order to minimize the line voltage drop on the dc bus, the droop control coefficient for all DGs are determined

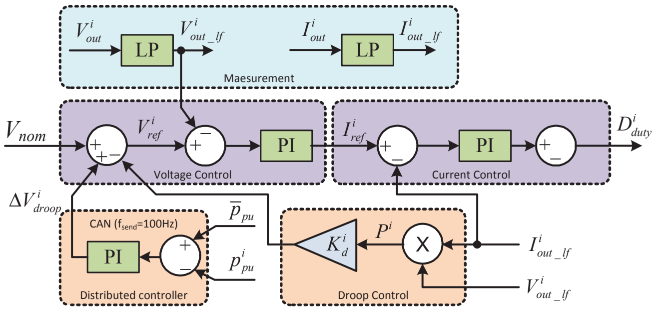

Fig. 7. The proposed control diagram.

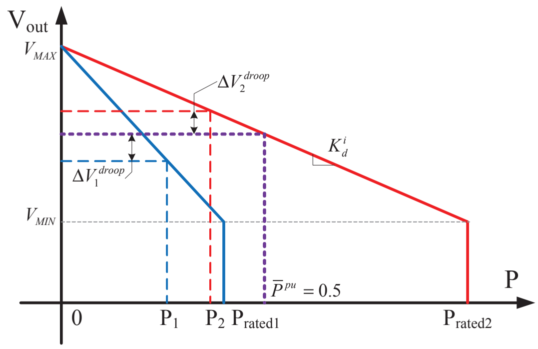

Fig. 8. Droop characteristics for each DGs with difference of power rated.

as following:

$$K_d^i = \frac{V_{MAX} - V_{MIN}}{P_{rated}^i} \qquad (3)$$

where K_d^i is the droop coefficient of i^th DG droop control, P_{rated}^i denotes the rated power of i^th DG, and V_{MAX} and V_{MIN} are the allowable maximum and minimum voltage of the dc bus, respectively. Then, the virtual voltage drop on i^th DG V_{droop}^i is given in (4) where P^i and p_{pu}^i are the output power and output power per unit of i^th DG.

$$V_{droop}^i = K_d^i P^i = p_{pu}^i \left(V_{MAX} - V_{MIN}\right) \qquad (4)$$

From (4), it is clear that the power per unit is proportional to the virtual voltage droop because $V_{MAX} - V_{MIN}$ is constant. Assuming that the proposed control method works properly, the power per unit of all DGs are balanced, therefore, the virtual voltage drop on all DGs are the same.

3) Distributed controller: To obtain the proportional load power sharing for each DG, a shifted voltage is added to the reference output voltage, which is illustrated in Fig. 5. In order to determine the shifted voltage, the output power per unit of each DG is identified through low-bandwidth communication. Then, the average power supply of all DGs is obtained as following:

$$\bar{p}_{pu} = \frac{\sum_{i=1}^{n} p_{pu}^i}{n}, \quad p_{pu}^i = \frac{P^i}{P_{rated}^i} \qquad (5)$$

where p_{pu}^i is the power of i^th DG in per unit. The shifted voltage of the droop control for each DG becomes as follows:

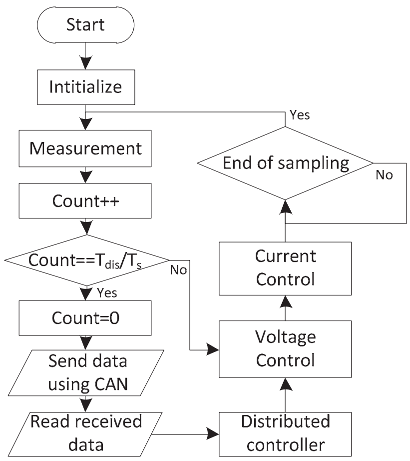

Fig. 5. Flowchart of proposed control scheme.

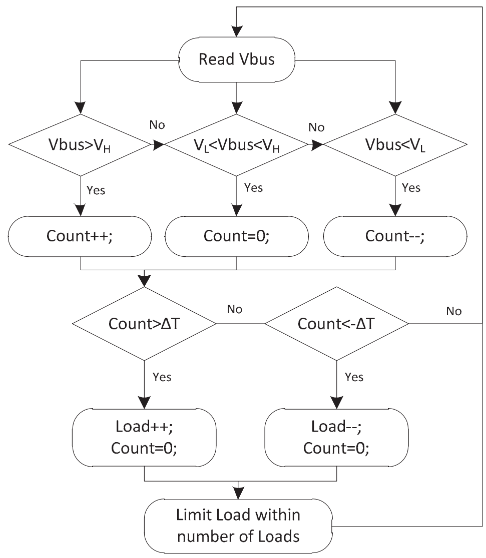

Fig. 6. Flowchart of load shedding procedure

$$\Delta V_{droop}^i = \left(k_P^d + \frac{k_I^d}{s}\right)\left(\bar{p}_{pu} - p_{pu}^i\right) \qquad (6)$$

where k_P^d, k_I^d are the gains of proportional–integral (PI) distributed controller. This control loop is executed every 10ms after receiving (sending) the data from (to) other DGs. The data sending and receiving flowchart is shown in Fig. 7, where T_{dis} is the period of sending or receiving data and T_s is the sampling period of DG controller.

4) Voltage control loop: The voltage control loop regulates the DG output voltage to obtain the voltage reference defined by the droop control and distributed control. In the voltage control loop, a PI controller is utilized to generate the reference current for the current loop as shown in Fig. 4. As a result, the reference voltage and current of i^th DG become

$$V_{ref}^i = V_{nom} - V_{droop}^i + \Delta V_{droop}^i$$
$$I_{ref}^i = \left(k_P^V + \frac{k_I^V}{s}\right)\left(V_{ref}^i - V_{out\_lf}^i\right) \qquad (7)$$

where V_{nom} is the nominal voltage of the dc bus, and ΔV^{i}_{droop} is the shifted voltage defined by the distributed controller. And, k^{V}_{P} and k^{V}_{I} are the PI gains of the voltage control loop.

5) Current control loop: The current control loop is implemented by the PI controller and the duty cycle of the DG converter, D^{i}_{duty}, is defined as following:

$$D^{i}_{duty} = \left(k^{C}_{P} + \frac{k^{C}_{I}}{s} \right) \left(I^{i}_{ref} - I^{i}_{out\_lf} \right) \quad (8)$$

where k^{C}_{P} and k^{C}_{I} are the gains of the PI current controller.

B. *Load shedding*

Under variable load condition, the DGs can become overload situation due to the dc bus voltage variation caused by the droop control. In order to regulate the dc bus voltage within the allowable range and to prevent overload problem, the load shedding schedule, which based on level of the dc bus voltage, is considered in this study [16].The flowchart of load shedding schedule is shown in Fig. 8.

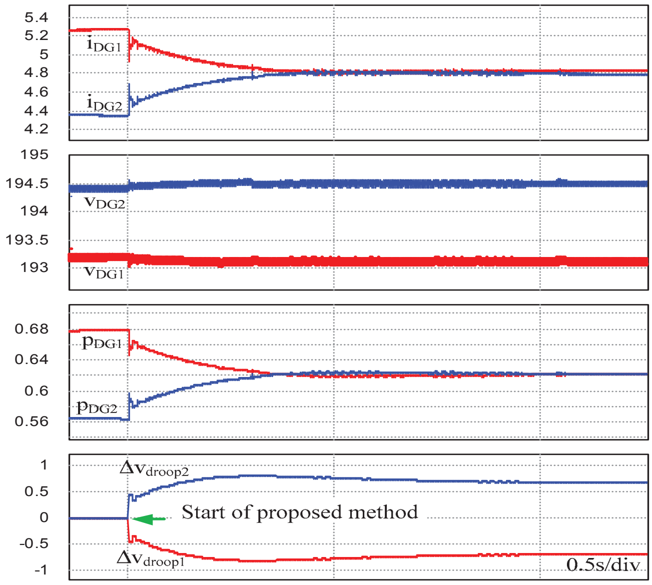

Fig. 9. Transient of proposed method

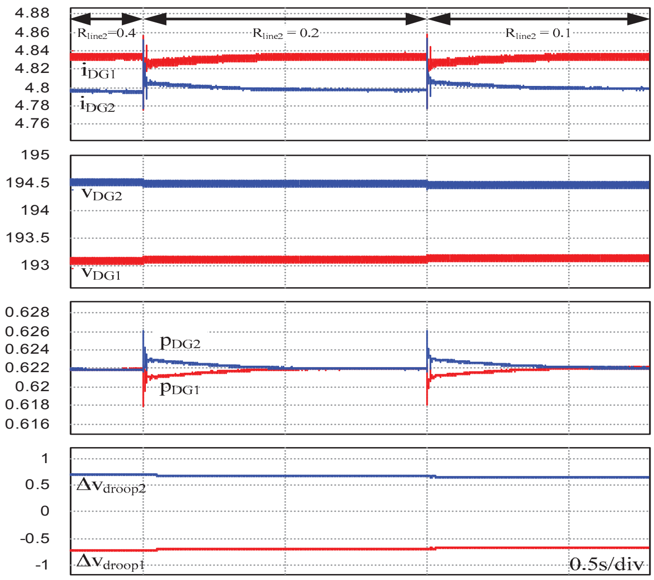

Fig. 10. Proposed method with changes of equivalent line impedance.

Table 1. DC Microgrid Parameters

Parameters	Value
Bus voltage	190V-200V
Line impedance 1 (r'_{line1})	0.1 Ω
Line impedance 2 (r'_{line2})	4x0.1 Ω , 0.4mH
Load 1, 2, 3	20 Ω , 66 Ω , 132 Ω

C. *Communication requirements*

In proposed control diagram, the information of the DG output power per unit is transmitted to the other DGs controllers. This requires 2 bytes transmission date for power per unit value and 1 byte for identification for each DG. Hence, the total data to transmit through the communication channel becomes 3n bytes, where n is the number of DG in the microgrid. Because the data sending interval is 10ms, the required communication bandwidth becomes low; the CAN-based interface is suitably used in the laboratory prototype.

IV. Simulation Results and Discussion

A dc microgrid with two sources as shown in Fig. 4 is simulated using PSIM 9.0.2. Parameters used for the simulation are given in Table 1. Each source is composed of dc-dc buck converter with inner voltage-current controller as shown in Fig. 5. The proposed method is implemented to generate the reference voltage for the voltage control loop.

Transient performance is simulated with load 1, and each power rating of DG is 1.5kW. With the conventional droop control, the output power per unit of DG1 (p_{DG1}) is 0.68 and DG2 (p_{DG2}) is 0.56 as shown in Fig. 9. After applying the proposed method, the power per unit of each DG becomes the same value of 0.62 within 1 second.

Fig. 10 shows the performance of the equivalent line impedance variation when the line impedance of DG2 (r'_{line2}) is changed from 0.4Ω to 0.2Ω and 0.1Ω while the line impedance of DG1 (r'_{line1}) is kept constant with 0.1Ω. After the line impedance r'_{line2} is changed, the system reaches the steady state after 0.5 second and the current variation is smaller than 0.1A, which is less than 1% of the load current.

To emulate the load shedding procedure, the dc microgrid is tested with the different power rated DGs, where the power rating of DG1 and DG2 are swept from 1.2kW to 2.2kW and 1.5kW to 3.2kW, ordinarily. The conventional and proposed methods are both realized under the same condition as shown in Table 1. Load 1 is considered as the most importance load and always connected to the dc bus. Meanwhile, load 2 and load 3 are variable loads, so they can be connected or disconnected depending on the power level. During startup time, the load 1 is connected, whereas the load 2 and load 3 are connected or disconnected according to the load shedding

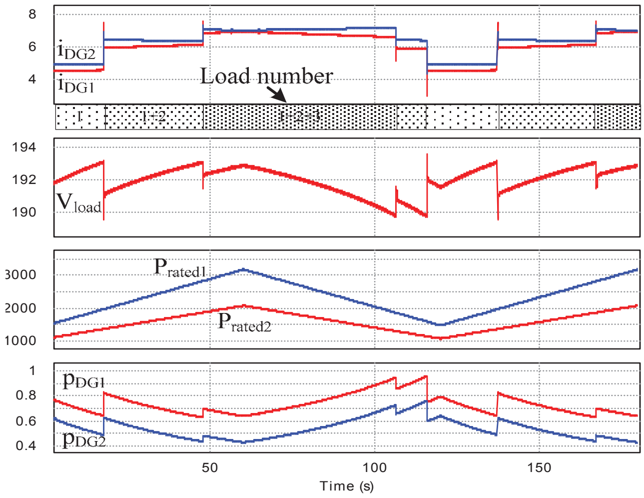

Fig. 11. Load shedding with conventional droop control.

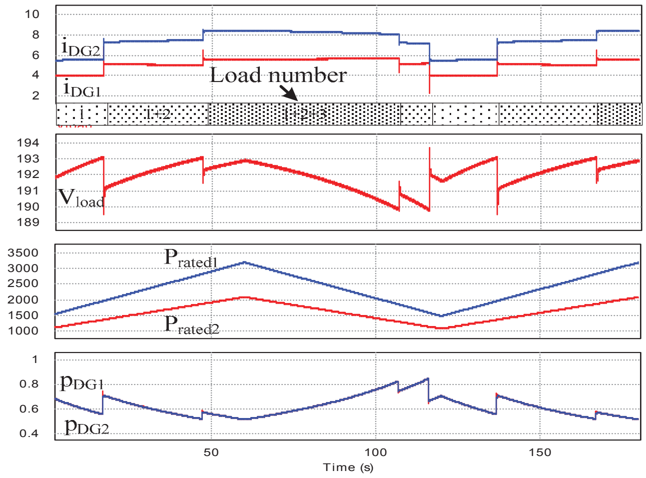

Fig. 12. Load shedding with proposed method.

control shown in the flowchart in Fig. 8. The power sharing of two DGs in the conventional method is not proportional to the DG capacity because of the high line impedance r'_{line2} . On the contrary, the proposed method shows remarkably that the power between DG1 and DG2 is shared proportionally to their capacity regardless of the loads variation. The simulation results with the proposed method are shown in Fig. 11 and Fig. 12.

V. Experimental Results

The parameters used in the experiment are the same as those in simulation in Table 1. Two DGs are controlled by two DSP TMS320F28335 microcontrollers. CAN interface is implemented with the built-in microcontroller CAN module. To emulate the delay time, low frequency with 100Hz (10ms) for sending and receiving data is considered. Each DG shares its power output information to calculate the average power per unit in (5).

To test the transient response of the proposed method, the load 1 is connected to the dc bus, and two DGs are connected with the rated power at 1.5kW individually. At the initial time, two DGs are controlled by the conventional droop control, and then, the proposed method is activated at 400ms. It can be seen that the transient time of the proposed method is 600ms. In addition, the shifted voltage for the droop control is 1V for DG2 (ΔV_{droop2}) and -0.7V for DG1 (ΔV_{droop1}) as shown in Fig. 13(a).

Fig. 13(b) shows the performance of the conventional method and the proposed method under a critical condition, where only load 1 is connected to the bus, and the rated power of DG1 and DG2 are 1.2kW and 1.8kW, respectively. In the conventional control method, due to the different equivalent line impedance, the DG1 operates under the overload condition, whereas DG2 supplies only 60% of its rated power. On the contrary, the proposed method shows an excellent performance regardless of the difference of the equivalent line impedance. Fig. 13(c) shows the load shedding for the conventional method, and Fig. 13(d) for the proposed method.

The experimental results coincide with those of simulation, and it is clear that the proposed control method can achieve an accurate proportional load power sharing together with the limited drop voltage of DG on dc bus within the given range.

VI. Conclusion

In this paper, an adaptive distributed power control method based on the equivalent line impedance is proposed to enhance the dc bus voltage regulation and to ensure the proportional load power sharing. In the proposed method, the droop coefficient is adaptively adjusted according to the rated power, and the equivalent line impedance variation is taken into account to regulate the DG's output power per unit. In order to realize the proposed control scheme, the low bandwidth communication based on a CAN interface available in the DSP controller is used to transmit data. Furthermore, the load shedding schedule is also considered to ensure the safe operation of the system.

The effectiveness of the proposed control method is verified by simulation and experiment with 2.8kW prototype. Based on the simulated and experimental results, we can say that the proposed method ensures the proportional load power sharing regardless of the load variation.

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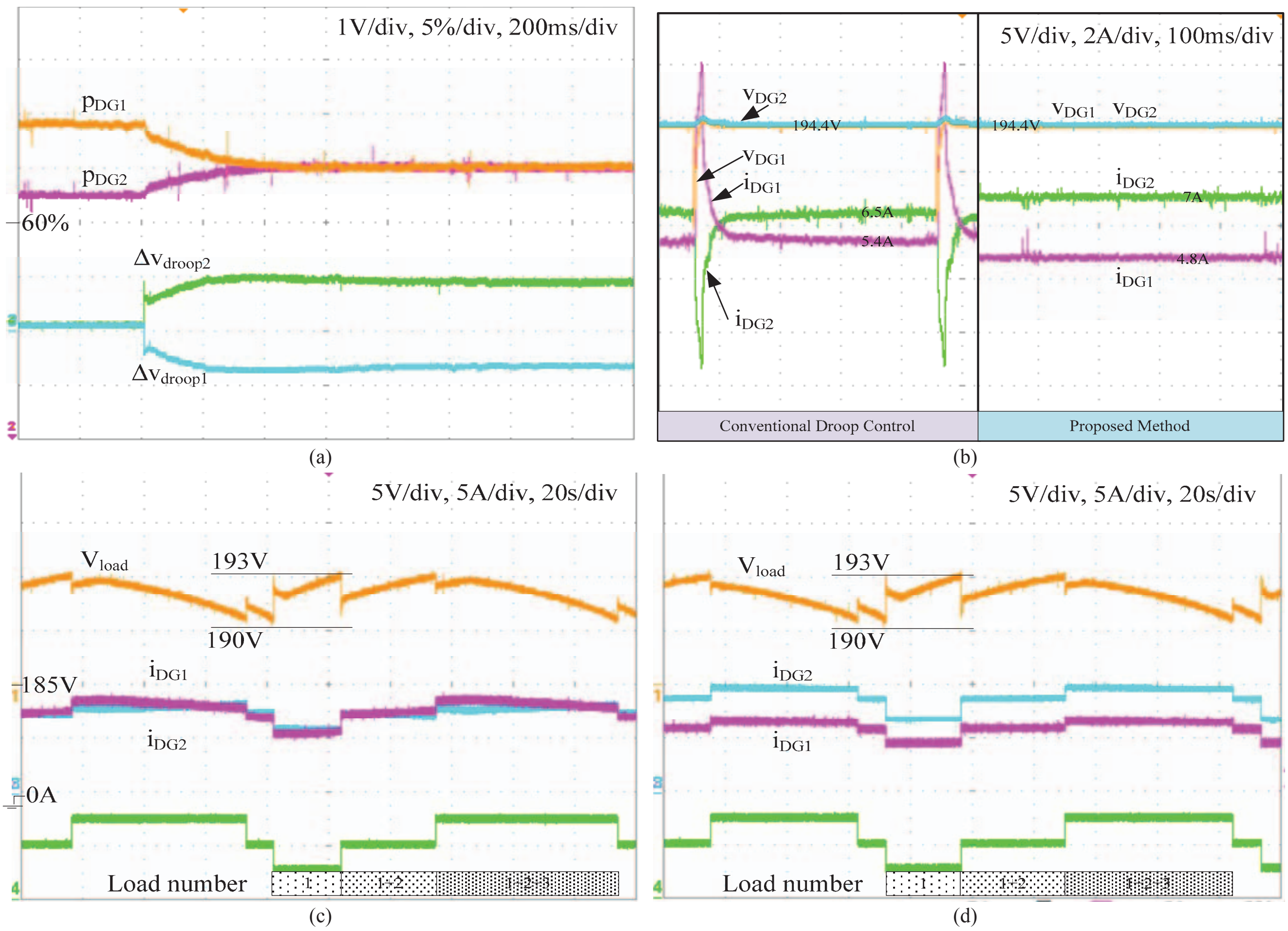

Fig. 13. Experimental results (a) Transient of proposed method (b) performance of conventional and proposed method (c) load shedding with conventional droop control (d) load shedding with proposed method.

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