Control of Power Leveling Unit with Super Capacitor using Bidirectional Buck/boost DC/DC Converter

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Abstract —**As a distributed generation system increases, a stable power supply becomes difficult. Thus control of power leveling (PL) unit is required to maintain the balance of power flow for irregular power generation. The unit is required to respond to change of voltage and bidirectional power flow. So the bidirectional buck/boost DC/DC converter is applied for the control of PL unit in this research.**

The PL unit with Super Capacitor (SC) is able to absorb change of power, and it is examined whether the stable power supply is possible. The output current of PL unit is controlled so as to keep power balance and DC bus voltage. The effectiveness of the proposed control is proved in simulation.

Keywords-component; Bidirectional buck/boost DC/DC converter, power leveling, super capacitor, smart grid system

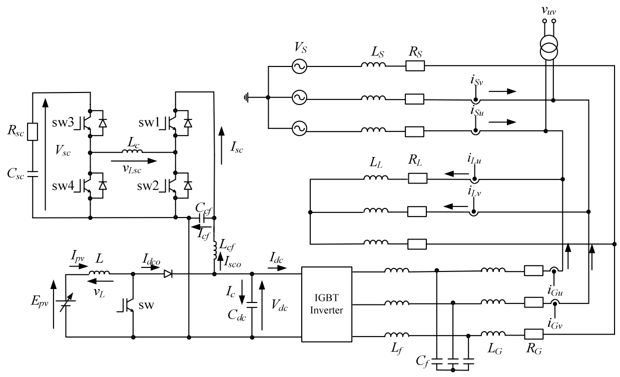


Fig.1 Circuit structure.

I. INTRODUCTION

In recent years, as exhaustion of fossil fuel, global warming are focused, renewable energy sources such as photo voltaic (PV) and wind force keep attention. New power supply systems, such as a smart grid using renewable power as distributed generation system are spreading. However, since the output of renewable power sources have fluctuation, stable power can not be supplied to the AC system. For this reason, problems of reverse power flow and voltage optimization occur. Therefore, power change is absorbed and the system to equalize is needed [1]-[3].

A super capacitor (SC) has advantages of no pollution and no environmental effects, and SC is low inner resistance, large capacity, and long life compared with the secondary battery. In this research, the control system of PL unit using the bidirectional buck/boost DC/DC converter[2] connected to SC is proposed. The bidirectional buck/boost DC/DC converter can work four-quadrant operation, which is positive and negative voltages and currents. Therefore, the current is able to flow for charge to SC and discharge from SC. Even if SC is maintaining the high voltage or the voltage became extremely small, it is possible for the PL unit to work. Inverter of the AC system can control the active power and reactive power independently using the d-q transform based on the phase of the AC grid voltage phase. Power supply to the load is properly adjusted by the inverter. Effective of the proposed system is verified by simulation.

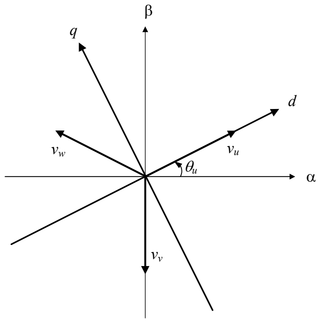


Fig.2 Definition of dq axis.

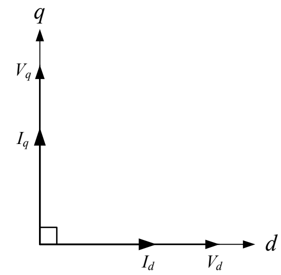


Fig.3 Vector diagram of dq axis.

II. CIRCUIT STRUCTURE AND A CONTROL METHOD

A. Circuit analysis and a control method on AC bus

Fig.1 shows a circuit structure of distributed generation system in this research. The d-q component is defined in Fig.2 and calculated by the d-q transformation in (1).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\theta_u & \sin(\theta_u - \frac{2}{3}\pi) & \sin(\theta_u + \frac{2}{3}\pi) \\ \cos\theta_u & \cos(\theta_u - \frac{2}{3}\pi) & \cos(\theta_u + \frac{2}{3}\pi) \end{bmatrix} \begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} \quad (1)$$

Then, three phase voltages are defined in (2)-(4).

$$v_u = \sqrt{\frac{2}{3}} V \sin\theta_u \tag{2}$$

$$v_v = \sqrt{\frac{2}{3}} V \sin(\theta_u - \frac{2}{3}\pi) \tag{3}$$

$$v_w = \sqrt{\frac{2}{3}} V \sin(\theta_u + \frac{2}{3}\pi) \tag{4}$$

(2)-(4) assigned to (1), the following equations are obtained.

$$V_d = V \tag{5}$$

$$V_q = 0 \tag{6}$$

From the relation of the vector in Fig.3, the power is calculated.

$$\begin{aligned} \overline{V}I &= \left(V_d - jV_q\right)\left(I_d + jI_q\right) \\ &= V_d I_d + V_q I_q + j\left(V_d I_q - V_q I_d\right) \end{aligned} \tag{7}$$

The active power P and reactive power Q are provided as follows.

$$P = V_d I_d + V_q I_q \tag{8}$$

$$Q = V_d I_q - V_q I_d \tag{9}$$

(5), and (6) assign to (8), and (9), the following equations are obtained.

$$P = VI_d \tag{10}$$

$$Q = VI_q \tag{11}$$

If V is constant, the active power P is determined by the active current I_d and the reactive power Q is determined by the reactive current I_q. In other words, in order to control the active power and reactive power independently, the active current I_d and reactive current I_q should be controlled respectively.

Fig.4 shows a block diagram of the inverter control and Fig.5 shows a block diagram of PL unit control. The control is performed combining two controls, which are the active and reactive power control for AC side by the inverter, and input and output power control by the PL unit. The rate of the output power supplying to the load in AC side can be controlled by the inverter. In Fig.1, the inverter operates as a grid connected inverter installed between AC bus and DC bus. LC filters are connected to the output terminal of the PL system and the inverter in order to suppress the switching ripple. The boost chopper is connected to the PV cell for regulation of PV power. The inverter control is performed by block diagram in Fig.4.

The d-q component converting from the output voltage and currents of the distributed generation system determine the active component and reactive component. Using them, power flow can be controlled by PI control. The control law becomes (12) and (13). Then V_{d0} and V_{q0} are reference voltage calculated from line-to-line voltage on AC bus.

$$V_d^* = V_{d0} + K_{pd}\left(I_{Gd}^* - I_{Gd}\right) + K_{id}\int_0^t \left(I_{Gd}^* - I_{Gd}\right)dt \tag{12}$$

$$V_q^* = V_{q0} + K_{pq}\left(I_{Gq}^* - I_{Gq}\right) + K_{iq}\int_0^t \left(I_{Gq}^* - I_{Gq}\right)dt \tag{13}$$

And the references of v_u^*, v_v^* and v_w^* are calculated by 2-phase

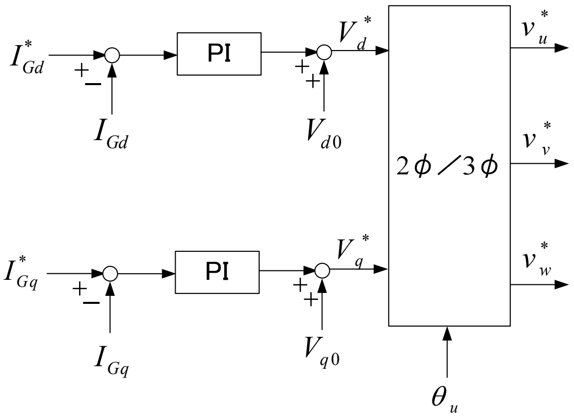


Fig.4 Block diagram of inverter control.

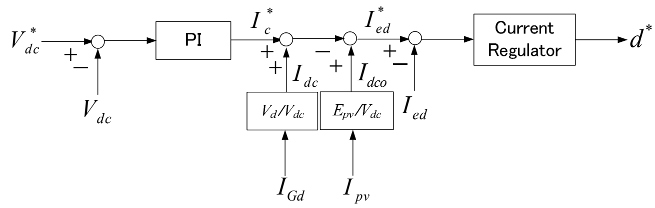


Fig.5 Block diagram of power leveling unit control.

to 3-phase transformation from the references V_d^* and V_q^*.The inverter is controlled by PWM with the reference values.

B. Operation of bidirectional buck/boost DC/DC converter

PL system connected with SC via the bidirectional buck/boost DC/DC converter interconnects to the DC system. PL unit has a role of adjustment of supply and demand of power as shown in Fig.6. If the power of PV system is larger than the power to send to AC bus, current of PL unit flows to charge. If the power of PV system is smaller, current of PL unit flows to discharge. The bidirectional buck/boost DC/DC converter operates as a four-quadrant chopper of voltage and current. Therefore the current is able to flow negative to charge to SC or positive to discharge from SC. Even if SC is maintaining the high voltage or the voltage became extremely small, the PL unit is able to work.

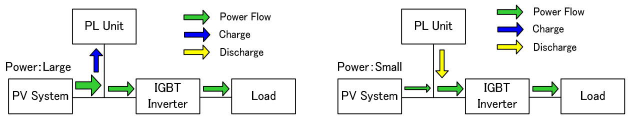
When the converter operates as buck chopper, the current path is illustrated in Fig.7. Then ON signal is always input to sw3 and OFF signal is always input to sw4. And PWM control is performed on sw1 and sw2.

$$V_{Lsc} = V_{dc} - V_{SC} \quad \text{(sw1: ON)} \tag{14}$$

$$V_{Lsc} = -V_{SC} \quad \text{(sw2: ON)} \tag{15}$$

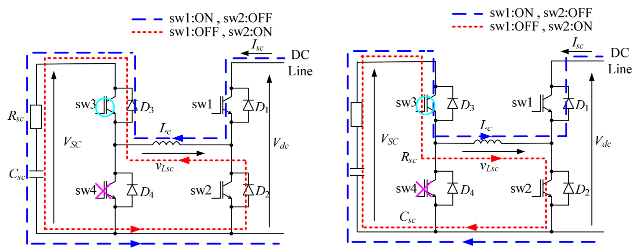
From above, PWM duty ratio d of the converter as buck chopper ($V_{sc} < V_{dc}$) is derived as (16).

$$d = \frac{V_{SC} + V_{Lsc}}{V_{dc}} \tag{16}$$



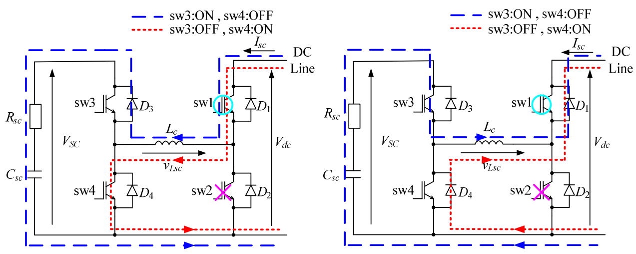
(a) Charge current. (b) Discharge current.

Fig.6 The role of PL unit.



(a) Charge current. (b) Discharge current.

Fig.7 Buck chopper operation.



(a) Charge current. (b) Discharge current.

Fig.8 Boost chopper operation.

When the converter operates as boost chopper, the current path is illustrated in Fig.8. Then ON signal is always input to sw1 and OFF signal is always input to sw2. And PWM control is performed on sw3 and sw4.

$$V_{Lsc} = V_{dc} - V_{SC} \qquad \text{(sw3: ON)} \tag{17}$$

$$V_{Lsc} = V_{dc} \qquad \text{(sw4: ON)} \tag{18}$$

From above, PWM duty ratio d of the converter as boost chopper ($V_{sc} > V_{dc}$) is derived as (19).

$$d = \frac{V_{dc} - V_{Lsc}}{V_{sc}} \tag{19}$$

C. *Control method of PL unit*

A reference I_{sc}^* of the PL unit is calculated from the active component current I_{Gd} and the output current I_{pv} of a PV cell. Further, in order to keep the DC bus voltage constant, feedback control of the V_{dc} is carried out. Output current is controlled by a current regulator based on discrete time system. Fig.5 is a block diagram when the bidirectional buck/boost DC/DC converter performs a boost operation as seen from DC bus. I_{sc}^* is calculated from the duty ratio of switching and the current of L_c when the bidirectional buck/boost DC/DC converter performed a buck operation as seen from DC bus. I_{sco} is obtained through LPF of I_{sc}. Here I_{sco} is approximated to I_{sc}. The following equations are derived from Fig.5.

$$I_{dc} = \frac{V_d I_{Gd}}{V_{dc}} \tag{20}$$

$$I_{dco} = \frac{E_{pv} I_{pv}}{V_{dc}} \tag{21}$$

$$I_{sc} = I_{dco} - I_c - I_{dc} \tag{22}$$

$$I_c^* = K_{pc}\left(V_{dc}^* - V_{dc}\right) + K_{ic}\int_0^t \left(V_{dc}^* - V_{dc}\right)dt \tag{23}$$

(20) and (21) are obtained from the law of conservation of power. (22) is obtained from the Kirchhoff's current law. In (23), DC bus voltage V_{dc} can be regulated by the PI control. In addition, a digital control in sampling period T_S is introduced for a current regulator of the PL unit.

$$L\frac{i(k+1) - i(k)}{T_S} = V_{in}(k) - V_{out}(k) \tag{24}$$

When the converter operates as buck chopper, replacing $i(k+1) = i^*$, a optimal duty ratio can be obtained by (16) and (24) .

$$d^* = \frac{V_{in}^*}{V_{dc}} = L\frac{I_{sc}^* - i_{sc}}{T_S V_{dc}} + \frac{V_{sc}}{V_{dc}} \tag{25}$$

When the converter operates as boost chopper, a optimal duty ratio can be obtained by (19) and (24).

$$d^* = \frac{V_{in}^*}{V_{sc}} = L\frac{I_{sc}^* - i_{sc}}{T_S V_{sc}} + \frac{V_{dc}}{V_{sc}} \tag{26}$$

The converter is controlled with the duty ratios. The real value can follow the reference value for every cycle T by this control.

D. *Power control based on the main AC bus*

A current reference I_{Gd}^* of inverter output to AC bus shown in Fig.4 can be given arbitrary value directly. Then excessive reverse power flow may give a negative influence to the power quality. In addition, when the reference value is less than power of the load, main power line will supply the power to the load. Therefore if power of distributed generation system is supplied as much as possible, the cost is low. The load current can be represented by the following equation.

$$I_{Ld} = I_{Sd} + I_{Gd} \tag{27}$$

To feedback the main circuit current flowing into the load, the reference current of the inverter output is calculated by the following equation.

$$I_{Gd}^* = I_{Sd} + I_{Gd} \tag{28}$$

In this control method, if the power is provided from only distributed generation system, the main power line does not send out the power. Therefore the power of distributed generation system is able to take full advantage.

III. SIMULATION

Simulation is performed to verify the proposed control method by using the circuit in Fig.1. The choppers and IGBT inverter are controlled on the discrete time system. Carrier frequency of the choppers and IGBT inverter is 10kHz and sampling time of the digital control is 100µs. Table I shows the parameters of the circuit. Simulation is achieved on five following conditions.

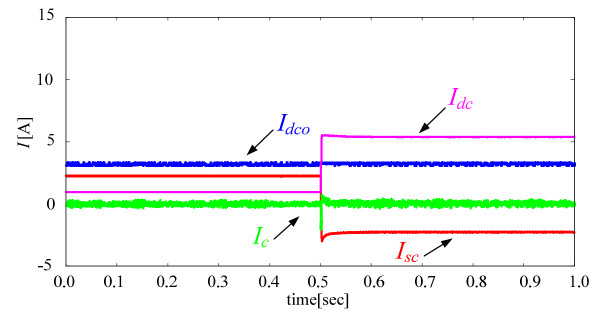
1. Power fluctuation
- At a certain time, the power of PV system or the inverter output are changed by step.
2. Load change
- At a certain time, the load changes to double by step.
3. Continuous fluctuation of solar cells
- The amount of power generation of PV system is always varied in short time simulating a variety of condition change.
4. Switch buck-boost operation
- In the PL unit, the buck-boost operation of bidirectional buck/boost DC/DC converter switches between charge and discharge.
5. Power control based on the main AC bus
- The control method introduced in II-D is applied.

Fig.9 shows results in case that the bidirectional chopper works as a boost chopper seen from the DC bus ($V_{sc} > V_{dc}$). It is controlled so as to keep balance of the charge and discharge of SC against the change of PV output in Fig.9(a), (b). In Fig.9 (b), the positive current means charge to SC and the negative one means discharge to the DC bus. The power supplied to AC side keeps constant in Fig.9(c). The inverter can supply the output power constantly in Fig.9(c). In Fig.9(d), DC bus voltage keeps constant, and the bidirectional buck/boost DC/DC converter is operating properly as a boost chopper.

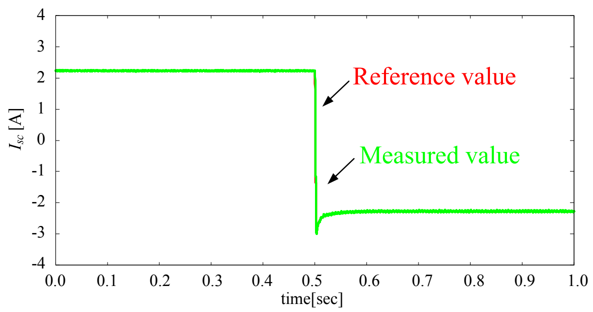
Fig.10 shows results in case that the buck/boost chopper works as a buck chopper seen from the DC bus ($V_{sc} < V_{dc}$). Slightly change has occurred in the DC side when the load changes from 50% to 100%. Although, when the load changes, the PL unit is able to work to absorb the fluctuation without problem. The power supplied to AC side keeps constant in Fig.10(c). In Fig.10(d), the DC bus voltage is kept constant, and the bidirectional buck/boost DC/DC converter is operating properly as a buck chopper.

TABLE I. Parameters of the circuit

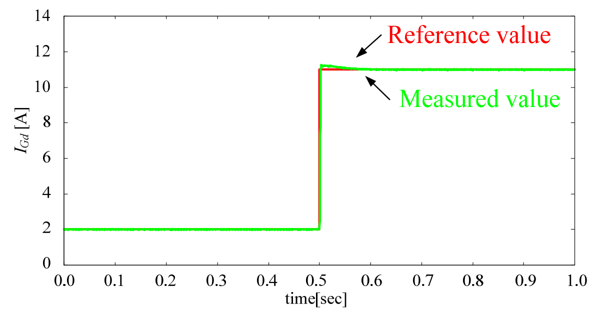
Source voltage	100 V	Frequency	60 Hz
R_S	0.25 Ω	L_S	218 µH
R_G	0.15 Ω	L_G	131 µH
R_L	15.0 Ω	L_L	13.0 mH
L_f	0.01 H	C_f	5.00 µF
V_{dc}	200 V	C_{dc}	5000 µF
L_c	10.0 mH	R_{sc}	0.20 Ω
C_{sc}	10.0 F	L	10.0 mH
E_{pv}	80.0 V	L_{cf}	0.20 mH
C_{cf}	60.0 µF		



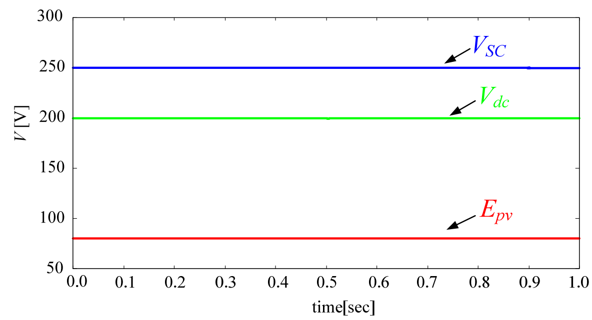
(a) Currents on DC bus.



(b) Output current of the PL unit.



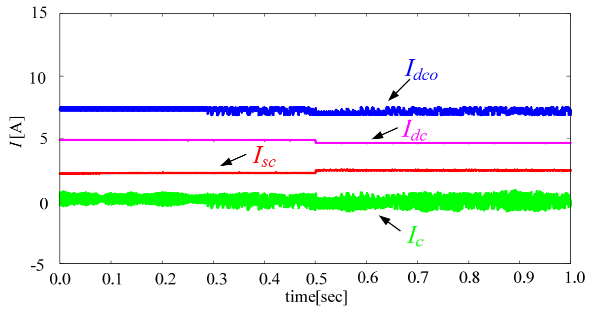
(c) Active current of inverter on AC bus.



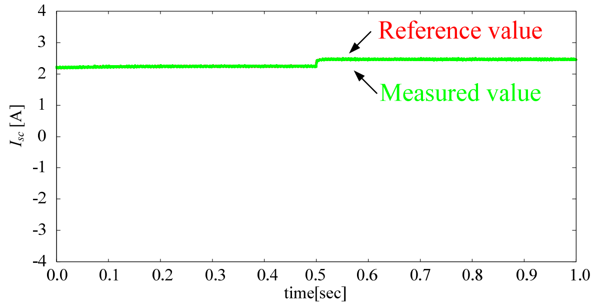
(d) Voltages in DC bus.

Fig.9 Results in case of boost chopper operation.

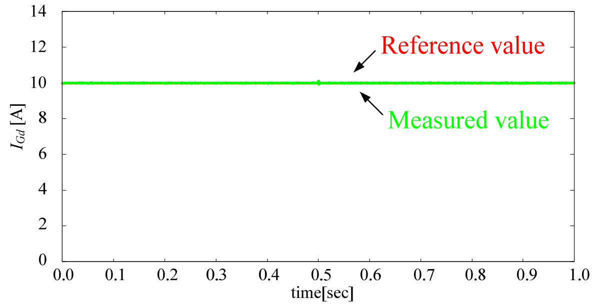
Fig.11 shows the results in case with fluctuation of PV power at the condition $V_{sc} < V_{dc}$. This power fluctuation is considered imitating change of PV condition. The fluctuation of PV current I_{dco} is shown in Fig.11(a). Then PL unit is fast enough to absorb minor fluctuations of the PV in Fig.11(a) and(b). Therefore I_{dc} is constant in spite of the fluctuation of PV power. Fig.11(d) shows voltages on the DC bus. Output voltage E_{pv} of the PV system is constant at 80V and DC bus voltage V_{dc} can be controlled to keep constant at 200V by the DC bus voltage control. As a result, the inverter output current



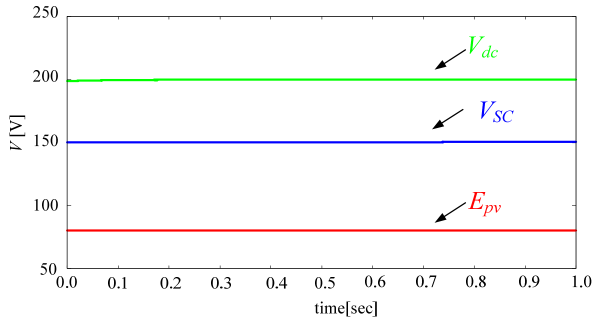
(a) Currents on DC bus.



(b) Output current of the PL unit.

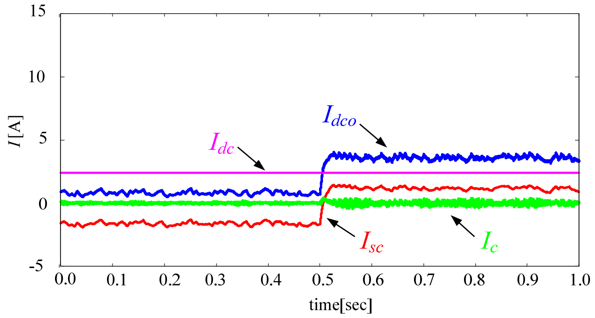


(c) Active current of inverter on AC bus.

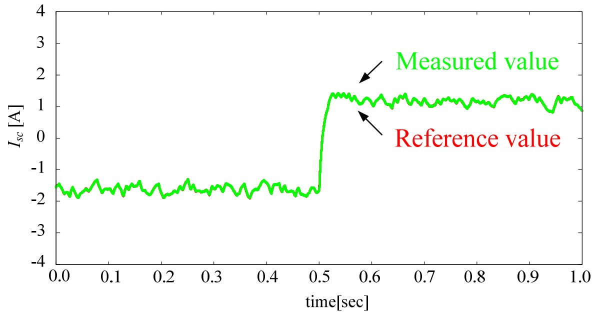


(d) Voltages in DC bus.

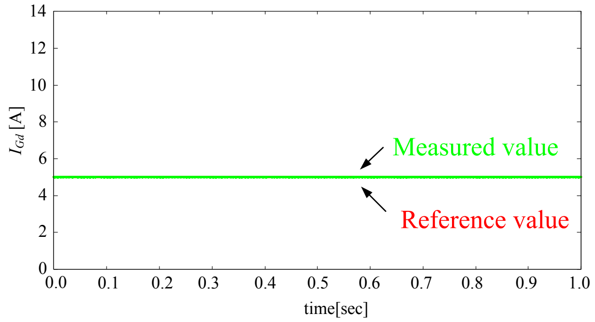
Fig.10 Results in case of buck chopper operation.



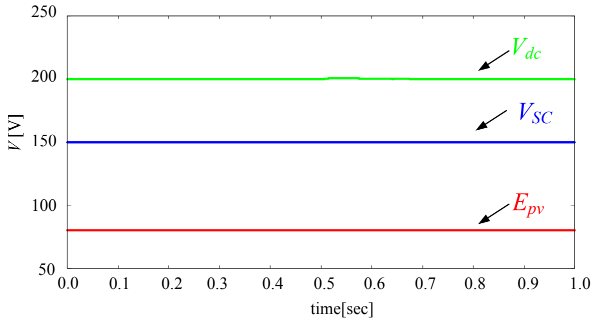
(a) Currents on DC bus.



(b) Output current of the PL unit.



(c) Active current of inverter on AC bus.



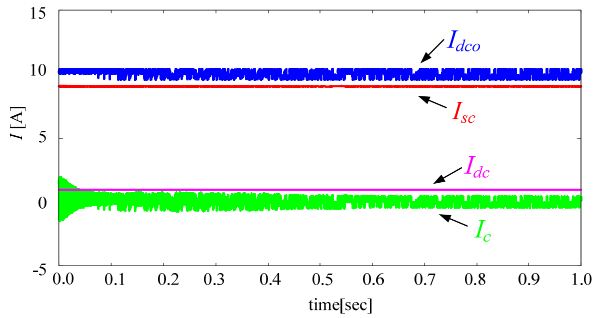
(d) Voltages in DC bus.

Fig.11 Results with PV fluctuation.

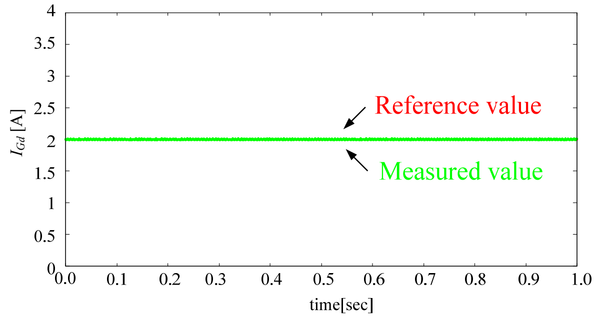
and the DC bus voltage is kept constant in Fig.11(c) and (d). Response of the output current of the PL unit is fast and accurate.

Fig.12 shows results with a switch of buck-boost operation. In this simulation, charge current I_{sc} flows. Therefore Voltage of SC V_{sc} gradually increases for the power charge to the capacitor. In Fig.12(c), the bidirectional buck/boost DC/DC converter is switched from buck operation to boost operation between 0.5s-0.6s. When the operation changed, small fluctuation of voltage occurs. However the currents of the AC bus and the DC bus are not affected in that period.

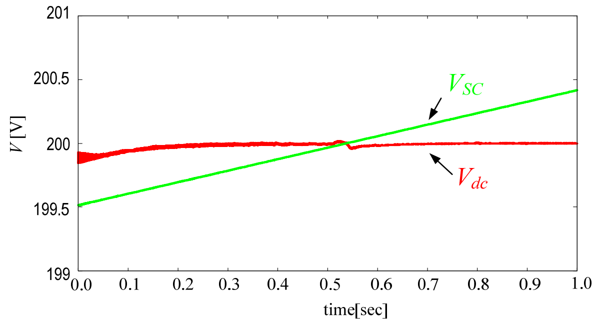
Fig.13 shows results with the power control based on the main AC bus. In Fig.13(c), I_{Sd} almost becomes zero. I_{Gd} and I_{Ld} are the same value. This means that all the power is supplied from only distributed generation system and the main system does not send out the power. Therefore PV power is



(a) Currents on DC bus.



(b) Active current of inverter on AC bus.



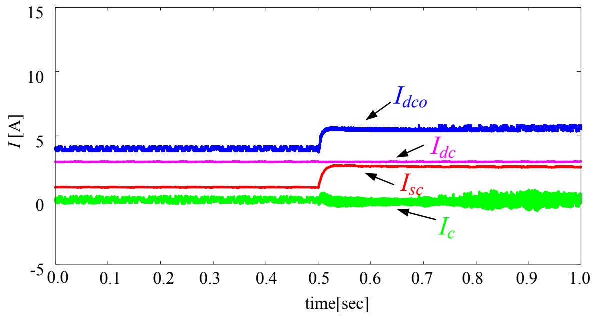
(c) Voltages in DC bus.

Fig.12 Results with switch buck-boost operation.

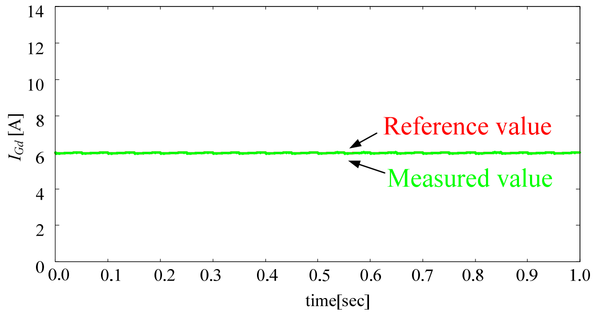
used effectively. In Fig.13(d), the voltage on DC bus V_{dc} is kept constant. Therefore I_c becomes 0 in Fig.13 (a). In DC bus, all the currents and voltages are able to be controlled stably.

IV. Conclusion

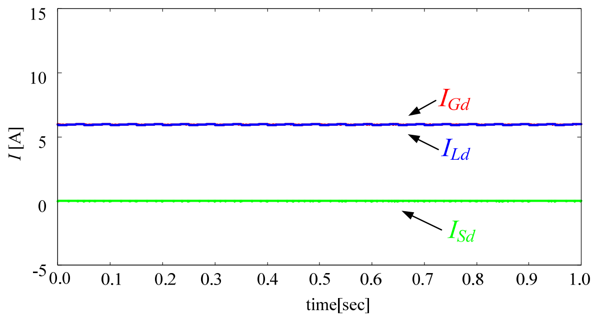
In this study, control of PL unit with SC using the bidirectional buck/boost DC/DC converter and the grid connected inverter was proposed. It is confirmed that the integrity is maintained both the power of PV and the inverter output power by PL unit. The effectiveness was confirmed by the simulation in various conditions such as charge or discharge to the SC, PV power fluctuation and so on.



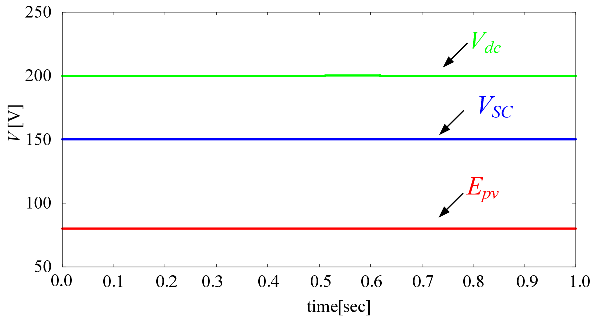
(a) Currents on DC bus.



(b) Active current of inverter on AC bus.



(c) Currents on AC bus.



(d) Voltages in DC bus.

Fig.13 Results with power control based on the AC bus.

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