Experimental Verification of DC to Single-phase AC Converter with Power Decoupling Capability using 1.2 kV SiC-MOSFET Module

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Abstract— **This paper presents a DC to Single-phase AC converter with 1.2 kV SiC-MOSFET power module for PV power conditioning systems (PCSs). The authors are aiming to develop a SiC-MOSFET power module with low on-resister in order to improve the conversion efficiency. In addition, the active power decoupling topology with small buffer capacitor has been considered in order to improve the system reliability. the active power decoupling circuit compensates the double-line frequency power ripple by the small firm or ceramic capacitor. However, the high voltage rating devices is required due to the voltage ripple of the buffer capacitor. In this paper, a first proto type SiC-MOSFET power module is tested by the experiment. This module has the high voltage rating as 1.2 kV in order to reduce the buffer capacitor. As the experimental result, it was confirmed that the fundamental operation. In addition, the maximum efficiency of 95.0 % was obtained at the rated output power.**

Keywords—Photovoltaic, Power decoupling, AC module, SiC-MOSFET

I. INTRODUCTION

Recently, photovoltaic (PV) systems have been actively researched as a sustainable power solution [1]-[3]. In the PV systems, power conditioning systems (PCSs) are necessary for utilization of the PV generated power. Typically, the PCSs are consisted of a DC/DC converter and a voltage source inverter (VSI) in order to connect the PV panels to the single-phase AC grid. These PCSs require the following capabilities: (1) high efficiency power conversion, (2) high reliability, and (3) small packaging design.

The switching devices based on a wide band-gap devices such as silicon carbide (SiC) or gallium nitride (GaN) may become a trend instead of IGBT and silicon MOSFET (Si-MOSFET) because these devices have a good performance which include fast switching and features low on-voltage drop compared with the silicon devices [4]. Therefore, it have been reported that the improvement of the power conversion efficiency by using SiC or GaN devices.

On the other hand, double-line-frequency power ripple occurs in the DC side due to the single-phase AC grid. This power ripple leads to a decrease in a performance of the maximum power point tracking (MPPT). Therefore, a bulky electrolytic capacitor is usually installed on the DC link in order to absorb the power ripple: i.e., a passive power decoupling method is used. However, passive power decoupling method limits the life time of the power converter due to the Arrhenius law.

Active power decoupling topologies have been researched actively in order to enhance the system reliability of the single-phase systems [5]-[10]. In this method, the double-line frequency power ripple is compensated by the small capacitor. Therefore, it is possible to remove the electrolytic capacitor from the PCSs, and a small capacitor such as a firm or ceramic capacitor is utilized for compensation of the power ripple. However, the some components require a high voltage rating when the small capacitor is applied by the active power decoupling method because the voltage ripple with low frequency component becomes increase. In this case, it is difficult to apply the Si-MOSFET with 500 or 600 V voltage rating because the diode recovery characteristics does not good. On the other hand, switching speed of IGBT does not faster than the Si-MOSFET. Therefore, the volume of the passive components such as the inductor increases.

According to this problem, SiC-MOSFET is the key component because it has the high speed switching speed characteristics and high voltage rating more than 650 V. The authors have been develop the SiC-MOSFET modules for this topology.

In this paper, a first proto type SiC-MOSFET power module is tested by the experiment. The test circuit consists of the active power decoupling circuit, and a current source inverter (CSI). The active power decoupling circuit compensates the double-line -frequency power ripple by the small capacitor.

The remainder of the paper is organized as follows. In section II, the circuit topology of the DC to single-phase AC is explained. In addition, the developing SiC-MOSFET power module is demonstrated. In section III, the compensation principle of the double-line frequency of the power ripple is explained. Finally, in section IV, the simulation and the experimental result are demonstrated.

II. CIRCUIT TOPOLOGY

Fig.1 shows the DC to single-phase AC grid-connected converter with a typical DC/DC converter. The DC/DC converter boosts the PV input voltage above the peak value of the grid voltage, and the generated power is supplied to the single-phase grid by the VSI. In this case, a bulky electrolytic capacitor C_{dc} is required in the DC link due to the double-line-frequency power ripple of the single-phase grid.

Fig. 2 shows the active power decoupling circuit [11]. The active power decoupling circuit consists of the typical DC/DC converter and additional switching device S_{bt}. The active power decoupling circuit regulates the buffer capacitor voltage V_{cbuf} in order to compensate the double-line frequency power ripple. In addition, the reverse-blocking diode does not necessary on CSI because the free-wheeling mode is achieved on the active power decoupling circuit. In this paper, the SiC-MOSFET power module is used for CSI and the part of active power decoupling circuit.

Fig. 3 shows the 1.2 kV SiC-MOSFET power module which consists of 3 phase configuration. In this module, a SiC-schottoky barrier diode is connected in parallel to each SiC-MOSFET in order to reduce the recovery loss. In addition, an aluminum nitride ceramic circuit board is applied to reduce the ground capacity. Furthermore, the rise of junction temperature is suppressed because it has high thermal conductively such as 67 W/mK.

III. COMPENSATION PRINCIPLE OF POWER RIPPLE

Fig. 4 shows the principle of the power decoupling between the DC and single-phase AC sides. When both the output voltage and current waveforms are sinusoidal, the instantaneous output power pout is expressed as

$$p_{out} = \frac{V_{acp} I_{acp}}{2}(1 - \cos 2\omega t) \tag{1}$$

where V_{acp} is the peak voltage, I_{acp} is the peak current, and ω is the angular frequency of the output voltage [12]. As shown in (1), the power ripple at twice the frequency of the single-phase power grid appears at the DC link.

In order to absorb this power fluctuation, the instantaneous buffer power p_{buf} should be controlled by

$$p_{buf} = \frac{1}{2} V_{acp} I_{acp} \cos 2\omega t \tag{2}$$

where the polarity of p_{buf} is defined as positive when the flying capacitor C_{buf} discharges. Note that the active power of C_{buf} is zero. As a result of the power decoupling, the input power is matched to the output power. Thus, the relationship between the input and output power is expressed as follows:

$$p_{in} = \frac{1}{2} V_{acp} I_{acp} = V_{IN} I_{IN} \tag{3}$$

where V_{in} is the DC input voltage, I_{in} is the DC input current.

In the active power decoupling circuit, the buffer capacitor C_{buf} becomes small when the fluctuation voltage increase as shown in Fig.3. The buffer capacitance is expressed as

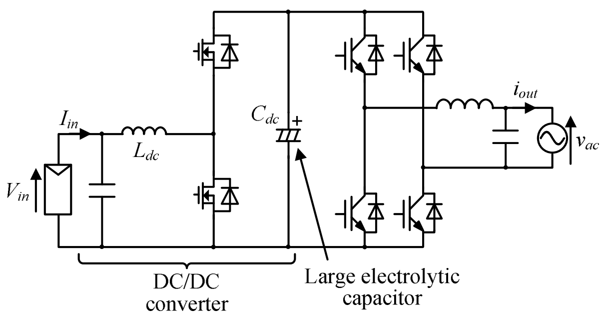


Fig. 1 DC to single-phase AC grid connected converter with typical boost converter.

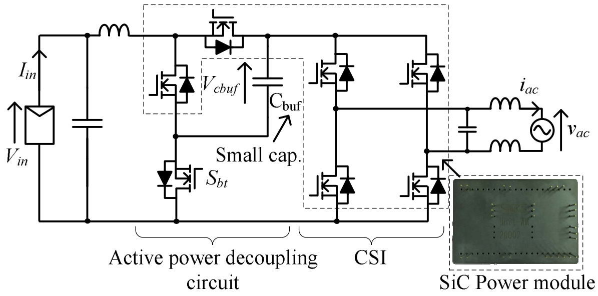
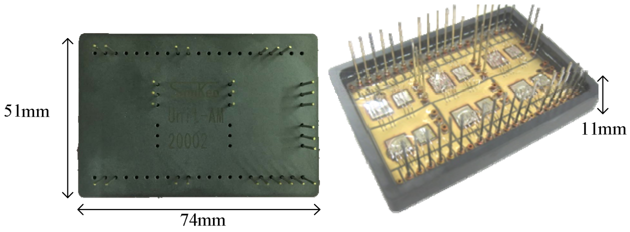
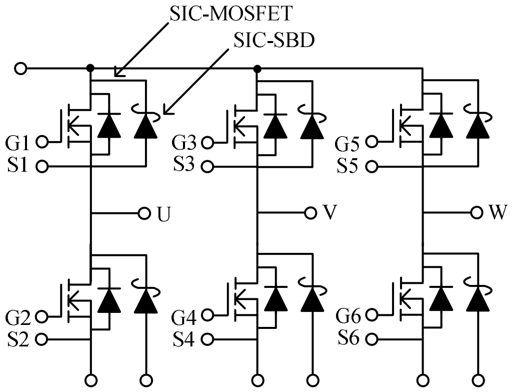


Fig. 2 Test circuit configuration. The active power decoupling circuit compensates the double-line frequency power ripple by small capacitor C_{buf}. The SiC power module is applied to CSI and active power decoupling circuit.



(a) Top view



(b) Power module configuration.

Fig. 3 1.2 kV SiC-MOSFET power module. The SiC-Shotokey barrier diode is connected in parallel to SiC-MOSFET.

$$C_{buf} = \frac{2P_{out}}{\omega\left(V_{cbuf\_peak}{}^{2} - V_{cbuf\_\min}{}^{2}\right)} \tag{4}$$

where $V_{\mathrm{cbuf\_peak}}$ is the peak voltage of the buffer capacitor, $V_{\mathrm{cbuf\_min}}$ is the minimum voltage of the buffer capacitor.

Fig. 5 shows the relationship between the fluctuation voltage ΔV_{cbuf} and the buffer capacitor C_{buf}. Note that, C_{buf} is calculated from (4). In addition, the minimum voltage of the buffer capacitor should set more than the peak grid voltage V_{acp} in order to avoid the short circuit current [13]. Finally, this application supposes the PV micro-inverter [14]. Therefore, the output power is set around several handled watt. According to Fig.4, the buffer capacitor decreases when ΔV_{cbuf} becomes large. Therefore, the voltage rating condition is the one factor to decide the minimum capacitance of C_{buf}. In this paper, the SiC-MOSFET power module which has high voltage rating is applied in order to avoid this problem.

IV. SIMULATION AND EXPERIMENTAL RESULT

Table 1 shows the simulation parameter, Fig.6 shows the simulation result of the active power decoupling circuit with small buffer capacitor. In this simulation, the buffer capacitor C_{buf} is set to 2.5μF.

According to Fig. 6, the constant input voltage is obtained by the active power decoupling circuit. In addition, the sinusoidal inverter output current is obtained. Finally, the buffer capacitor maximum voltage is match to Fig.5. According to these result, the buffer capacitance becomes small when the fluctuation voltage of V_{cbuf} is set to large. Especially, a firm capacitor has the small energy density in comparison with the electrolytic or ceramic capacitor. Therefore, it is important to improve the power density of the active power decoupling circuit when the firm capacitor is used for the decoupling capacitor.

Fig.7 shows the experimental result. Note that, the output power is 300 W, switching frequency is 20 kHz, buffer capacitor is 44μF, and the grid voltage is 200 V_{rms}. In this experiment, the buffer capacitor is set to large in comparison with the simulation result in order to confirm the fundamental operation of the SiC-MOSFET power module.

According to Fig.7, the constant DC voltage and the sinusoidal inverter output current are obtained. In addition, it is confirmed that the buffer capacitor voltage is fluctuated by the double-line frequency by the power decoupling control.

Fig.8 shows the efficiency characteristics of the experimental circuit. According to Fig.8, the maximum efficiency is 95.0% at the rated power of 300 W. Note that, the efficiency curve still increases because the power module has a large capacity such as 1200 V/ 40 A although the rated power of the experimental circuit is 300 W.

V. CONCLUSION

In this paper, DC to single-phase AC converter with power decoupling capability using 1.2 kV SiC-MOSFET is demonstrated. The active power decoupling circuit requires the high voltage rating devices in order to reduce the buffer capacitance. From the simulation result, the constant input voltage is obtained by the 2.5μF of the buffer capacitor. From the experimental result, the constant DC voltage and the sinusoidal inverter output current are obtained. Finally, it was confirmed that the maximum efficiency is 95.0%.

In the future work, the switching characteristics of the SiC-MOSFET module will be considered.

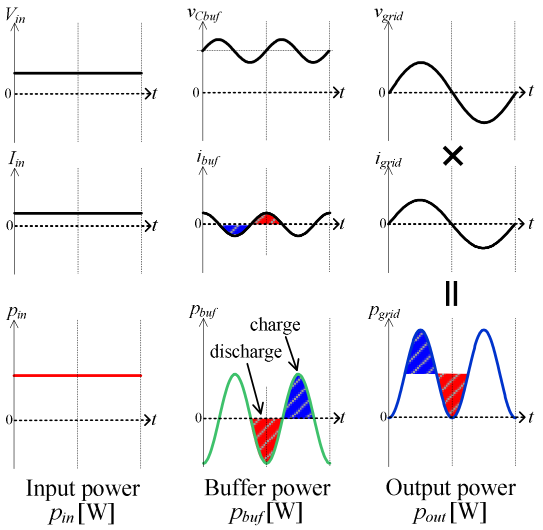


Fig. 4 Principle of power decoupling between DC and single-phase AC.

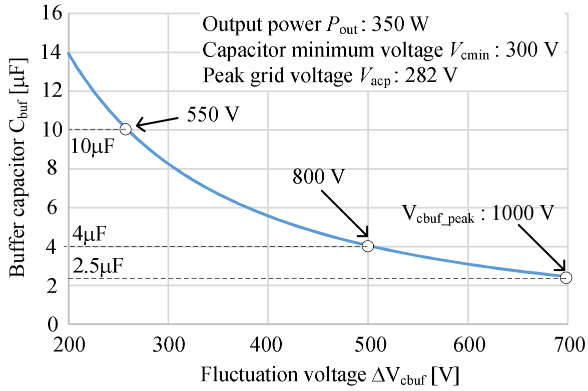


Fig. 5 Relationship between fluctuation voltage and buffer capacitance.

Table1 Simulation parameter

Symbol	Quantity	value
V_{in}	Input voltage	50 V
P_{in}	Input power	350 W
C_{buf}	Buffer capacitor	2.5 μF
V_{ac}	Grid voltage	200 V_{rms}
V_{cbuf_min}	Buffer capacitor minimum voltage	300 V
f_{ac}	Grid frequency	50 Hz

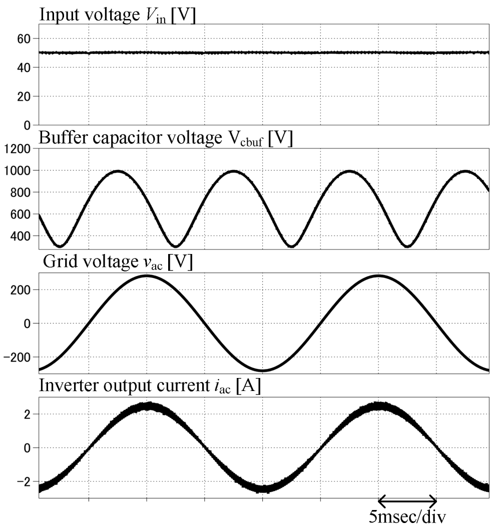


Fig. 6 Simulation result.

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Table 2 Experimental parameter

Symbol	Quantity	value
V_{in}	Input voltage	90 V
P_{in}	Input power	300 W
C_{buf}	Buffer capacitor	44 μF
V_{ac}	Grid voltage	200 V_{rms}
f_{ac}	Grid frequency	50 Hz
f_{sw}	Switching frequency	20 kHz

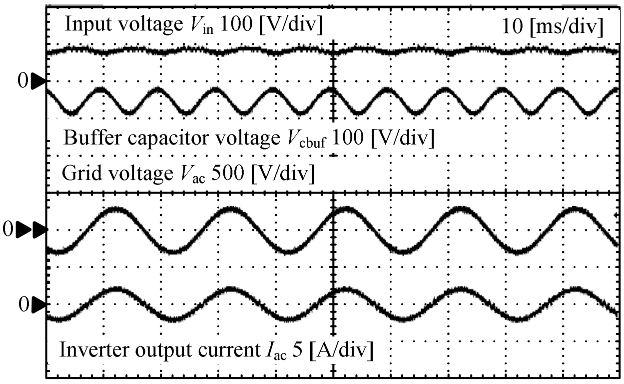

Fig.7 Experimental result. Sinusoidal output current waveform and constant DC input voltage are obtained. Note that, buffer capacitor voltage is fluctuated by the power decoupling control.

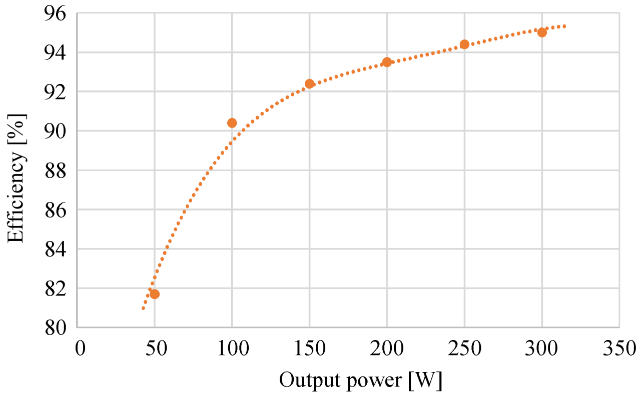

Fig.8 Efficiency characteristics. Conversion efficiency reached to 95.0% when output power is 300W.