Solar Energy 141 (2017) 228–235

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A compact SiC photovoltaic inverter with maximum power point tracking function

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ARTICLE INFO

Article history:
Received 21 September 2016
Received in revised form 18 November 2016
Accepted 23 November 2016

Keywords:
Silicon carbide
Solar cell
Inverter
Photovoltaic device
Maximum power point tracking
Lithium-ion battery

ABSTRACT

A compact 150 W photovoltaic inverter was developed using SiC devices, which integrated a maximum power point tracking charge controller and a direct current (DC) - alternating current (AC) converter into a single module. The DC-AC converter circuit was built with four SiC metal-oxidesemiconductor field-effect transistors, while the DC-DC converter circuit built with four SiC Schottky barrier diodes. An increase of the switching frequency led to the module of a reduced size ($250 \times 180 \times 28$ mm^3), which is just one third volume of a commercial Si-based inverter available today. Besides being compact, the conversion efficiency of the DC-AC converter was approximately 3% higher than that of the commercial Si-based inverter. In addition, the MPPT controller showed a conversion efficiency exceeding 96%, which raised the total efficiency under practical operation conditions up to 86%.

1. Introduction

1.1. Advantages of wide bandgap semiconductor materials

Recent power device requirements include a high blocking voltage, a low ON resistance, a high switching frequency, and good reliability. These requirements have led to great interest in power devices based on wide bandgap semiconductors such as GaN and SiC (Labedev and Chelnokov, 1999; Monroy et al., 2003; Okumura, 2006). The main advantage of wide bandgap semiconductors is their very high electric field capability. Wide bandgap semiconductors possess high critical field strengths. This means that a thinner epi layer is required to block the same voltage compared with Si devices. Thus, switching devices with much lower ON resistances can be fabricated using GaN or SiC. A lower ON resistance improves the efficiency of inverters due to reduced conduction and switching losses, and also decreases the module size due to the increased power density. The high electron mobility of GaN allows switching operations with higher frequencies, which also decreases the module size because of the smaller passive components. The excellent thermal stability of SiC and GaN should enable devices based on these materials to operate at high temperatures.

1.2. Survey of SiC-based photovoltaic inverter development

The first photovoltaic inverter using SiC diodes was reported by Frank and Bruno (2001), while that using SiC transistors was reported by Stalter et al. (2007). At present, SiC Schottky barrier diodes (SBDs), metal-oxide-semiconductor field-effect transistors (MOSFETs), junction field-effect transistors (JFETs), and bipolar junction transistors (BJTs) are available in the market. There have been considerable reports on the applications of SiC devices on power converters (Chinthavali et al., 2009; Yamane et al., 2013, and Li et al., 2013). Concerning direct current (DC)-DC converters, Hensel et al. (2011) and Ho et al. (2011) reported interleaved boost converters built with SiC BJTs and SiC SBDs, respectively. Concerning DC-alternating current (AC) converters single-phase inverters, using SiC JFETs and SiC MOSEFTs were reported by Kranzer et al. (2008) and by Burger et al. (2008), respectively. Three-phase inverters using SiC JFETs and SiC MOSEFTs were reported by Stalter et al. (2010) and by Burger et al. (2009), respectively.

Abbreviations: DC, direct current; AC, alternating current; MOSFET, metaloxidesemiconductor field-effect transistor; SBD, Schottky barrier diodes; MPPT, maximum power point tracking; PWM, pulse width modulation; JFET, junction field-effect transistor; BJT, bipolar junction transistor; IGBT, insulated gate bipolar transistor; HEMT, high electron mobility transistor.

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http://dx.doi.org/10.1016/j.solener.2016.11.041
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Recently, all SiC inverters were reported by De et al. (2013) and by Nashida et al. (2014). A comparative study of Si- and SiC-based power converters was given by some authors (Burkart and Kolar, 2013; Sintamarean et al., 2013; Ho et al., 2013). A comprehensive review on SiC-based photovoltaic inverters was given in Kim et al. (2013). In the literatures, most of power converters using SiC devices were focused on multi-kW class applications. This is because advantages of a lower ON-resistance of SiC devices were considered to be lost in sub-kW class inverters. In addition, most of developed power converters were examined as a stand-alone equipment. Concerning photovoltaic power applications, however, performances of total systems using these converters should be also discussed.

1.3. Aim of this article

Previously, the authors reported a photovoltaic power storage system comprising a SiC-based DC-AC converter (Oku et al., 2015, 2016; Matsumoto et al., 2016). This SiC-based inverter was prepared by replacing Si power MOSFETs in a Si-based inverter by SiC MOSFETs, but the overall circuit remained optimized for Si MOSFETs. In this work, we have newly developed a photovoltaic inverter optimized for SiC devices. This photovoltaic inverter integrates a DC-AC converter and a maximum power point tracking (MPPT) controller (Lauria and Coppola, 2014) into a single module. The capacity of handling power was set at 150 W to enable portability. The aim of this study is to evaluate the feasibility of SiC devices for sub-kW class photovoltaic inverters. This sub-kW class photovoltaic inverter is available for the applications where compactness and efficiency are of tremendous importance, such as portable electronic devices, solar-powered cars, and emergency power supply systems. This study also aimed to compare the SiC- and Si-based inverters with respect to the performance of a total photovoltaic power generation system.

The next section describes setup of the developed photovoltaic system and the power module. In Section 3, the total efficiency and the electric power stability are investigated for the photovoltaic power generation system including spherical Si solar cell panels (Oku et al., 2014), an MPPT controller, and a storage battery as well as the inverter. In Section 4, the efficiency and the electric power stability are compared between the SiC- and Si-based systems.

2. Experimental

2.1. Photovoltaic power storage systems

Fig. 1(a) illustrates setup of conventional photovoltaic power storage systems that we reported in Oku et al. (2015, 2016) and in Matsumoto et al. (2016). There are two conventional systems capable of operating independently. One system employs a commercial Si-based DC-AC converter (Meltec, SXCD-300) denoted by “Si inverter”, while another using an in-house SiC-based DC-AC converter denoted by “SiC inverter 1”. The SiC inverter 1 was prepared replacing four Si MOSFETs (Fairchild, FQPF16N25C) (Fairchild semiconductor, 2013) in SXCD-300 by four SiC MOSFETs (Rohm, SCT2120AF) (ROHM Semiconductor, 2015a). Spherical Si solar cell panels (Clean venture 21, CVFM-0540T2-WH) wired in parallel were used as the power source. Principle features of these cell panels are lightness, flexibility, and economical efficiency. The maximum operating current and voltage for a single solar panel were 3.34 A and 16.2 V, respectively. The operating point was controlled to maximize the output power with the aid of an MPPT controller (EPsolar, Tracer-2215BN). The MPPT stabilized the electric power by charging and discharging a 12.8 V Li-ion battery (capacity: 20 Ah) (O’Cell, IFM12-200E2). The current and voltage at the input and output terminals of the inverters were monitored by power meters (Hioki, PW3336). The measurement interval was 200 ms and reported data are the average measurements over each minute. The temperature, humidity (Hioki, LR5001), and solar radiation power (Uizin, UIZ-PCM01-LR) were monitored simultaneously during measurements. Filament lamps were used as the load.

Fig. 1(b) illustrates setup of a photovoltaic power storage system using a newly developed SiC-based inverter (SiC inverter 2). In this inverter, an MPPT controller and a SiC-based inverter were integrated into a single module. The MPPT circuit is driven by the input voltage regulation (Texas Instruments, 2016). The inverter circuit consisted of a front stage DC-DC converter followed by a second stage DC-AC converter. The DC-DC part was a push-pull converter where four SiC Schottky barrier diodes (SBDs) (Rohm, SCS210AJ) (ROHM Semiconductor, 2015b) were used as rectification diodes. The DC-AC part was a single-phase full-bridge inverter, where four SiC MOSFETs (Rohm, SCT2120AF) were used as switching transistors. The switching frequency of the pulse width modulation (PWM) signal was increased from 20 kHz for the conventional inverters to 100 kHz. The rated output power was set to 150 W. As the power source, spherical Si solar cell panels wired in parallel were also used unless otherwise stated. The current and voltage at the output terminals of the solar cell, the Li-ion battery, and the inverter were monitored synchronously by power meters (Hioki, PW3336). The measurement interval was 200 ms and reported data are the average measurements over each minute. The temperature, humidity (Hioki, LR5001) and solar radiation power (Uizin, UIZ-PCM01-LR) were monitored simultaneously during measurements. Also, filament lamps were used as the load.

2.2. SiC-based inverter module

Fig. 2(a) and (b) are photographs of the developed photovoltaic power module (SiC inverter 2) and the DC-AC converter circuit with an MPPT controller, respectively. The module of a reduced size (1260 cm^3) achieved just one third volume of the conventional Si-based inverter (SXCD-300: 2037 cm^3, Tracer-2215BN: 1738 cm^3). Weight of the module was just 1.25 kg. This small module size was resulted predominantly from the increase in the switching frequency. Besides, the weight of a spherical Si solar cell panel was 2.13 kg. The total weight including the inverter module, a single solar cell panel, and a 20 Ah battery was 5.96 kg.

3. Results

3.1. Conversion efficiencies for individual circuits

First, we have characterized conversion efficiencies for the MPPT controller and the DC-AC converter of the developed SiC inverter, separately. The conversion efficiency of the MPPT controller was measured by connecting an alternative power supply to the photovoltaic DC terminal while making the inverter circuit inactive. Fig. 3(a) presents an MPPT efficiency measured with respect to DC supplied power. The MPPT efficiency exceeded 95% when the photovoltaic power ranging between 15 and 65 W, and the peak efficiency reached 96.4%.

The conversion efficiency of the DC-AC converter was measured under a battery operation, while changing the load power. This eliminated influence of the MPPT controller. Fig. 3(b) presents efficiencies measured with respect to AC output power. The inverter efficiency exceeded 85% when the output power ranging between 60 and 150 W, and the peak efficiency reached 86.8%. The current and voltage at a connecting node between the DC-DC and DC-AC circuits were monitored by means of a shunt resistor connected