Development of Micro DC-DC Converter Realizes High Efficiency and Temperature-Tolerance in CPV Module

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***Abstract*—This paper describes the micro DC-DC converter realizing high efficiency and temperature-tolerance in concentrator photovoltaics (CPVs) applications. Fundamental experiments are carried out to verify the feasibility of the micro DC-DC converters in high concentration CPV module. As a result, it is experimentally demonstrated that the prototype circuit can automatically starts the operation of the converter according to the rise of the CPV cell voltage. In addition, it is analytically confirmed that the designed circuit has a potential to achieve the efficiency over 90.0%.**

I. Introduction

Recently, concentrator photovoltaics (CPVs) are one of promising next-generation photovoltaic technologies owing to their excellent conversion efficiency [1-4]. According to thermodynamics theory, solar concentration can be exploited to increase the theoretical conversion efficiency limit. In the CPV module, current mismatch among the CPV cells due to optical performance difference of misaligned individual cells and partial shading aggravates module efficiency. On the other hand, suitable installation site is generally limited only in the region of high direct solar irradiation. “CPV+ concept” has been recently introduced to broaden the potential market of CPVs [5]. In this concept, low-cost solar cells and CPV cells are combined in a high-concentration CPV module. Most of diffuse solar radiation is captured and harvested by the low-cost solar cells; in contrast, direct solar radiation is concentrated on the CPV cell. As a result, the DC conversion efficiency of CPV module based on global solar radiation can be significantly improved. Motivated by above challenging research issues, exploration of suitable method for electrical integration of CPV cells and\or two different types of cells in CPV module is of interest. The use of micro inverter technology will be one of the suitable methods.

For flat PV systems, research and development of the micro inverters connected to each single PV module are becoming the trend for the future grid-connected PV systems [6-10]. In conventional method, a single large power capacity inverter is connected to multiple PV modules in a series connection. Therefore, the output power of PV panels drastically changes depends on shading and weather conditions. In contrast, micro inverters can extract the energy of PV cells efficiently by minimizing such effects and can improve the system reliability by reducing output voltage of PV cells. This advantage is attractive for not only the conventional flat PV but also CPV. However, to date, limited to the author’s knowledge, no studies applying micro inverters to the CPV module has been reported.

This study aims to develop micro inverters to the CPV module especially with “CPV+ concept” proposed by one of the authors. In order to implement the micro inverters to the CPV module, further downsizing, high efficiency, and affordable temperature-tolerance are required for micro DC-DC converters. In the CPV module micro DC-DC converters are closely connected to each solar cell or each small groups of solar cells, thus the converter should operate at high temperature because the temperature of surroundings of CPV cell generally becomes high due to the concentrated beam solar radiation. Micro DC-DC converters should also operate at high switching frequency using gallium nitride (GaN) and silicon carbide (SiC) and so on. In addition, micro DC-DC converters should automatically start up and shut down depending on the output voltage of CPV cells. Toward the realization of such micro converter, in this study, design concept is introduced and fundamental experiments are carried out to verify the feasibility of the micro DC-DC converters to control the output voltage of a typical CPV cell. As a result, it is experimentally demonstrated that the output voltage of the CPV cell is controlled based on the electricity generation characteristic of the cell to achieve the maximum power point. Furthermore, the result of loss analysis indicates that the designed circuit can achieve the efficiency over 90.0%.

II. Micro DC-DC Converter in CPV+ Module

Fig. 1 shows the conceptual image of combination of "CPV+ concept" and micro DC-DC converters. Concentrator element such as Fresnel lens concentrates beams solar radiation onto the CPV cell, e.g., multi-junction cell. The low-cost cell such as silicon (Si) cell captures diffuse solar radiation incoming through the lens. A micro DC-DC converter is installed into the concentrator module as well as solar cells and connected to each CPV cell.

Fig. 2 shows example circuit configuration for the present concept. A micro DC-DC converter is connected to each solar cell, forming a converter module. The converter module is connected in series in order to increase voltage because the output voltage of the CPV cell and low-cost cell is generally small. That of the CPV cell used in this experiment is approximately 3 V. An inverter is connected to the output of the strings of DC-DC converter modules in order to interconnect to the grid. For the micro DC-DC converter, SiC or GaN should be employed in order to achieve high-temperature operation of micro DC-DC converters. In addition, those wide band semiconductors can contribute to the downsizing of the micro DC-DC converters due to fast switching. The unique feature required to the micro DC-DC converter is automatic start of the operation utilizing lower voltage of the CPV output.

A. *Configuration of micro DC-DC converter*

Fig. 3 shows the circuit configuration of the micro DC-DC converter, which is a boost chopper. A technique of synchronous rectifier is adopted for the switch S_1 in order to reduce the drop voltage and the conduction loss of power devices compared with that of a diode. A shunt resistor is used in order to detect the inductor current instead of a current sensor.

B. *Control circuit*

The power supply of the control circuit is a part of the output voltage of the CPV cell. As a result, once the CPV cell starts to generate its power from the sunlight, the control circuit starts the operation to drive the main circuit. General purpose ICs are used for the control circuit. The power supply ICs (REG710NA-5, REG710NA-3.3: Texas Instruments) are used in order to obtain 5 V and 3.3 V for the power supply of ICs. PI regulators are implemented for the control of current and voltage, which are an auto voltage regulator (AVR) and an auto current regulator (ACR). In addition, ICs operated by single supply are used in order to minimize IC components.

III. Specification And Experimental Results

Table I shows the experimental conditions. In order to verify the feasibility of the proposed concept, fundamental experiments are carried out. It is noted that the conventional Si devices are used instead of GaN and SiC for the first-step experiments. The switching frequency is set to 50 kHz.

Fig. 4 shows the photograph of the fabricated prototype micro DC-DC converter. All components are mounted on a PCB board sized 70×70 mm^2. In order to eliminate the effect

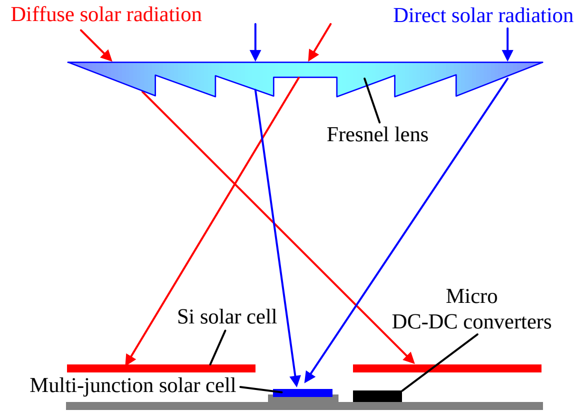

Figure 1. Conceptual image of the use of micro DC-DC converter in CPV module based on CPV+ concept.

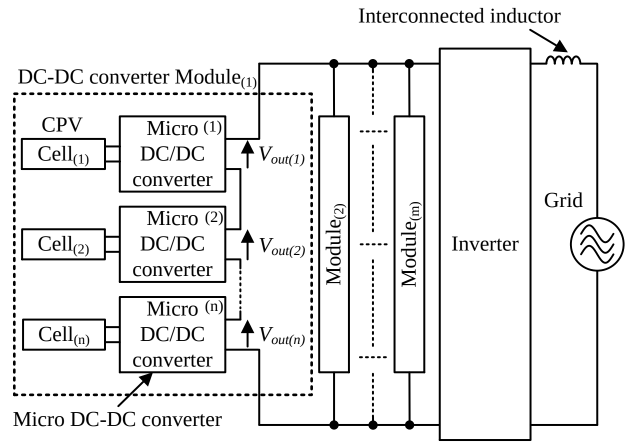

Figure 2. Circuit configuration of the CPV system using micro DC-DC converters.

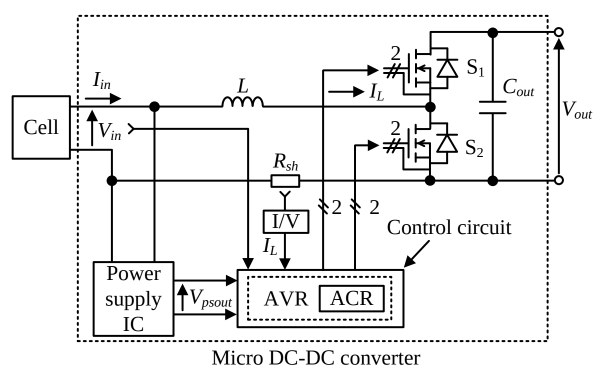

Figure 3. Circuit configuration of micro DC-DC converter.

of line-inductance and achieve downsizing of the micro DC-DC converter, all components are closely connected. Note that, heat sink is not used for the MOSFETs; besides some components are not optimal materials for simplifying fabrication of the prototype circuit. The size of the circuit board will be less than 30 × 30 mm^2 by replacing the components to chip components.

TABLE I. EXPERIMENTAL CONDITIONS

Surface area of CPV lense		200 (mm) × 200 (mm)
Surface area of CPC cell		7 (mm) × 7 (mm)
Switching frequency		50 (kHz)
Rated output voltage of CPV cell		2.5 (V)
Shunt resistance		10 (mΩ)
Boost inductor	Inductance L	9.4 (μH)
	Winding resistance R_L	5 (mΩ)
Output capacitance C_{out}		100 (μF)
MOSFET (TPCA8028-H)	On resistance R_{DSon}	2.3 (mΩ)
	Rise time t_r	5.0 (ns)
	Fall time t_f	9.8 (ns)

A. Characteristic of CPV cell

Fig. 5 shows a I-V curve and a P-V curve of the CPV cell at direct normal irradiation (DNI) of 704 W/m^2. From Fig. 5, it is seen that the output voltage of the CPV cell which achieves maximum power is approximately 3 V. Generally, the variation of this voltage is not very large in the CPV cell due to high fill factor for broad range of DNI. Therefore, the simplest control strategy is to control the output voltage of the CPV cell to be nearly constant in order to perform approximate maximum power point tracking (MPPT). The present fundamental experiment follows this strategy. However, in actual system, multi-step voltage control strategy should be employed to perform more precise MPPT depending on electrical characteristic of the CPV cell and other types of solar cell in case with CPV+ concept.

B. Output voltage control

Even if the load of grid side is changed, the output voltage of DC-DC converter should be controlled to be nearly constant level by the control circuit without using a large electrolytic capacitor. This contributes to high-temperature tolerance and long lifetime of micro DC-DC converters.

C. Starting of prototype circuit

Fig. 6 shows the waveforms of prototype circuit. The power supply IC automatically starts the operation simultaneously with the rise of the CPV cell voltage. When the prototype circuit starts the operation, the chattering of voltage occurs. However, the control circuit and the main circuit start stably the operation after 60 ms.

D. Efficiency and power loss

Fig. 7 shows the experimental results for the efficiency of the prototype micro DC-DC converter without the synchronous rectifier of the switch S_1. The efficiency is measured from the output power of the CPV cell to the power of the load. It is noted that the power consumption of the control circuit is included as a loss component. A maximum efficiency of approximately 65% was obtained in the experiment in case of V_{in} = 3.0 - 3.5 V.

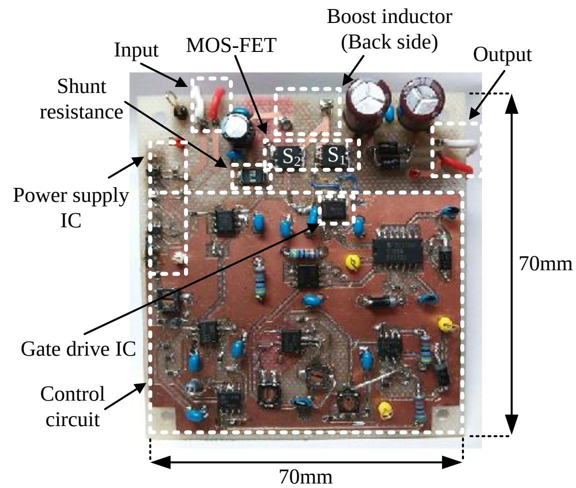

Figure 4. Photograph of the prototype micro DC-DC converter.

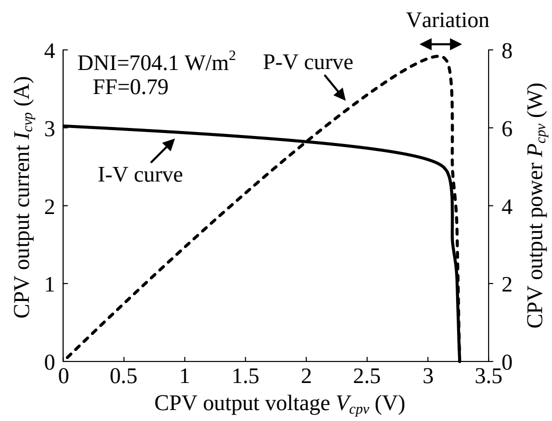

Figure 5. Current – voltage (I-V) curve and power – voltage (P-V) curve of CPV cell.

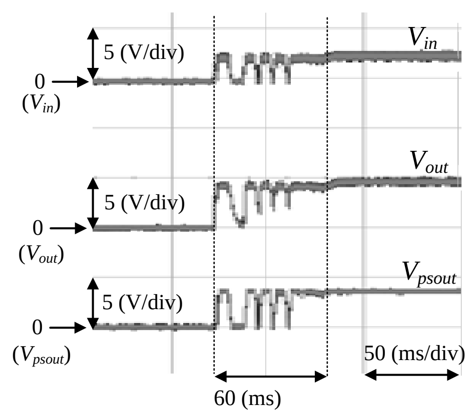

Figure 6. Waveforms of micro DC-DC converter at the starting of circuit operation.

Fig. 8 shows the loss analysis using theoretical equation for the next prototype circuit. The validity of the theoretical equation was confirmed by the circuit simulator Piece-wise

Linear Electrical Circuit Simulation (PLECS, *Plexim GmbH*). In particular, the power loss is calculated from the instantaneous voltage and the instantaneous current in the simulation circuit, based on the table of switching frequency data in the appropriate datasheet. In the present analysis, the power loss includes that of the MOSFETs, the copper loss of the boost inductor. The core loss of the boost inductor and the power consumption of control ICs are not considered. Note that the synchronous rectifier is adopted in order to achieve high efficiency although it was not used in the present experiment. In addition, the switching frequency is set to 250 kHz in order to reduce the size of the micro DC-DC converter. The loss analysis result shows that the gate drive power consumption and the switching loss of MOSFETs are dominant part in total power loss. Therefore, MOSFETs which has a fast switching characteristic should be selected in order to achieve high-efficiency of prototype micro DC-DC converter even if the switching frequency is high.

IV. CONCLUSION

In this paper, the use of micro DC-DC converter in CPV system was introduced and the technical requirements for the converter and possible solutions were described. High efficiency, long term temperature-tolerance, and automatic starting and shutdown of the converter operation are important requirements to realize the present concept. The first-step experiment with the fabricated converter circuit and analytical study for the next prototyping demonstrated that the required performance can be achieved by the better designed circuit configuration. Further research and development will be conducted to improve the feasibility of the use of micro DC-DC converter in CPV systems.

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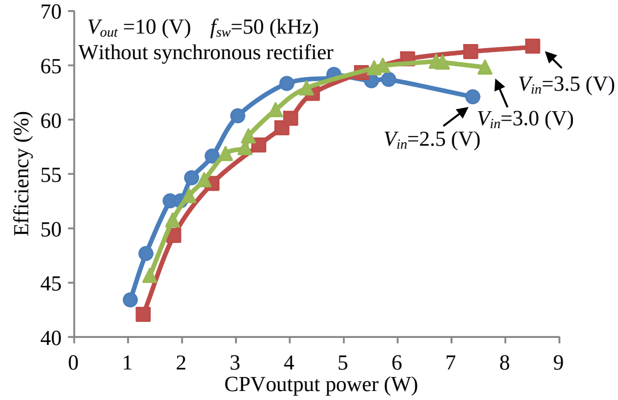

Figure 7. Expeimental efficiency of the prototype micro DC-DC converter.

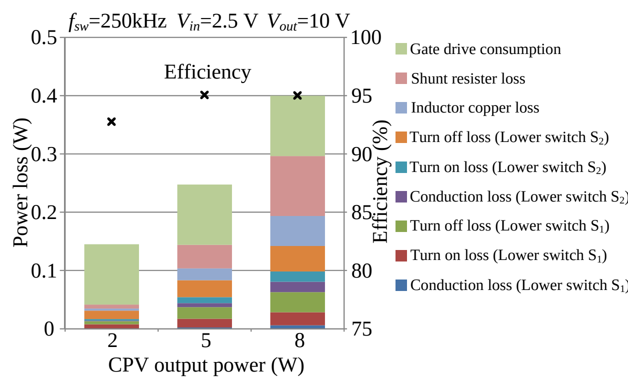

Figure 8. Loss anaylysis results of the micro DC-DC conveter circuits desigined for next prototyping.

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