A Compact Three-Port DC-DC Converter for Integrated PV-Battery System

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***Abstract*—In this paper, a new non-isolated three-port DC-DC converter (NITPC) to integrate a battery storage with a PV module is proposed. The intermittency of renewable energy and the unpredictable load demand are eliminated by firming a backup battery with the PV module to supply extra power when it is required. The proposed converter is reconfigurable and able to operate as a conventional boost converter, a buck-boost converter or a forward converter in different modes to support several power flow combinations and achieve power conditioning and regulation among the PV module, battery and an output port simultaneously. Nevertheless, the converter only consists of two switches, one coupled inductor, one diode and two capacitors. Thus, the system size and number of components are reduced compared with the traditional DC-DC converters. High output regulated voltage is achieved by using a coupled inductor and by combining the PV module and the battery in series. Simulation and experiment are carried out to verify the proposed circuit.**

***Index Terms*—three-port converter, photovoltaic, battery, Single-input Single-output (SISO), Single-input dual-output (SIDO), Dual-input single-output (SIDO), Dual-input dual-output (DIDO), maximum power point algorithm (MPPT), renewable energy.**

I. Introduction

There is an increasing demand for renewable energy sources recently due to their economical viability, high electricity prices and green initiatives. Solar energy, in particular, is one of the most useful sources of sustainable energy in many industrial and residential applications. However, the intermittency of solar power negatively affects the efficiency, durability, power handling capability, and reliability of the power system. To mitigate such problem, a power electronic converter is used to interface the photovoltaic (PV) module with another power source with the load. This power converter is used to track the maximum power point (MPP) of the solar panel, manage battery charging and regulate output voltage [1], [2].

Traditionally, a single DC-DC power converter with two ports is used to connect only one energy source with the load [3], [4]. To use more than one input power source or storage element, there is a need to use multiple power converters. In addition to reduced efficiency, the cost, the number of components and the complexity of the system increase [5], [6].

In recent years, several multiport converters (MPC), illustrated in Fig. 1, have been proposed to connect the renewable energy source with the storage system. MPC has several advantages including its low cost, mass and component count. It increases the system reliability and uses a centralized control, resulting in less communication delay and errors. Moreover, using multi-port converter will offer multi-input multi-output (MIMO) feature, so the power could flow between two ports

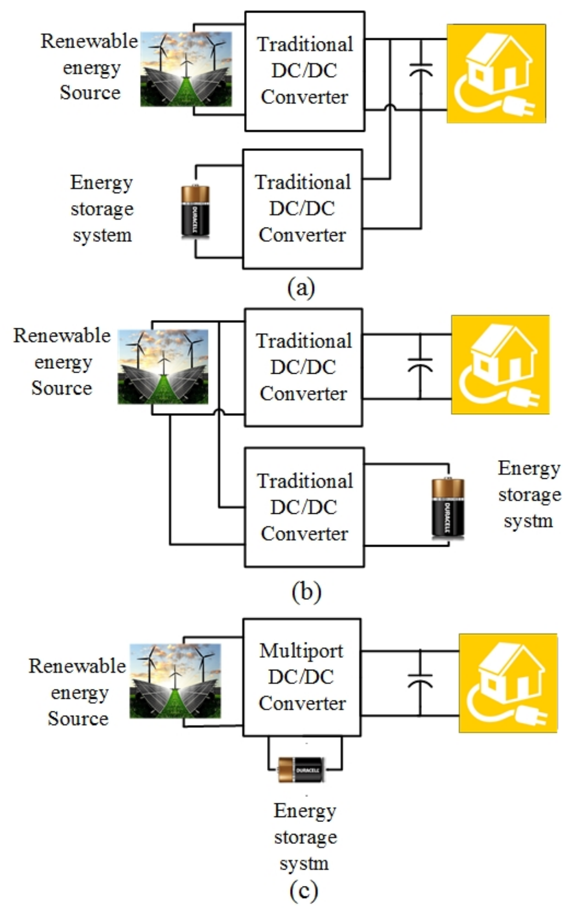

Fig. 1. Traditional MPC: a) Tradition DISO, b) Tradition SIDO.

only as a single-input single-output (SISO), or between three ports simultaneously, which is known as single-input dual-output (SIDO) or dual-input single-output (DISO).

MPC can be classified into three groups namely: non-isolated, partly isolated and isolated converter. The isolated converter uses a high-frequency transformer to achieve a high voltage regulation ratio and the galvanic isolation feature [5], [7]. It can also easily achieve zero voltage switching (ZVS) by using phase shift control for all switches in the full bridge converter. Nevertheless, the isolated converter requires a high number of switches and associated gate driver circuits. They may lead to more switching losses. Also, transformer-based topology would require significant effort in dealing with leakage energy and more complicated control strategy to direct power flow among different ports [4], [7]–[9]. In some applications, when the high voltage regulation ratio is required, and the galvanic isolation feature is not necessary between the all ports, partly-isolated converter is a better option [10]–[12]. Non-isolated converter has some advantages over other categories such as higher efficiency, smaller volume, less number of components, and easier to implement and control. Authors in [1], [5], [13], [14] have proposed non-isolated converters. Although the number of the switches is lowered, the voltage gain is limited. In [15] a novel high-voltage nonisolated converter has been proposed by using a coupled inductor with a different turns ratio. Meanwhile, three power switches and five diode are used to implement the circuit, but the component count is still high.

In this paper, a new non-isolated three-port-converter is proposed. By adding one switch and a couple inductor to the circuit proposed in [13], the intermittency of the renewable energy and any unpredictable change in demand will be eliminated by having better control for the battery charging and MPPT simultaneously. Also, the coupled inductor is used to extend the output voltage to a higher level. The paper is organized as follows: In Section II, the proposed circuit is introduced and the operation mode is analyzed. In Section III, the system setup is discussed. In Section IV. The results are explained, followed by the conclusion in Section V.

II. Operation Principle

A. Proposed Circuit

The proposed three-port converter, shown in Fig. 2, has three ports namely, a unidirectional input port, a bi-directional battery port and an output port. The circuit has only two power switches, one diode, two capacitors, and one coupled inductor. V_{PV} is the input port, it is connected to the main source of power which is the photovoltaic module. The battery port V_B is connected to battery storage system so that it can be used either to provide a high voltage gain due to its series configuration with the input port or supply more power to the output in order to solve the intermittency issue. Meanwhile, the proposed circuit is able to achieve MPPT, manage battery charging/discharging and regulate output voltage. The coupled inductor formed by L_P and L_S and its turn ratio N_1/N_2 is

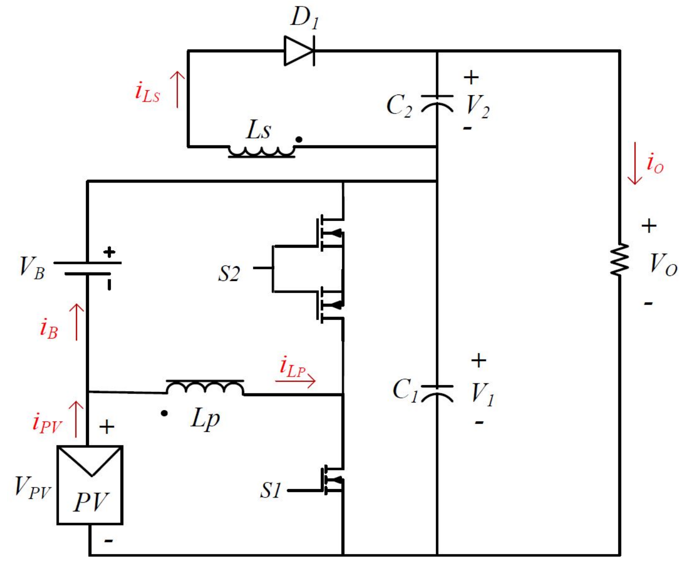

Fig. 2. proposed circuit.

used to provide a higher voltage boost. The output capacitors C_1 and C_2 are large enough to smooth the output voltage.

B. Operation Modes

The power flow among the ports in the proposed three-port converter has six potential operation modes. These modes are listed below:

1) Single-input single-output (SISO) PV-battery mode: this mode is active when the PV module stores power in a battery no-load unloading condition, as depicted in Fig. 3(a).
2) Single-input single-output (SISO) PV-load mode: this mode is active when the PV module supplies power the load assuming the battery is not connected or non-operational, as depicted in Fig. 3(b).
3) Single-input single-output (SISO) battery-load mode: This mode is active only when the battery supplies power to the load. In this mode, the PV module is either shaded or not supplying power at night time, as depicted in Fig. 3(c).
4) Dual-input single-output (DISO) mode: this mode is active when the PV module and the battery supply power simultaneously to the load, as depicted in Fig. 3(d).
5) Single-input dual-output (SIDO): this mode is active when the PV module supplies power to the load. The unused generated power from the PV is stored at the battery as depicted in Fig. 3(e).
6) Dual-input dual-output (DIDO): this mode is active when the PV supplies power to the load and the battery is charged and discharged by approximately same amount of power as depicted in Fig. 3(f).

C. Steady-State Analysis

- (SISO) PV-battery mode: in this mode, S_1 and S_2 are operating in a complementary mode. The power generated by the PV module charges the battery to be used later. The combination of V_{PV}, L_P, S_1, S_2 and V_b is considered as a buck-boost converter. Thus, the battery charges effectively. Fig. 4(a) shows the current bath flow

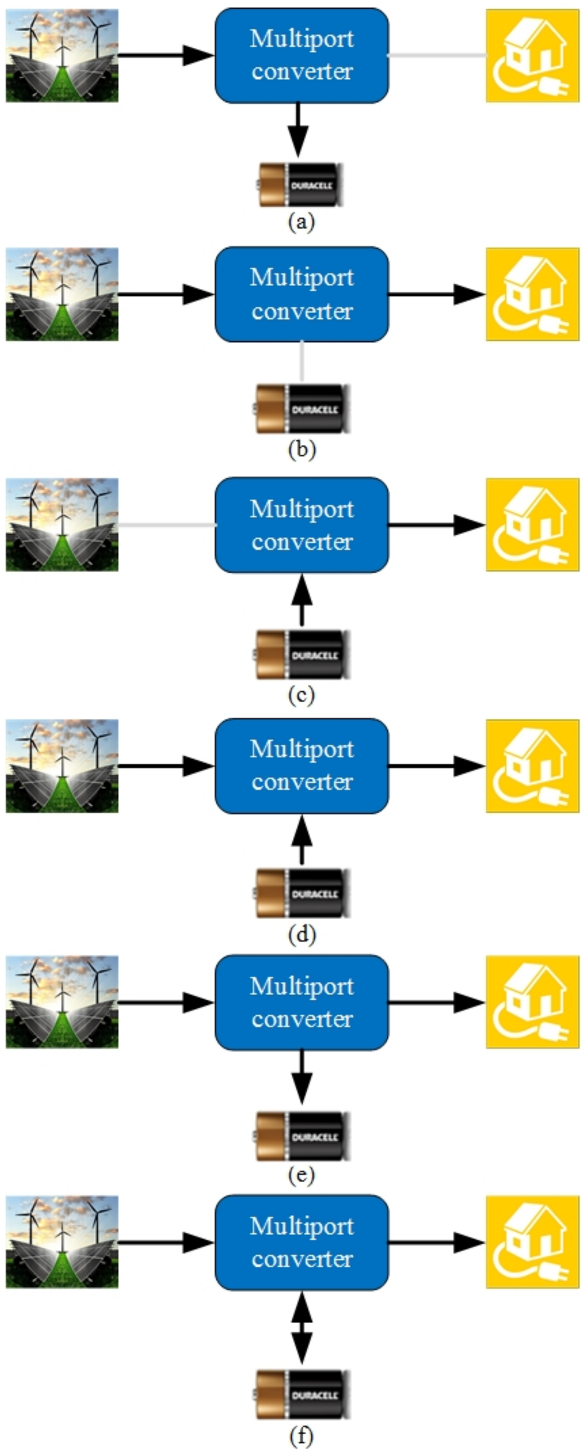

Fig. 3. Power flow TPC and operation modes: (a) (SISO) PV-battery mode, (b) (SISO) PV-load mode, (c) (SISO) battery-load mode, (d) DISO mode, (e) SIDO mode, (f) DIDO mode.

for the proposed converter.

- (SISO) battery-Load mode: in this mode, only two ports are active, the battery and the output port. The combination of $V_{PV}, L_P, L_S, S_1, D_1, C_2$ and V_2 is considered as a forward converter, and the current path flow is shown in Fig. 4(c).
- (SIDO), (DISO) and (DIDO) modes: in these three modes, the following three assumptions are made: the combination of $V_{PV}, L_P, L_S, S_1, D_1, C_2$ and V_2 is considered as a Flyback converter, the combination of V_{PV}, L_P, S_1, S_2 and V_b is considered as a buck-boost converter and the combination of $V_{PV}, L_P, S_1, S_2, C_1$ and V_1 is considered as a boost converter. All ports, in these modes, are active, the only difference is the current flow of the battery port.

If the input power is less than the output power, the current will be drawn from the PV module and the battery to supply the load. Thus, and the converter will be operating at Dual Input Single Output (DISO) mode. The current will flow the path shown in Fig. 4(d).

If the input power is greater than the output power, some power will be stored in the battery; then, the converter will operate at Single input Dual output (SIDO) mode. As it is illustrated from the current path flow, Fig. 4(e), when the switch S_1 is closed and S_2 is opened, the inductor and the battery begins charging by the PV module. Then, when S_2 is closed and S_1 is opened, the inductor starts discharging, and the current will continue in the same direction, charging the battery and transferring the power to the output port by the coupled inductor.

On the other hand, Dual Input Dual Output (DIDO) mode, Fig. 4 (e) and Fig. 4 (f), is a balanced mode between SIDO and DISO modes and it is the most dominant mode. The key waveforme for this mode is shown in Fig. 5, and the switching modes fot DIDO are describded as follow:

Switching mode I [$t_0 < t < t_1$]: in this switching mode, switch S_1 is turned ON while S_2 is turned OFF. The primary inductor, L_P, starts to charge by the input source V_{PV}. D_1 is revised bias due to the polarity of the secondary winding of the coupled indutor. The battery current starts to decrease until it reaches to zero at $t = t_1$ then this mode ends.

Switching mode II [$t_1 < t < t_2$]: in this switching mode, switch S_1 remains ON and S_2 is turned OFF. the primary inductor keep chargeing and D_1 keep revíresed bias. Nevertheless, the battery starts dischrging and this mode ends at $t = t_2$.

Switching mode III [$t_2 < t < t_3$]: in this mode, switches S_1 is turned OFF while S_2 is ON. The primary inductor starts to discharge and its energy flies to the secondary inductor and the battery at the same time. This mode ends at $t = t_3$.

Switching mode IV [$t_3 < t < t_4$]: in this switching mode, switch S_1 remains OFF and S_2 ON. The battery starts to discharge in order to supply more power to the load. This mode ends at $t = t_4$.

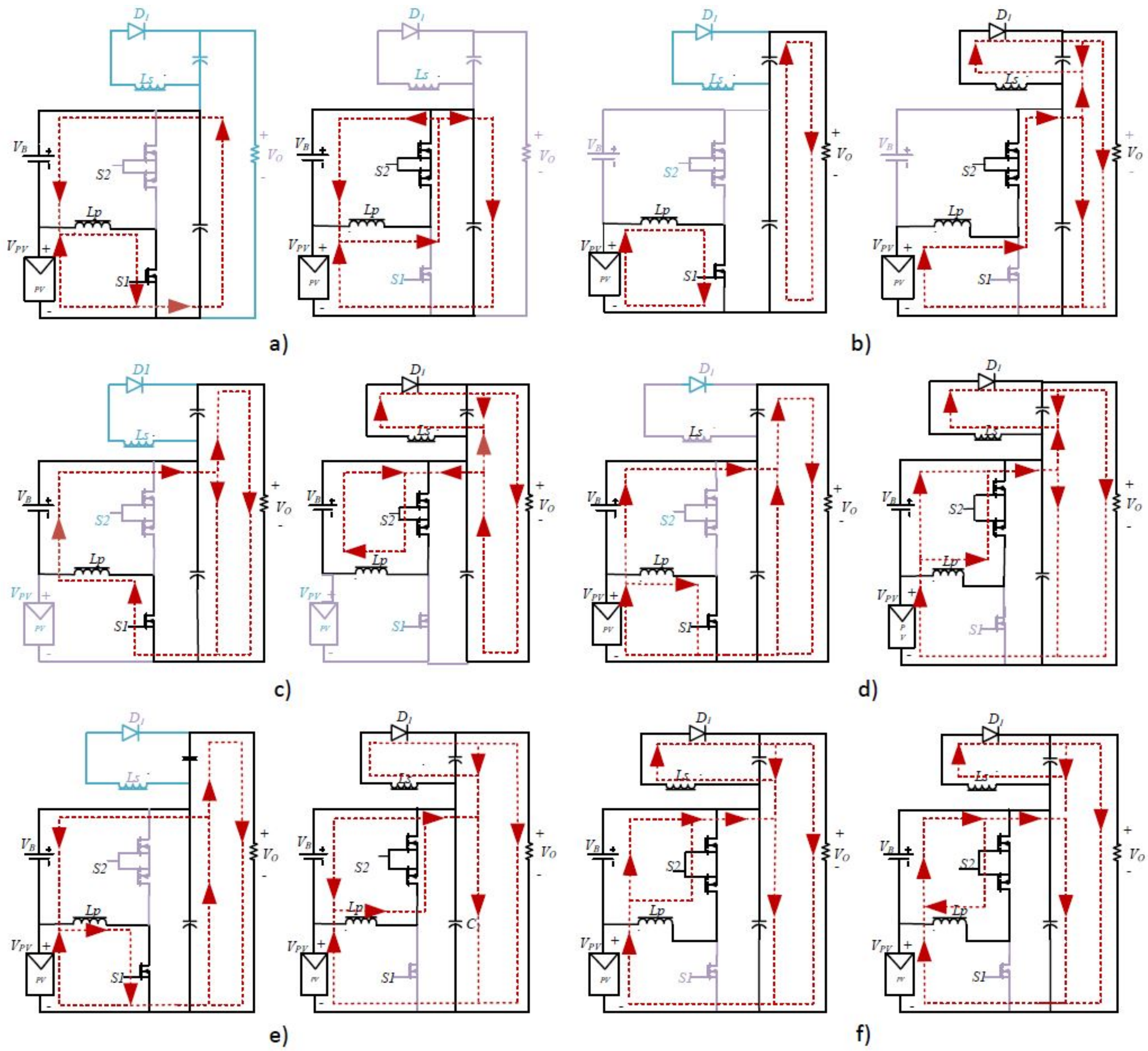

Fig. 4. Power flow TPC and operation modes:(a) (SISO) PV-battery mode, (b) (SISO) PV-load mode, (c) (SISO) battery-load mode, (d) DISO mode, (e) SIDO mode, (e&f) DIDO mode.

Switching mode V [$t_4 < t < t_0$]: in this switching mode, the current direction on the primary inductor will be flipped due to the direction of the current in the battery and the secondary inductor that is coupled with the primary, this mode ends at $t = t_0$.

III. EXPERIMENTAL VERIFICATIONS

In order to verify the performance of the proposed converter, initially, the proposed circuit simulated using LT-spice/SwitcherCAD III. Then, after confirming the operation modes and the power flow for all modes, the laboratory prototype shown in Fig. 7 is built and tested under different testing conditions. The schematic diagram of the fabricated

TABLE I
DETAILS OF COMPONENTS.

Component	Model/Value
Digital controller	TMS320F28335
MOSFET	IRF540N
MOSFET Driver for S1	TC4426
MOSFET Driver for S2	IR2184PBF
D1	MBR2035CT
Coupled inductor core	RM14/I-3C95
N_2/N_1	1/2
L_1	100 uH
L_2	400 uH
C_1&C_2	470 uF

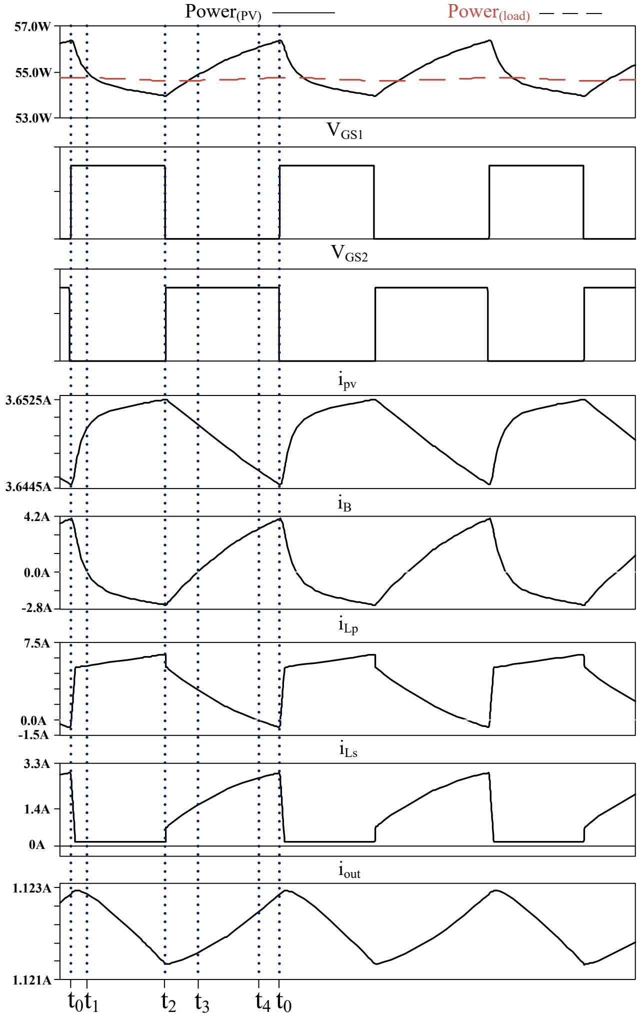

Fig. 5. Key switching waveforms for DIDO mode (Mode e and f in Fig. 3).

PCB shows in Fig. 6, and the components used are listed in Table I.

A 60 W solar panel is used as a main source of power, and it is connected to the input port. The solar radiation emulated by using a set of artificial lights (500 w halogen light). A 12V, 12Ah lead-acid battery is connected to the unidirectional port (battery port) to store the unused power and to supply more power to the load when required to reduce the intermittency effects. The output port is connected to a programmable DC electronic load to mimic the change in the power consumption.

A PI controller with P&O algorithm is used to track the MPP and regulate the output voltage respectively. A Texas Instrument DSP, TMS320F28335 is used to control the power flow and generate PWM signals to drive the switches. The switching frequency is set at 50 kHz.

IV. EXPERIMENTAL RESULTS

The voltage waveform for the dominant mode, DIDO, is shown in Fig. 8. The photovoltaic panel is operated at 18.5 V which is the voltage at the MPP while the output voltage regulated around 48 V. Nevertheless, the battery is charging and discharging by each cycle. The average battery current is zero. That means the battery charging and discharging by the same amount of power. Also it helps to boost the output voltage up due to the circuit combination between the PV module and the battery.

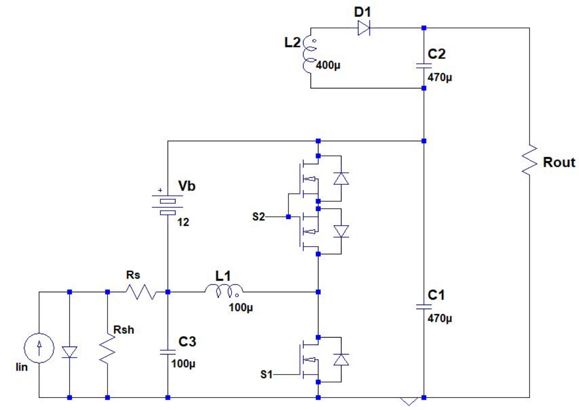

Fig. 6. schematic diagram.

The efficiency of the proposed converter is varied between 97.02% for SISO PV-load mode, 93.09% for SISO PV-battery mode, 92.45% for SISO battery-load mode, 95.49% for DISO, 97.26% for SIDO and 95.04% for DIDO. The proposed converter can achieve MPP by using Perturb and Observe (P&O) algorithm and regular the output voltage around 48 V for the all modes at a lower duty cycle. The operation duty cycle for the main switch changing between 32% and 47%.

V. CONCLUSION

A new non-isolated multiport converter is proposed and experimentally verified to integrate a backup battery with a PV module. A converter has an input unidirectional port for the PV module, a bidirectional port for a backup battery and

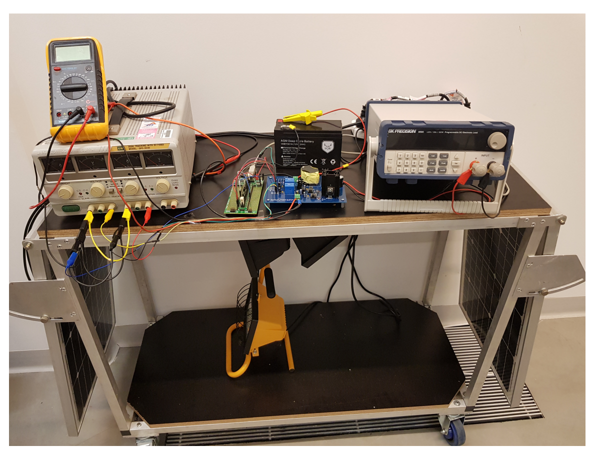

Fig. 7. Laboratory prototype.

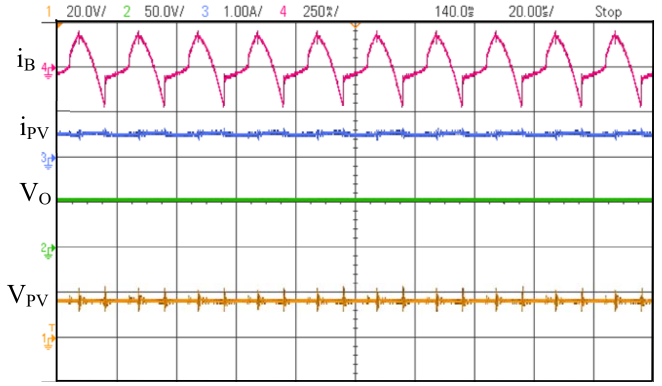

Fig. 8. Experiment result, DIDO mode. Time base: 20µs. V_{PV}: 10V/div. V_{PV}: 10V/div.V_{PV}: 10V/div.V_{PV}: 10V/div.

an output port. The converter can provide a high regulated output voltage by connecting the renewable energy source in series with the battery, and by using a coupled inductor. In addition, the proposed MPC can easily solve the problem of intermittency by using simple control method. The highest efficiency for the proposed converter equals 97.26% while the lowest equals 92.45%.

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