International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 9, No. 1, March 2018, pp. 260~268
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v9.i1.pp260-268

Steady State Analysis of Non-Isolated Single-Input Multi-Output SEPIC Converter for Stand-alone Applications

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Article Info

Article history:

Received Sep 17, 2016
Revised Nov 22, 2015
Accepted Dec 3, 2016

Keyword:

Multiport Converter (MPC)
Single Ended Primary Inductor Converter (SEPIC)
Single-input Multi Output (MISO)

ABSTRACT

This paper proposes a non-isolated three port SEPIC converter for stand-alone photovoltaic applications. The proposed topology uses the Single Input Multi Output (SIMO) structure. This topology consists of a single photovoltaic source as input and it is a unidirectional power converter. Mathematical analysis for the proposed system is performed and simulations are carried out using MATLAB/Simulink. The design parameters of capacitors and inductors are calculated from small ripple analysis. The simulation analysis for the proposed open loop topology is verified using a real time hardware setup.The entire process is carried out in Continuous Current Mode (CCM) of operation. The experimental results for hardware are verified with simulations and compared.

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1. INTRODUCTION

Renewable energy is of potential interest nowadays to replace the conventional fossil fuel power generation [8]. Future power systems will require interfacing of various energy sources [5], [11]. To enable multi-source technology, a multi-port converter (MPC) is of practical use. The multi-port converters supply could accommodate a variety of sources and combine their advantages. MPCs are mainly classified into four categories. Based on, (1) topology (series and parallel) (2) port placement (Single Input Multi-output, Multi-input Single Output and Multi-input Multi-output) (3) coupling (isolated and non-isolated) (4) conversion process (unidirectional and bidirectional) [2], [3]. DC-DC converters are most popularly known for its capability to increase or decrease the magnitude of the dc input voltage and also can invert its polarity [7].

A DC-DC converter operates by frequently operating the power electronics switches [1], [6]. A Buck-Boost, Cuk and SEPIC converter, can increase or decrease the output voltage than the input voltage [12]. In cuk and SEPIC converter the input current is continuous unlike in buck-boost converter, this leads to an advantage in better power factor. Another advantage of SEPIC converter is that it has non-inverting output unlike in cuk converter and buck-boost converter [4], [13]. Also in SEPIC converter, a series capacitor is used to transfer energy from input to the output and thus can respond more graciously to a short circuit output, and being capable of the true shutdown .In the proposed topology PV source is used as input supply. The system works as a unidirectional converter where power flows only from source to load.The input and the outputs are connected in parallel fashion [9].

The duty cycle for both the output port should be properly adjusted to get different output result at different ports. The greater duty cycle results more output voltage [15]. Two separate sources (both photovoltaic cells) having same power ratings have been considered in [10]. To use both the sources effectively, the two sources operate at different duty cycles. The source having the higher value of voltage operates for lower duty cycle whereas the source having the lower value of voltage operates for higher duty cycle. Figure 1 represents the block diagram of single input Multi-output unidirectional SEPIC converter, in this paper Photovoltaic Source is used to supply the SEPIC Converter [16], [19]. The Multiport SEPIC Converter is operated with different duty cycles. The power flow is unidirectional due to the presence of single voltage source [18]. The output varies accordingly to the variation in the input. The source is operated with higher duty cycle for higher output and for lower duty cycle for lesser value [21].

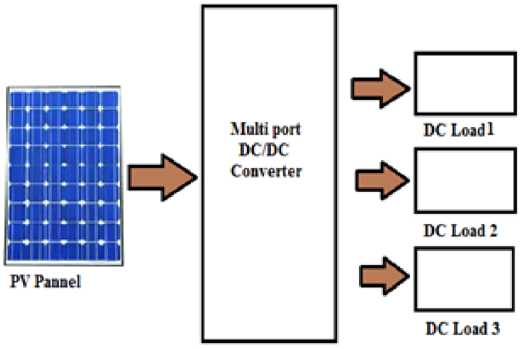

Figure 1. Block diagram of proposed SIMO converter

2. SINGLE-INPUT MULTI-OUTPUT UNIDIRECTIONAL SEPIC CONVERTER

In this paper, single input Multi-output SEPIC/SEPIC converter is proposed.The proposed structure is the combination of Pulsating Voltage Cells (PVC) [20]. PVCs can be of two types, for input side it is Pulsating Voltage Source Cell (PVSC) and for the output side it is Pulsating Voltage Load Cell (PVLC) [14]. Each PVSC connects with a common PVLC through a coupling capacitor forming a complete SEPIC structure.

The input supply voltage is V_1 (PV source), and output voltage be V_2 and V_3 for resistance and motor as two loads shown in Figure 2. D_1, D_2 and D_3 are the respective duty cycles of switch S_1, S_2 and S_3 (PVSC, $PVLC_1$ and $PVLC_2$). There are three modes of operation. Figure 3 shows mode-1 of proposed SEPIC converter.

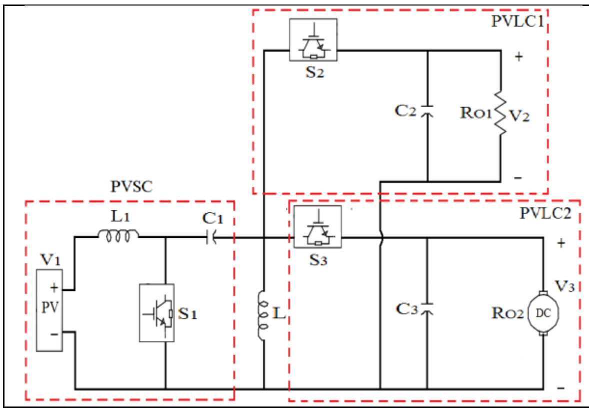

Figure 2. Circuit diagram of single input multi-output unidirectional SEPIC converter

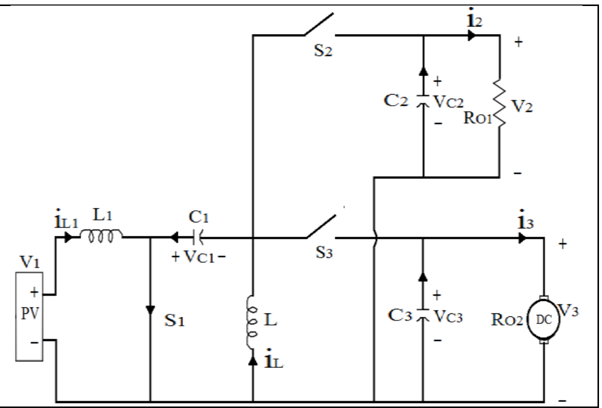

Figure 3. Mode-1 of proposed SEPIC converter

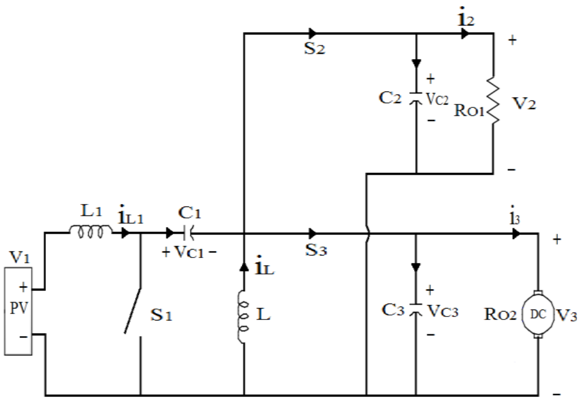

Figure 4. Mode-2 of proposed SEPIC converter

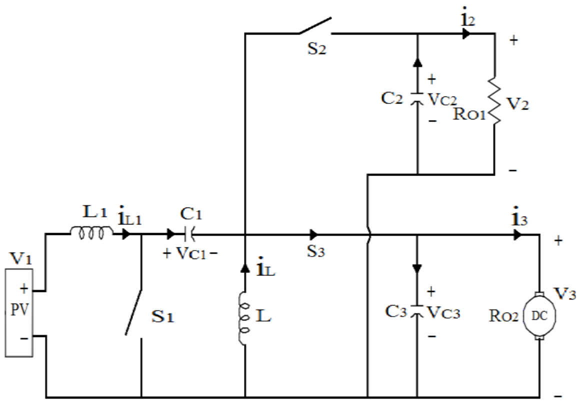

Figure 5. Mode-3 of proposed SEPIC converter

Figure 4 shows mode-2 of proposed SEPIC converter. Where in mode 2, the switch S_1 remains OFF and switches S_2, S_3 remain in ON condition for a period of D_2. Now the capacitor C_1 starts charging through the inductor L_1 which releases its stored energy and common inductor L being charged initially supply current to the load. The output cells capacitor C_2 and C_3 are also storing energy during this mode. Figure 5 shows mode-3 of proposed SEPIC converter where in mode 3, switches S_1 and S_2 are switched OFF and switch S3 alone conducts for a period of Deff (Deff=D_3-D_2). The inductors L_1 and L_2 supply the current to the load and the capacitor C_2 supplies to the load V_2. The capacitor C_3 continues to store energy during this mode.

3. STEADY STATE ANALYSIS OF SINGLE-INPUT MULTI-OUTPUT UNIDIRECTIONAL SEPIC CONVERTER

Steady state analysis of the proposed three port SEPIC converter is done in continuous current mode assuming the ripple voltages and current values negligible. In mode 1, the applied voltage, current and voltage across the capacitor are given by,

$$L_1 \frac{di_{L1}}{dt} = V_1 \quad (1)$$

$$L \frac{di_L}{dt} = V_{C1} \quad (2)$$

$$C_1 \frac{dV_{C1}}{dt} = i_L \quad (3)$$

$$C_2 \frac{dV_{C2}}{dt} = \frac{-V_2}{R_{O1}} \quad (4)$$

$$C_3 \frac{dV_{C3}}{dt} = \frac{-V_3}{R_{O2}} \quad (5)$$

Steady state equations for mode 2 is given by,

$$L_1 \frac{di_{L1}}{dt} = -V_1 - \left(V_{C1} + V_{C2}\right) \quad (6)$$

$$L \frac{di_L}{dt} = -V_{C2} \quad (7)$$

$$C_1 \frac{dV_{C1}}{dt} = i_{L1} \tag{8}$$

$$C_2 \frac{dV_{C2}}{dt} = i_{L1} + i_L - \frac{V_2}{R_{O1}} \tag{9}$$

Steady state equations for mode 3 is given by,

$$L_1 \frac{di_{L1}}{dt} = -V_1 - (V_{C1} + V_{C3}) \tag{10}$$

$$L \frac{di_L}{dt} = -V_{C3} \tag{11}$$

$$C_1 \frac{dV_{C1}}{dt} = i_{L1} \tag{12}$$

$$C_2 \frac{dV_{C2}}{dt} = -\frac{V_2}{R_{O1}} \tag{13}$$

$$C_3 \frac{dV_{C3}}{dt} = (i_{L1} + i_L) - \frac{V_3}{R_{O2}} \tag{14}$$

Combining all the equations, the operating period for mode 1, 2 and 3 are D_1, D_2 and D_{eff} respectively. The circuit parameters are derived from the above equations as,

$$L_1 = \frac{V_1 D_1}{f\ \Delta I_{L1}} \tag{15}$$

$$C_1 = \frac{I_1 D_{eff}}{f\ \Delta V_{C1}} \tag{16}$$

$$L = \frac{V_2 (D_2 + D_{eff})}{f\ \Delta I_L} \tag{17}$$

$$C_2 = \frac{V_2 (D_2 + D_{eff})}{f\ \Delta V_{C2} R_1} \tag{18}$$

$$C_3 = \frac{V_3 D_1}{f\ \Delta V_{C3} R_2} \tag{19}$$

From these parameters the applied voltage values and duty cycles are calculated as, V_1=25V, D_1=60%, D_2=30%, D_{eff}=10% and,

$$\Delta I_{L_1} = \Delta I_L = 0.5$$

$$\Delta V_{C_1} = \Delta V_{C_2} = \Delta V_{C_3} = 0.5$$

With tolerable ripple values, the calculated values of the components from this analysis are given as,

L_1=3mH C_1=416µf

L=3.08mH C_2=539µf, C_3=462µf

The estimated ripples from simulation

$\Delta I_{L_1} = 0.55,\ \Delta I_L = 0.4.$

4. SIMULATION RESULTS FOR SINGLE-INPUT MULTI-OUTPUT UNIDIRECTIONAL SEPIC CONVERTER

To verify the operation of proposed converter, simulation has been carried out in MATLAB/SIMULINK platform.When the switch is closed, the current through the inductor increases and energy is stored in it.At that time, the capacitor in that circuit discharges and supplies the load. The simulation results of the converter operating in CCM are shown in Figure 6 to 11. The simulation results of the converter operating in CCM are shown in Figure 6. It represents the voltage across switches and capacitors and current through all the inductors connected in PVSC, PVLC1 and PVLC2 of the three port proposed SEPIC converter. Figure 9 to 10 represents the output voltage and output current waveform of load 1&2 respectively. Figure 11 represents the torque and speed waveform of load 2. In this proposed converter load 2 is used as a dynamic load.

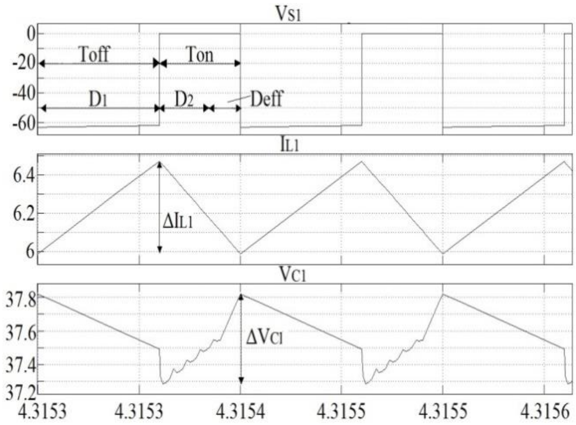

Figure 6. Voltage and current waveforms across S_1 inductor i_{L1} and capacitor C_1 in the proposed converter

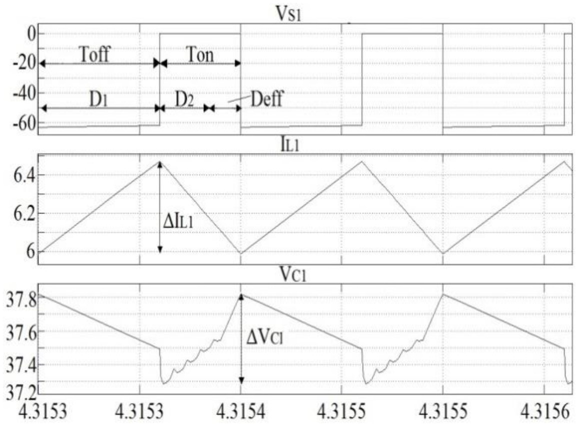

Figure 7. Voltage and current waveforms across S_2 inductor i_{L2} and capacitor C_2 in the proposed converter

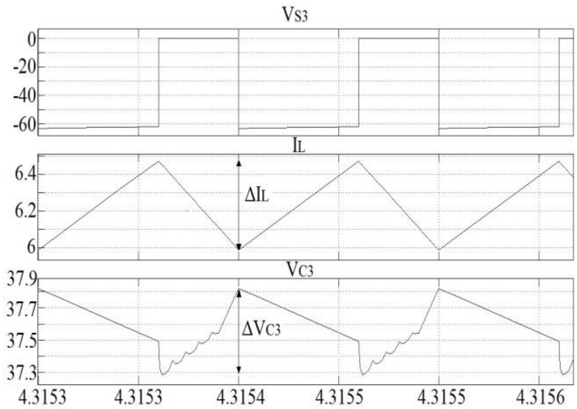

Figure 8. Voltage and current waveforms across S_3 inductor i_L and capacitor C_3 in the proposed converter

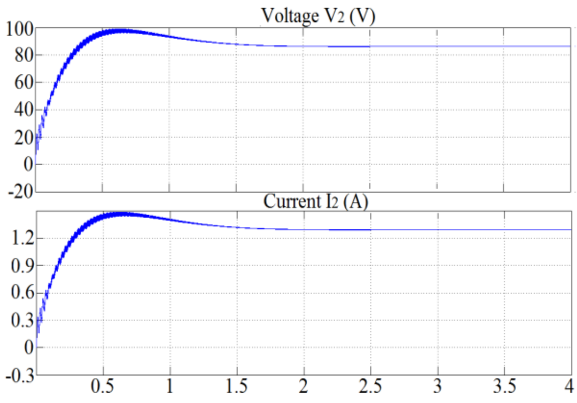

Figure 9. Output voltage and current waveforms of load 1

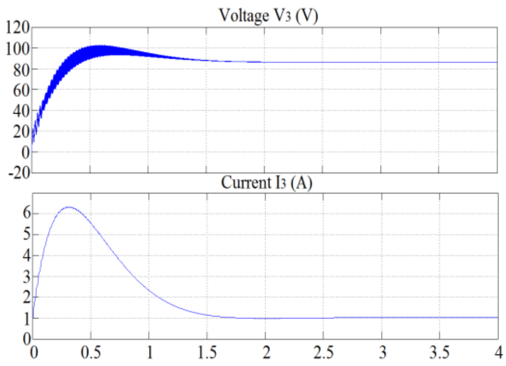

Figure 10. Output voltage and current waveforms of load 2

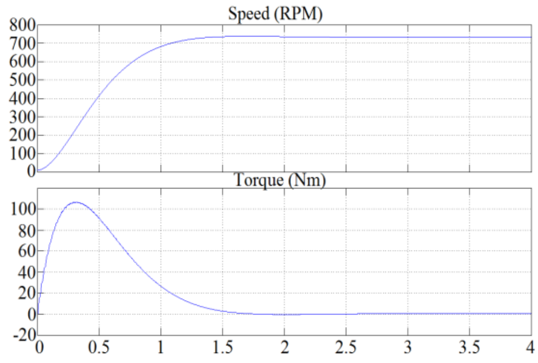

Figure 11. Speed and torque output of load 2

4.1. Hardware Implementation

The Proposed open loop unidirectional topology is verified with a real time hardware setup.The components of the setup are designed as it operates up to a maximum power capacity of 1kW.

The component details used in the circuit are given in Table 1 as follows,

Table 1. Hardware Circuit Component Specifications

Component	Model	Specification
Microcontroller	DSPIC30F2010	28 IC pins 6 PWM channel (21-26) 5V operating voltage 10MHz operating frequency (9-10)
Driver	TLP250	8 pins 12V operation voltage
IGBT	FGA15N120	15A, 1200V
MOSFET	ISA04N60A	1MHz, 600V, 4A

The values of circuit parameters are represented in Table 2 as follows,

Table 2. Circuit Parameter Values

PVSC inductor, L_1	15mH
Common inductor, L	15mH
PVSC1 capacitor, C_1	0.54mF
PVLC1 capacitor, C_2	0.54mF
PVLC2 capacitor, C_3	0.46mF
Switching frequency, f	5000Hz

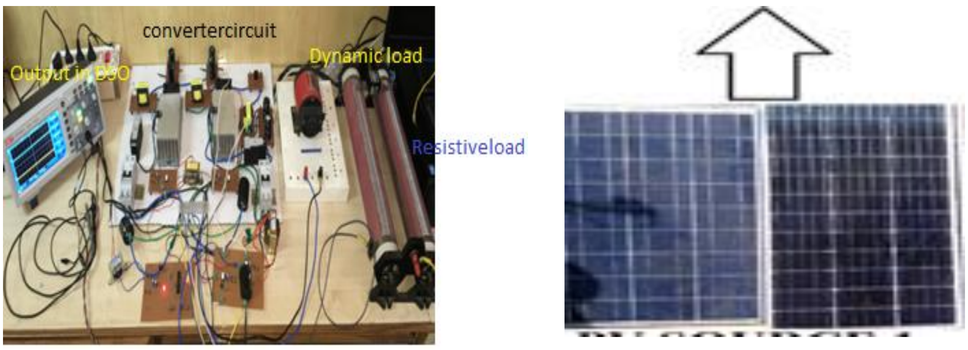

Figure 12. Hardware setup of proposed converter

In this circuit, microcontroller is used for generating switching pulses in continuous current mode of operation. The input voltage to PVSC is V_1=35V. The duty cycle for corresponding switches are D_1=60%, D_2=30% and D_3=10%. A 50W universal motor is given as dynamic load to the unit. With the given input and duty cycle, the calculated value of the output voltages for V_2=85.6V and V_3=86V.

The output of MATLAB simulation of the proposed topology for the similar parameters is approximately V_2=86.66 and V_3=85.66V. The output voltages of the proposed hardware setup for the given input and duty cycle is V_2=85V and V_3=84V. This indicates that for the similar value of parameters, input and the outputs corresponding to mathematical analysis, MATLAB simulation and hardware setup is approximately same.

4.2. Hardware Results and Discussions

Figure 13 represents the input voltage and Figure 14 to 19 depicts the output waveforms across the switches and capacitors.

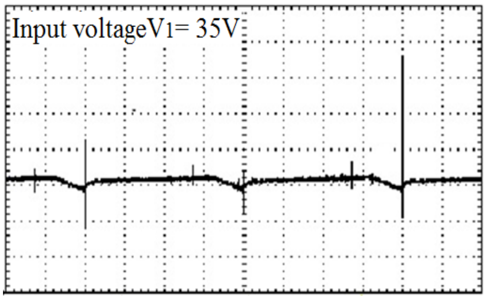

Figure 13. Input voltage V_1

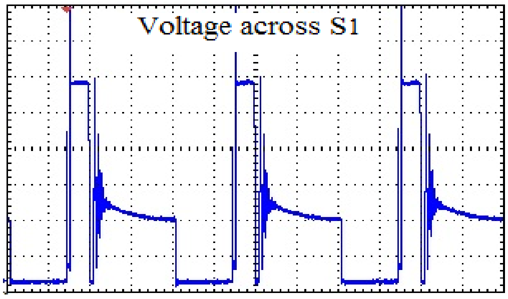

Figure 14. Voltage across switch S_1

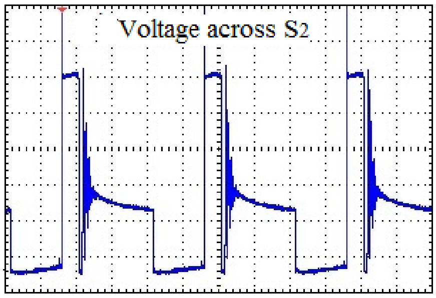

Figure 15. Voltage across switch S_2

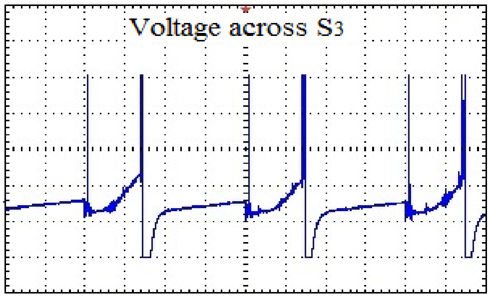

Figure 16. Voltage across switch S_3

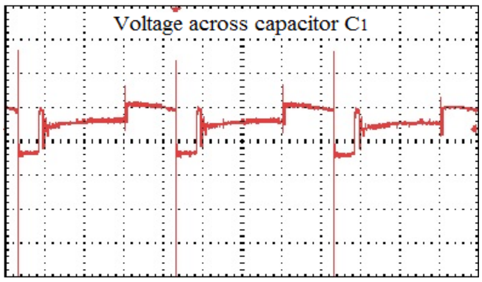

Figure 17. Voltage across capacitor C_1

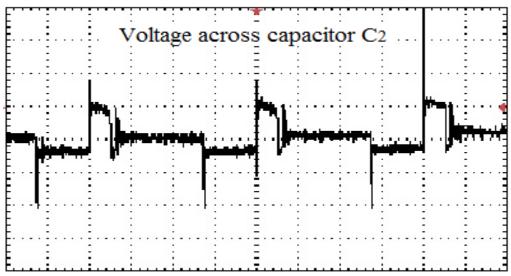

Figure 18. Voltage across capacitor C_2

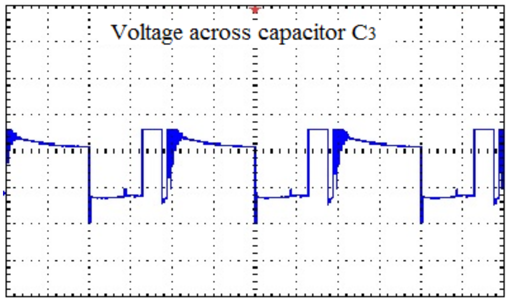

Figure 19. Voltage across C_3

Figure 20 and 21 represents the output voltage waveform for both the loads at PVLC1 and PVLC2

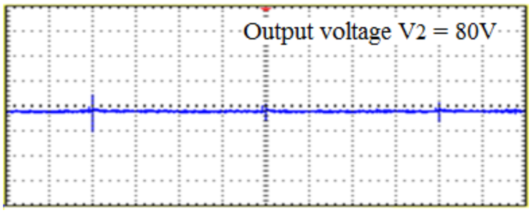

Figure 20. Output voltage of resistive load

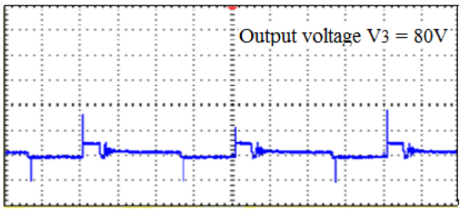

Figure 21. Output voltage of dynamic load

5. CONCLUSION

In this paper the proposed multiport converter is capable of interfacing two outputs by using single voltage source as photovoltaic cell (PV). The operation of proposed converter with single voltage source with a PV is verified.The authentication for the performance and operation of the converter is done with MATLAB simulations and mathematical analysis. The authentication of simulation results and mathematical analysis of the proposed open loop topology have been proved by a real time hardware setup. Input to the hardware setup is provided from solar PV of 35V, and the unit operates with duty cycles of 67%. The output voltage of the hardware unit V_2 and V_3 is 80V, which matches with the output voltage of simulation and mathematical model. Also the modes of operation of the proposed open loop topology have been verified with the hardware results. Performance comparison between the ideal calculation and results obtained from the hardware and simulation are verified.

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