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DUAL INPUT/OUTPUT DC-DC CONVERTER FOR SOLAR PV APPLICATIONS

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Abstract: An inductor-based DC-DC converter with dual input and output (DIDO) is presented in this paper for renewable energy systems. SOC (State of Charge) control for battery and time-sharing control for switches has been proposed for power flow management between battery, solar PV, and standalone DC load. The converter integrates solar and battery sources at the input and provides a constant output for the load. The surplus energy is stored in the battery and can be utilized later in the absence of renewable energy sources. Both the input sources can power up the load individually and simultaneously. The converter operates in several modes depending upon the availability of input sources and load conditions. Sboost is main boost converter switch, and it will operate at both Dual Output Boost Mode (DOBM) and Dual Input Boost Mode (DIBM). The switches and diodes are used to set the battery as an output to store excess solar PV power and used to set battery as an input. The output capacitor and input capacitor are connected across the load and the input terminal respectively to reduce the output voltage and input voltage ripples. The steady state performance of the single stage converter has been explained with the relevant analytical expressions derived along with the characteristics. The simulation of the entire system is simulated by MATLAB- SIMULINK software and the characteristics are presented. A hardware prototype of the proposed system has been fabricated and dsPIC16F887 controller have been implemented.

***Index Terms* - DC-DC power converter, DIDO converter, Batteries, Solar power generation, Boost converter, Photovoltaic power systems.**

I. Introduction

The energy from solar PV is intermittent in nature. In order to operate standalone PV systems reliably, it is necessary to use both battery storage and other renewable energy sources. This can be achieved by many single input/output (dual port) DC-DC converters in parallel or multiport DC-DC converters. The controller maintains a constant DC load voltage and a power flow management system to balance the power flow between solar PV, battery, and stand-alone DC loads. Moreover, the DC-DC converter provides uninterruptible power supply to the standalone load from a battery in both extra and shortage PV power uninterruptable situations by means of the efficient energy storage and energy management systems.

Solar PV Module

Among all the environmental energies, solar energy is the most popular because of its high-power density and availability. Also, the rechargeable battery can provide a very high instantaneous output power. Photovoltaic (PV) cells are used to convert solar energy into electrical energy. Under a certain light intensity, the PV cells' output power depends on the load, and it achieves the highest for a particular load when the PV cells operate at the maximum power point (MPP). When the light intensity changes, the MPP changes accordingly. The power generated by the solar PV module for a given temperature and level of irradiation depends on PV voltage and current drawn by the load. Parameters of the solar PV are stated in table I.

Energy Storage (Battery)

The battery operates as an energy barrier for the harvested solar energy, as well to maintain continuous operation of the system. During times of surplus PV power, it stores excess energy and during times of deficit or absence of PV power, it complements or replaces the solar PV module as the power resource. There are mainly two types of rechargeable batteries use up for stationary power applications – the lead acid battery and the lithium-ion battery. Since lead acid batteries are inexpensive and have less safety issues, it is used for the proposed system.

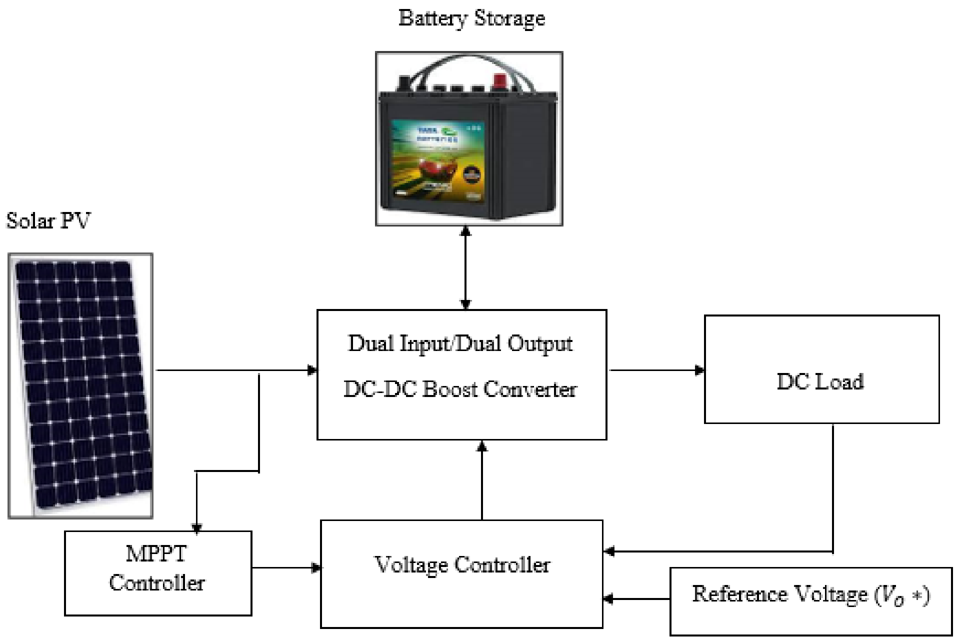

Fig. 1: Block diagram for power flow management system

single-inductor dual-input dual-output (SI-DIDO) dc–dc converter for solar energy harvesting applications that reduces the system cost. It has unsteadied voltage sources as the inputs and generate different regulated output voltages, our converter is powered by hybrid supplies using PV cells and the rechargeable battery. One of the input sources is from the PV cells with an unsteady PV voltage. The PV cells output power would be affected by the converter's equivalent input impedance. The converter requires to generate a voltage at its outputs to power the load, but it must also regulate the PV cells output voltage (i.e., one of its dual inputs) so that it matches the pre-detected MPP to get the maximum power from the PV cells. PV cell output varies depending on environmental and load conditions, such that the power produced by the cells can be larger or smaller than the power consumed by the load. The converter has to manage the energy utilization among its two input sources and two output energy consumers.

TABLE I: Parameters of the solar PV module at temperature 25°c

S. No	Parameters	Values
1	Open Circuit Voltage (V_{OC})	18.23 V
2	Short Circuit Current (I_{SC})	2.13 A
3	Voltage at Pmax (V_{mp})	14.3 V
4	Current at Pmax (I_{mp})	2.0 A
5	Rated Maximum Power (P_{max})	28 W

II. METHODOLOGY AND MODES OF OPERATION

The single stage inductor based dual input/output DC-DC converter (DIDO) used in the proposed power flow management system is shown in **Figure. 2**. The solar PV module is interfaced to the converter by diode Din, which prevents reverse current flow to the module. To reduce the solar PV voltage ripple, a capacitor Cin is connected in parallel to the solar PV module. The switches S2 and diode D2 is used to set the battery as an output to store excess solar PV power. The switch S3 is used to set the battery as an input to supply power to the standalone DC load. The capacitor C_o is connected across the output to reduce the output voltage ripples.

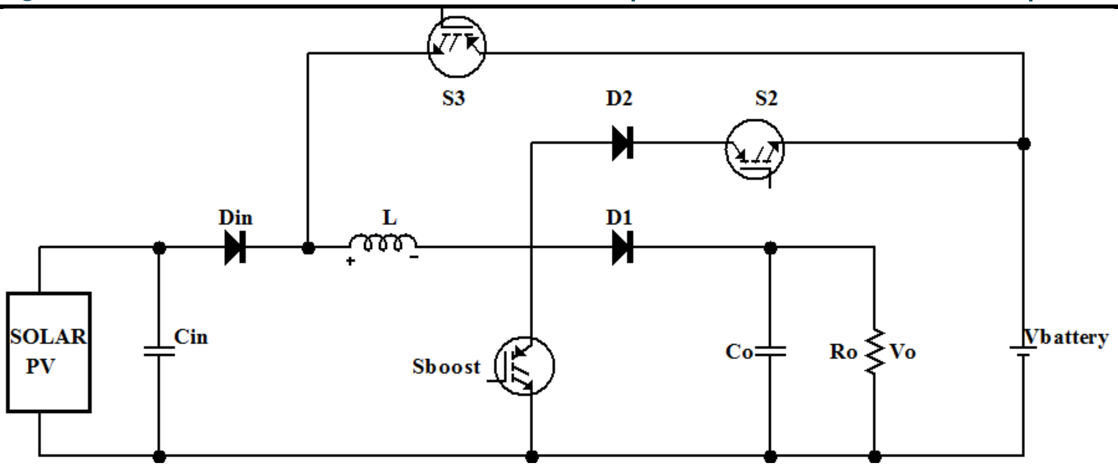

Fig.2: Proposed Single Stage Inductor based Dual input/output Boost DC-DC Converter

Dual output boost mode (DOBM)

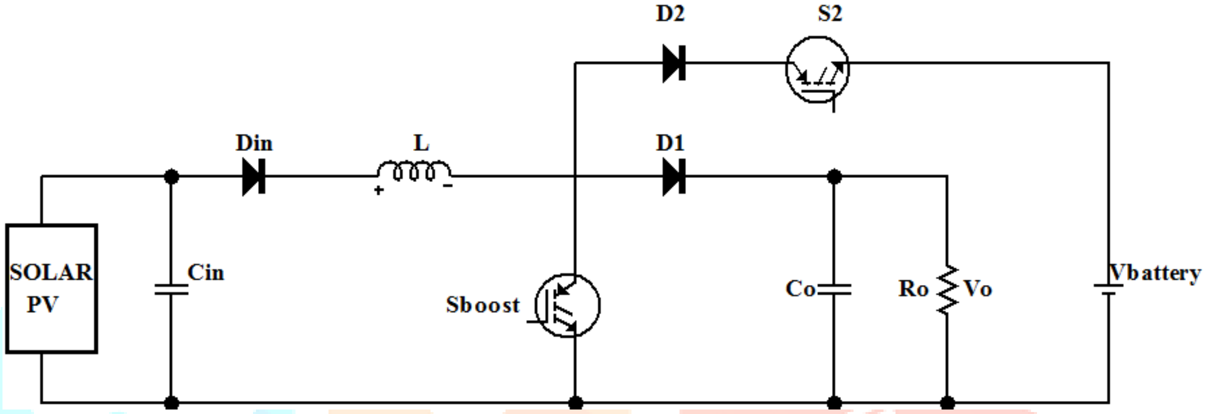

Fig.3: Dual Output Boost Mode

A solar PV module will act as a power source for the battery when DOBM is performed through the switch S2, and the DC load will be powered by the diode D1 during DOBM. The single inductor based dual input/output DC-DC converter has three states as shown in **Figure. 3**.

In the first state, the inductor is charged by power from the solar PV module through switch S_{boost}. In the second state, switch Sboost is turned off and the inductor discharges to the DC load through the diode D1. In the third state, the surplus power is discharged to the battery by turning on the switch S2. Because the voltage required by the standalone DC load is higher than that of the battery, the diode D1 is in reverse bias, which cuts off the standalone DC load.

Dual input boost mode (DIBM)

In the DIBM, the battery and the solar PV module act as input power sources for DC load. The switch S3 sets the battery as an additional input power source. The single inductor based dual input/output DC-DC converter has four circuit states are shown in **Figure. 4**.

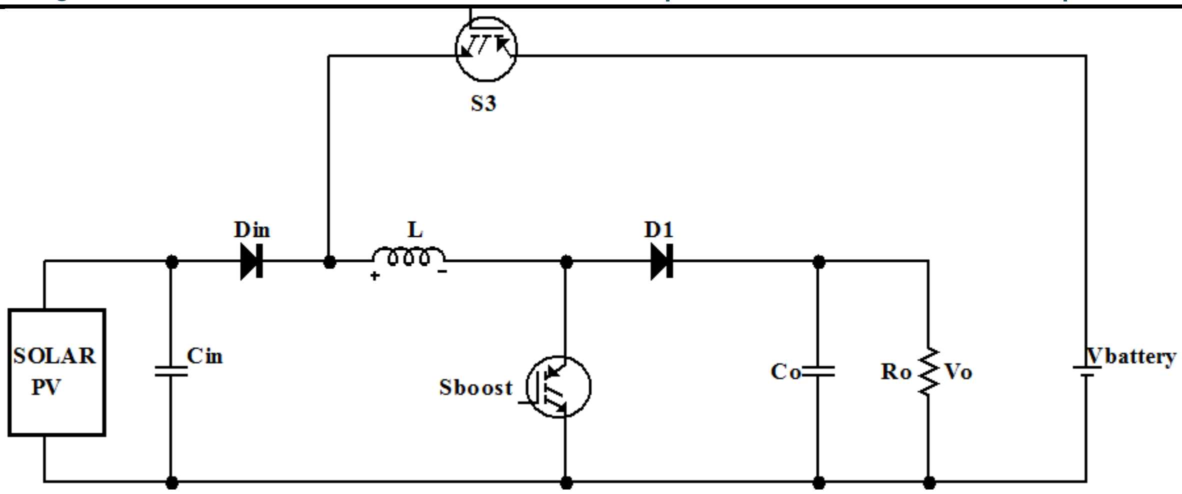

Fig.4: Dual Input Boost Mode

In the first, the inductor is charged by the solar PV module. The switch Sboost is turned on. In the second state, the inductor is charged by the battery. The switch Sboost is turned on. The switch S3 is turned on for the second state to set the battery as the input power source. The diode Din is reverse biased as the battery voltage is higher than the voltage of the solar PV module.

Within the third circuit state, the switch Sboost is turned off and the inductor discharges to the output load. In this state, the battery is utilized as the power source by permitting the switch S3 to remain on. During the fourth circuit state, the switch Sboost is gone off and the inductor discharges to the output. In this state, the switch S3 is turned off and the solar PV module becomes the power source.

III. MODELING AND ANALYSIS

The output current of the solar PV module used in modelling is,

$$I_{PV}= I_L - I_o(e^{\frac{q(V+IR_S)}{nKT}} -1) \qquad (1)$$

I_{PV}=Solar PV current

I_L=inductor current

I_o=load current or output current

q = charge of an electron

K=Boltzmann's constant

n= diode ideality factor

- The required input voltage of the solar PV module used in modelling is,

$$V_{PV}= V_o\, D_{Din}+ V_{bat}\, D_{S2} \qquad (2)$$

V_{PV}= Solar PV voltage

V_o=output voltage

V_{bat}=battery voltage

D_{Din}=duty ratio of diode Din

D_{S2}= duty ratio of switch S2

- With volt second principle, the standalone DC load V_o in DOBM is discovered as,

$$V_o= \frac{V_{PV} - V_{bat}\, D_{S2}}{D_{D1}} \qquad (3)$$

- With volt second principle, the standalone DC load V_o in DIBM is discovered as,

$$V_o = \frac{V_o\, D_{Din} + V_{bat}(D_{Sboost} - D_{S3})}{D_{Sboost}} \quad (4)$$

Were,

D_{Sboost}=duty ratio of Sboost switch

D_{S3}= duty ratio of S3 switch

- The following expressions were implemented for the DOBM to operate the power switches S_{boost} and S_2,

float dobm (d_{MPPT}, d_{volt})

{

$d_{Sboost} = d_{MPPT}$;

$d_{D1} = d_{volt}$;

$d_{S2} = 1 - d_{D1} - d_{Sboost}$;

return(ds2);

}

- The following expressions were implemented for the power switches S_{boost} and S_3, to control the converter in DIBM.

float dibm (d_{MPPT}, d_{volt}))

{

$d_{Sboost} = d_{volt}$;

if ($d_{MPPT} \leq d_{Sboost}$)

{

$d_{Din} = d_{MPPT}$;

}

Else

{

$d_{Din} = d_{Sboost}$;

}

$d_{S3} = \frac{d_{Sboost} - d_{Din}}{D_{Sboost}}$;

return(ds3);

}

IV. RESULTS AND DISCUSSION

A. Simulation Results

Simulation of the converter is performed for the verification of the feasibility. Solar PV array with temperature is 25 constant and irradiance of 300 with boost converter with multiple switches are simulated in MATLAB and resulting waveforms are shown in **Figure. 7**.

The single stage inductor based dual input/output DC-DC converter in the power flow management system was fabricated in **Figure. 5** by using IGBT switches (KGT25N120NDH) rated at 23 A, 100 V and diodes (body diode of FR540N) rated at 23 A. Three 24 V 60 W solar PV module were used as power sources and resistive standalone DC load was used. A 36 V 40 Ah lead acid battery is used as energy storage. The input capacitor C_{in} and DC load capacitor C_o were rated at 100µF and 3600µF respectively. A 100µH toroidal inductor rated at 20 A is used. The converter is switched at 100 Khz. The controller is implemented by using MATLAB/Simulink programming.

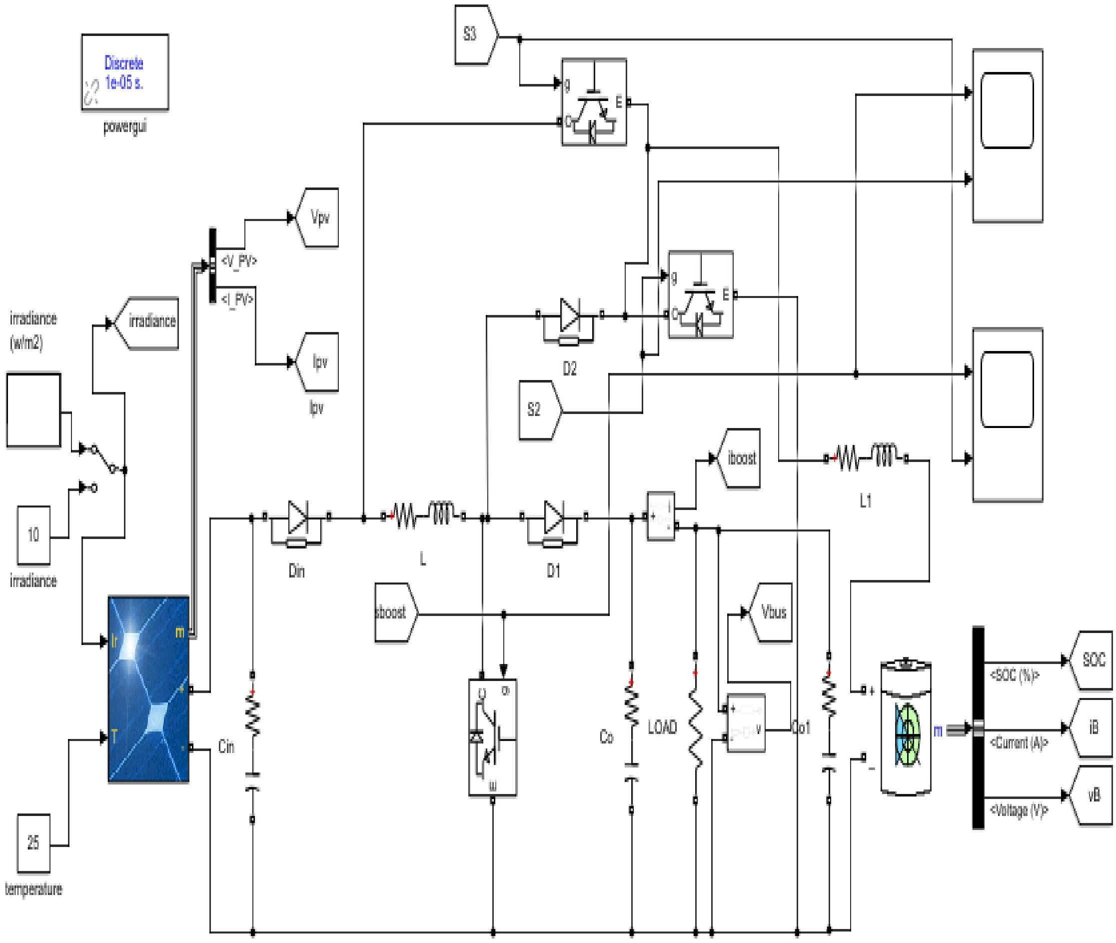

Fig 5: Simulation diagram of single stage inductor based dual I/O DC-DC boost converter

Figure. 6 shows 48 V is taken as reference voltage. Reference voltage is compared with load voltage and Compared voltage is fed to PI controller and then battery reference value is taken as output. Voltage and current of solar PV array is multiplied for obtain the power of solar PV.

Simulation of Gate pulse generation block contains the pulse generator to generate a gate pulse. Battery current and battery reference value is compared to get duty cycle. Duty B is given to pulse generator. If the generated pulse is one, then positive switch(S3) is ON. If gate pulse is not equal to one negative switch(S2) is ON.

Dynamic response of the converter due to increase in solar PV input from 12V to 16V: The converter is operating at DIBM with both solar PV and battery satisfying a standalone DC load demand of 12V. The solar PV input was increased to 16 V. The MPPT controller increases d_{MPPT} to shift the solar PV to the new MPP. The voltage controller increases d_{Volt} as the effective input voltage and it is reduced due to increase in d_{Din}. Due to increase in d_{Din}, dS3 decreases and hence the power drawn from the battery decreases.

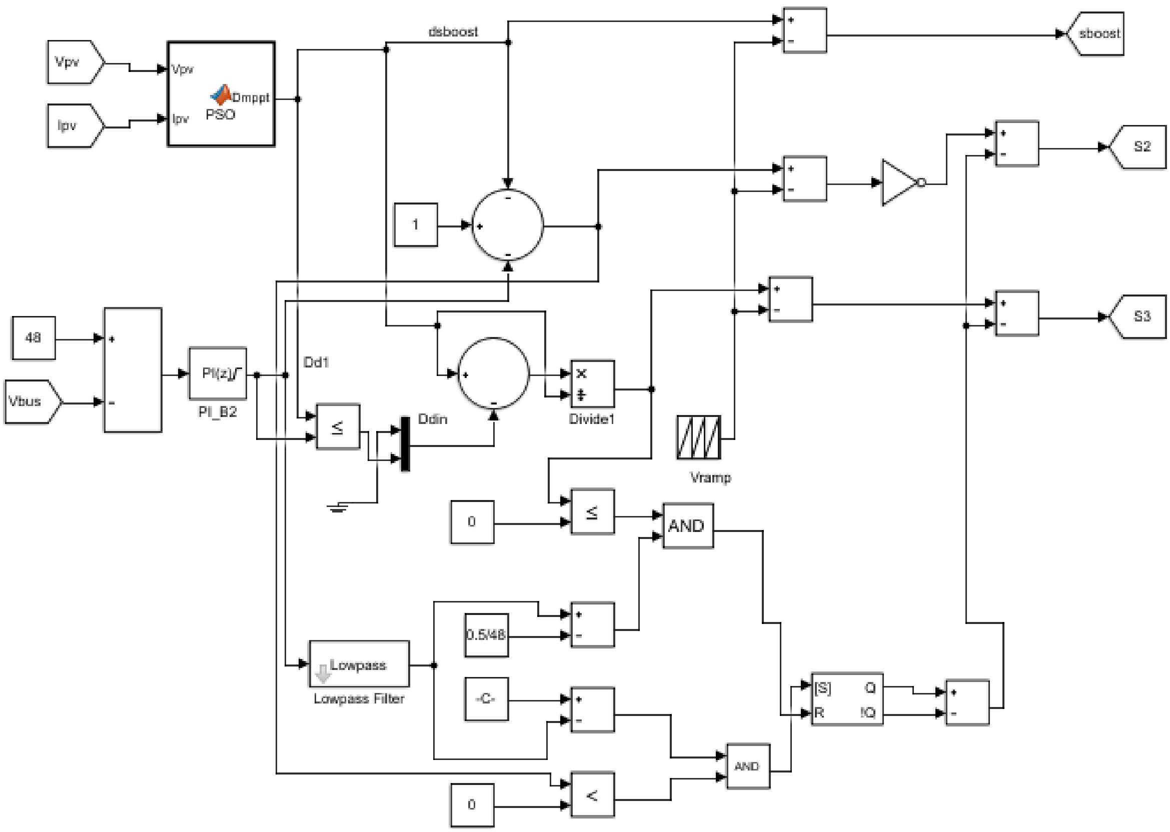

Fig.6: Simulation diagram of control circuit

In the Dual Output Boost Mode, the solar PV module acts as a power source feeding the battery through the switches S_{boost} and S_2 and the DC load through the diode D1. So, the gate pulses taken for the switches S_{boost} and S_2. In the Dual Input Boost Mode, the solar PV module, and the battery acts as a power source feeding through the switches S_{boost} and S_3 and the DC load through the diode D1. So, the gate pulses taken for the switches S_{boost} and S_3.

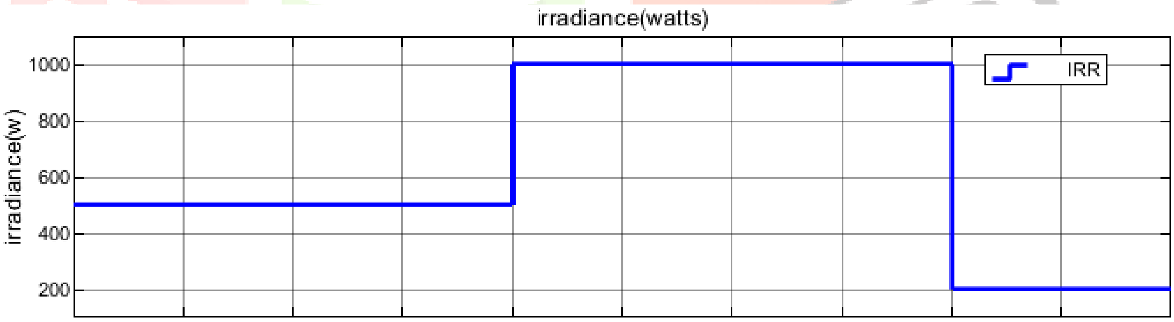

Fig.7.1: Solar PV side Irradiance waveforms

Three different levels of irradiance is given in **Figure 7.1** first irradiance level is 500 and other two levels are 1000 and 200 at temperature is 25°C. Depending on this irradiance solar panel voltage and solar panel current is varied.

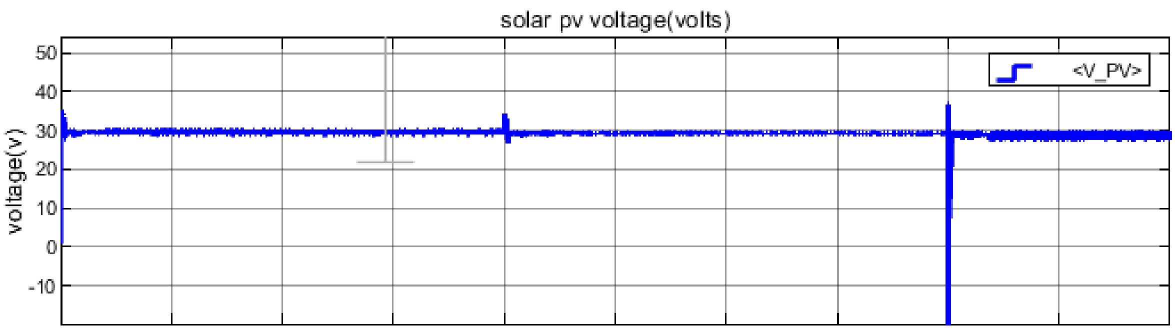

Fig.7.2: Solar PV voltage waveform

Solar PV voltage is shown in **Figure 7.2.** Maximum voltage extracted from solar PV panel is 29 voltages. solar panel current values are varying depending on different levels of irradiance. solar panel current is 8A for 200 irradiances. solar panel currents are 37A and 18A for 1000 and 500 irradiances levels respectively.

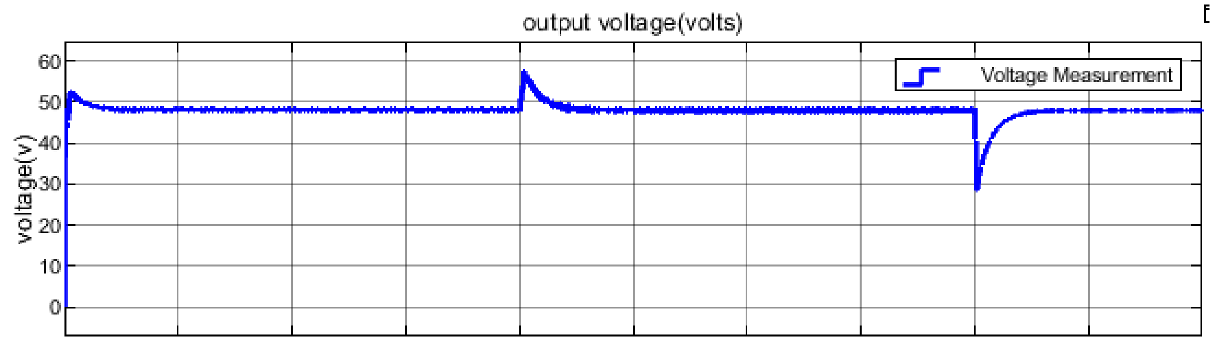

Fig.7.3: Output voltage waveform

Output voltages for different irradiance shown in **Figure 7.3.** Output voltage is constant for different irradiance levels. The boost converter output voltage is 48 V. Output current values are varying depending on different levels of irradiance. Output current is 7A for 200 irradiances. Output currents are 37A and 18A for 1000 and 500 irradiances levels respectively.

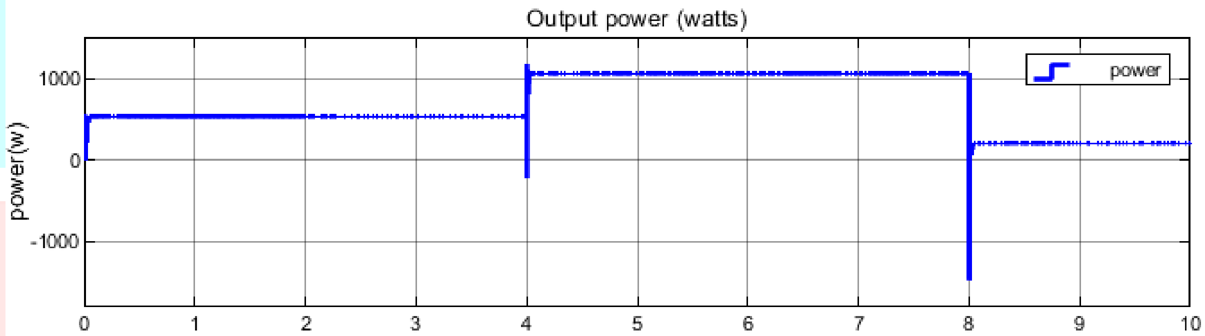

Fig.7.4: Output power waveform

. Output power waveform is shown in **Figure 7.4.** Output power values are varying depending on different levels of irradiance. Output power is 210W for 200 irradiances. Output powers are 990W and 548W for 1000 and 500 irradiances levels respectively.

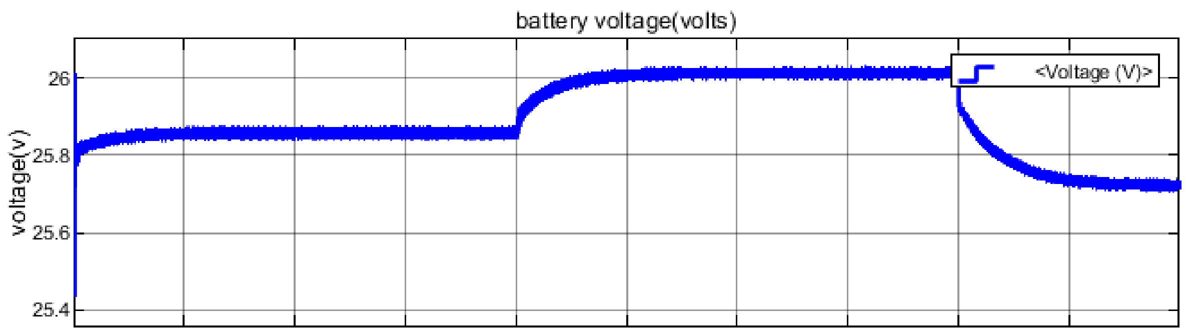

Fig.7.5: Output Battery voltage waveforms

Output battery voltage waveform is shown in **Figure 7.5.** Output battery voltage values are varying depending on battery current. when the battery voltage is increasing, battery is in charging condition. when the battery voltage is decreasing, battery is in discharging condition. Output voltage is 25.7V for 200 irradiances. Output currents are 26V and 25.9V for 1000 and 500 irradiances levels respectively.

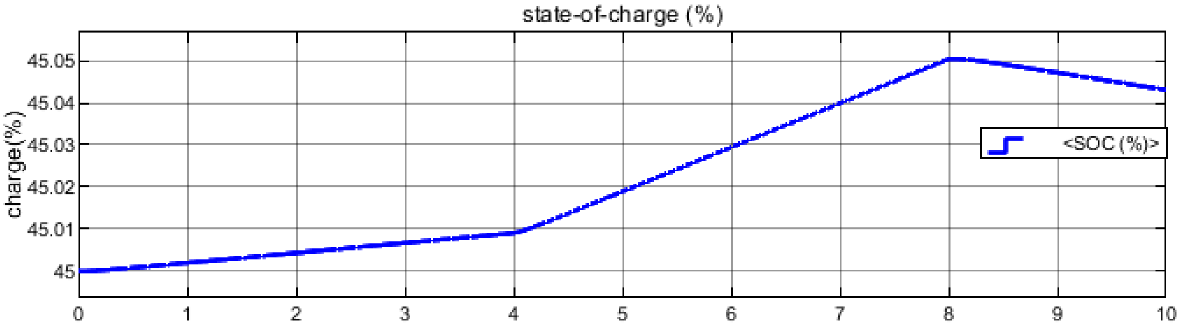

Fig.7.6: State of charge waveform

Battery side State of charge waveform is shown in **Figure 7.6.** State of charge is decreasing when irradiance is decreasing. State of charge is increasing as 45.05 when irradiance is 1000. State of charge is decreases from 45.05 when irradiance is 300.

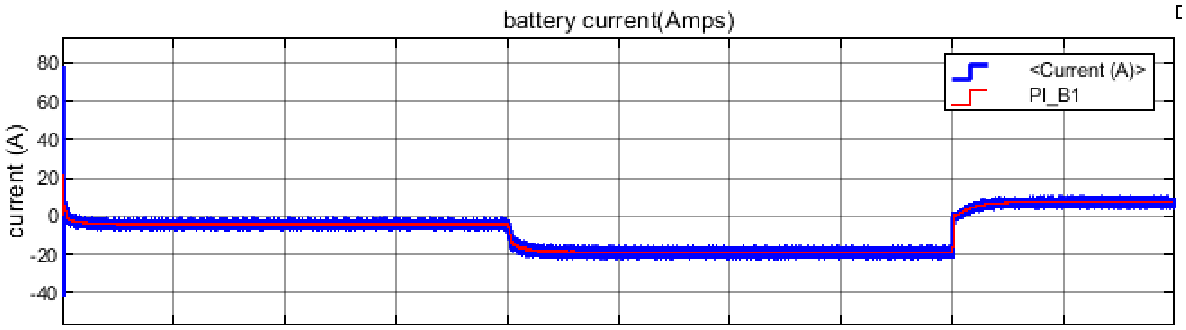

Fig.7.7: Output Battery current waveform

Output battery current waveform is shown in **Figure 7.7.** Output battery current values are varying depending on battery voltage. when the battery current is increasing, battery is in discharging condition. when the battery current is decreasing, battery is in charging condition. Output current is 10A for 200 irradiances. Output currents are -20A and -2A for 1000 and 500 irradiances levels respectively.

The solar PV module is the primary source of power for the standalone DC load. The power generated by the solar PV module for a given temperature and level of irradiation depends on PV voltage and current drawn by the load.

B. Experimental Results

The microcontroller that has been used for this project is from PIC series. CMOS microcontrollers are made of complementary metal oxide semiconductors (CMOS) and use separate instructions and data buses that allow simultaneous access to program and data memory. PIC microcontrollers use separate instruction and data buses providing the first RISC-based microcontroller. The gate driver circuit is an integral part of power electronics systems. Drivers of power semiconductor devices are often used to interface high-power electronics and control circuits.

TABLE II: Components rating

Components	**rating**
Solar PV panel	28 watts
Input capacitor	100 µF
Inductor	5 mH
Output capacitor	100 µF
Battery	Lithium -ion
Switches-MOSFET	3 quantities
Diodes	3 quantities
Microcontroller	dsPIC16f887

Fig.8: Hardware setup for single stage inductor based dual I/O DC-DC boost converter (DIBM)

Change in power management mode from DOBM to DIBM due to power deficit: The power flow management system was initially operating at DOBM at 28 Watts of solar PV. The solar voltage level is 9V, which results in power deficit. The MPPT algorithm adjusts the duty ratio d_{MPPT} (= d_{Sboost}) to reach the new MPP. The deficit results in a fall in v_o. The voltage controller compensates by increasing the duty ratio d_{Volt} (=d_{D1}) to regulate load voltage. During this process, the duty ratio dS2 is gradually reduced to zero, thereby reducing the power flow to the battery to zero. At this point, voltage control is lost. This combined with fall in DC load voltage v_o below V^*_o is used by the mode change control to shift the converter to DIBM. In DIBM, the voltage control signal d_{Volt} is routed to d_{Sboost} and it increases the voltage to V^*_o.

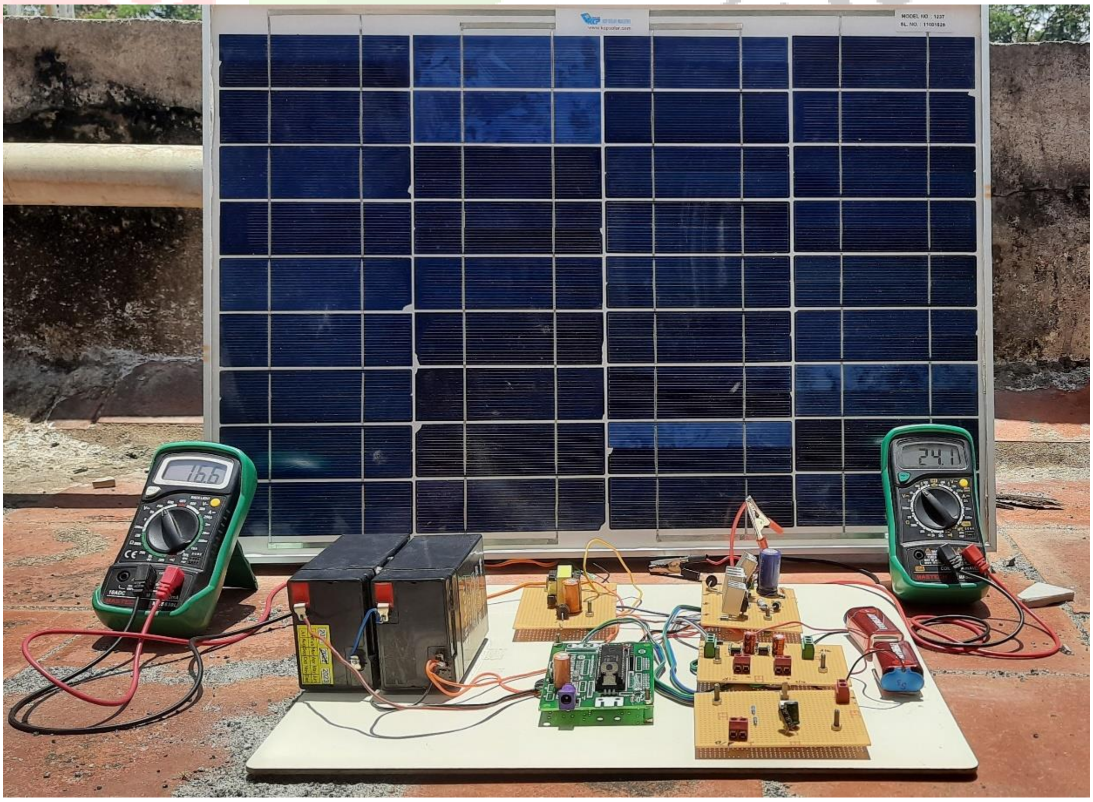

Fig.8: Hardware setup for single stage inductor based dual I/O DC-DC boost converter (DOBM)

Mode change to DOBM due to increase in load voltage from 9V to 16V: The standalone DC load voltage demand was 12V, which is supplied by both solar PV and battery with the converter in DIBM. Figure.8 shows, the standalone DC load voltage demand is reduced to 12 V. Due to surplus power, the voltage increases. The voltage controller reduces d_{Volt}. After it reaches equal to d_{MPPT}, the MPPT control takes over control of switch S_3, which results in loss of voltage control. In that case, the converter is switched from DIBM to DOBM to divert surplus power to the battery bank. The voltage control is now restored, and the standalone DC load voltage is regulated to V^*o.

TABLE III: Measured values from hardware setup

SOLAR PANEL VOLTAGE(V_{ph})	BATTERY VOLTAGE(V_b)	OUTPUT VOLTAGE(Vo)	MODE
8.2	11.7	24	DIBM
10.9	11.8	24	DIBM
11	11.9	24	DIBM
12.6	12.0	24	DOBM
14.2	12.5	24	DOBM
14.9	13.6	24	DOBM

V. CONCLUSION

A single stage inductor-based DC-DC converter capable of accommodating multiple input and output ports is presented for a standalone renewable energy powered system. A time-sharing control and SOC (State of Charge) control has been proposed for power flow management between solar PV, battery, DC loads and extract maximum power from solar PV. Several operational modes of the proposed converter are investigated under different conditions. Simulation studies of the converter have been conducted in MATLAB/Simulink for Dual Input-Dual output mode. The obtained results indicate that the proposed converter provides good response to variations in input voltages due to irregular availability of power from solar (PV) energy systems and the characteristics are presented. Hardware setup for DIDO converter with solar panel and battery as a power source is presented for dual input boost mode and dual output boost mode. Constant output voltage for various modes is obtained. The converter is capable of operating both in surplus and deficit PV power. Hardware results for various irradiations like partial shading, full shading is verified successfully.

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