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Research paper

PV fed Water Pumping System in a Smart Home

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Abstract

This paper proposes renewable energy based water pumping system in a smart home using a bidirectional DC-DC converter. A backup battery is connected in the system for uninterrupted power supply to the water pump. Depending upon source availability, DC-DC converter acts either in boost mode or in buck mode to supply uninterrupted power to the water pump. Using MATLAB/Simulink software, the proposed system is simulated and its performance is analyzed for various operating conditions and the results are furnished in this paper. A small scale laboratory prototype is fabricated and tested for the designed system. Experimental results acquired from the prototype testing correlates with the simulation results validating the feasibility of the proposed water pumping system.

Keywords: *Backup Battery; Bidirectional DC-DC Buck Boost Converter; Rooftop PV Array; Zero Voltage Switching Technique.*

1. Introduction

Advances in home automation technology led researchers to concentrate on smart home system. Smart home systems are reliable, secure, efficient and easily controlled [1]. Uninterrupted supply and easy power flow control with smart power electronic interfaces has made smart home popular [2]. As per the availability of power sources, automated controlling systems utilize power efficiently by controlling the power flow [3, 4]. Invention of fast operating components and smart technologies has made home automation system error free, convenient, reliable and energy efficient compared to conventional controlling system [5].

Energy crises have led researchers to adopt renewable energy sources instead of conventional petroleum products [6]. Renewable energy sources like geothermal energy, wind energy, wave energy and solar energy are used from ages. Among all the renewable energy sources available, photovoltaic (PV) power is accepted by most of the researchers for its easily availability, no poisonous byproduct, easy accessibility, long life time and high efficiency [7]. Net energy taken from the utility grid by the smart home system reduces by integrating PV array. Integration of PV array generated power with smart home system creates a benchmark in smart home research area.

Utilization of PV generated power for water pumping system in a smart home is a promising area of PV application [8]. Among all the dc loads available in a smart home system, water pumping system is commonly used and integration of PV array with water pumping adds advantage to the water pumping system. With change in irradiation and temperature, PV array output power changes [9]. Due to intermittent nature of solar power, a backup battery is connected with the water pumping system for providing uninterrupted power supply [10]. This backup battery operates the main system during low power generation from the PV array [11]. When surplus power is generated, the battery gets charged by the power generated from PV array. For integrating the PV array with smart home system, a bidirectional buck boost converter is connected as a power electronic interface [12].

This paper proposes a smart home system employing a DC-DC converter for feeding the PV array generated power to the water pump. A backup battery is also used in the system to supply the uninterrupted power to the water pump under low irradiation conditions. When excess PV array power is available, backup battery is charged by PV array.

Proposed solar water pumping system mainly consists of PV array, bidirectional buck boost converter, controller, backup battery and water pump. With the availability of solar power, the controller operates the switches of the DC-DC converter either in buck mode or in boost mode for controlling power flow direction. Also a switch is connected in series with the PV array to isolate the system from the PV array during low irradiation condition. At that time, the backup battery acts as a source to the water pumping system. Detailed description of the proposed system is explained in the following section.

2. Proposed water pumping system

The proposed water pumping system consists of PV array, bidirectional DC-DC converter, controller, backup battery and water pump is depicted in Fig.1. The PV array is considered to be a roof top PV array, which generates dc power from solar irradiation. The generated dc power is used to operate the water pump directly as only the speed of the water pump is going to vary depending on irradiation. In smart home, for providing uninterrupted power supply to the water pumping system, a backup battery is also connected which provides power to the proposed system in the absence of solar power. The backup battery is interfaced with the system by using a bidirectional DC-DC buck boost converter. Details regarding different components used in the proposed system are provided in the following sub sections.

2.1. Photovoltaic array

PV array converts solar energy into dc power. With the change in solar irradiance, the output power of the PV array varies. A roof top PV array is considered as the primary source of power for this proposed solar water pumping system. A switch, S_1 is connected in series with the PV array to isolate it from the proposed system during low irradiance condition and the power to water pumping system is supplied by the backup battery.

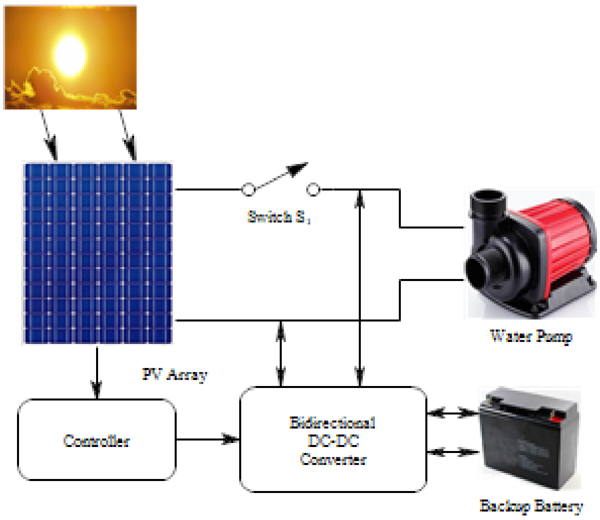

Fig. 1: Block Diagram of the Proposed Water Pumping System.

2.2. Bidirectional buck boost converter

The backup battery is connected to the solar water pumping system using a bidirectional DC-DC converter [13]. Backup battery voltage is considered to be lesser than the water pump operating voltage. Therefore, the converter operates in boost mode for driving the water pump.

When the PV array generates surplus power, the solar pump uses the required amount of the generated power from the PV array and the remaining PV power is fed to the backup battery. During battery charging condition, the bidirectional converter step down the generated PV array voltage to the battery terminal voltage in buck mode. During low solar irradiance, the generated PV power is insufficient to operate the water pump. Thus, in this mode, PV array is isolated from the system using the switch, S_1 and the water pump is operated using the stored energy from the backup battery. The converter step up the battery voltage to match with the water pump terminal voltage in boost mode.

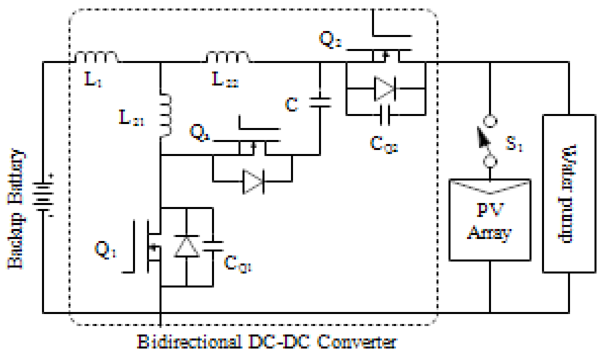

Fig. 2: Schematic Diagram of the Proposed Water Pumping System.

Fig.2 shows the schematic diagram of the proposed water pumping system employing bidirectional converter. This converter uses one auxiliary switch, Q_a and two main switches Q_1 and Q_2. The switches, Q_1 and Q_2 operate with zero voltage switching (ZVS) technique. Detailed explanation of different modes of operation of bidirectional DC-DC converter is given in literature [13].

2.3. Controller

The controller used in this proposed system regulates the operation of switches in the bidirectional DC-DC converter. During low irradiation conditions, PV array current is sensed and if its value is less than the reference value, switch, S_1 is turned off isolating the PV array from the system and vice versa during high irradiation, connecting the PV array to the system by turning on the switch, S_1. During low irradiation conditions, the DC-DC bidirectional converter operates in boost mode for feeding the power from the backup battery to water pump with switch, Q_2 turned off. Battery voltage, V_b is boosted to the water pump terminal voltage, V_L and is fed to the water pump. The gate pulse for switch, Q_1 is generated with the duty cycle as per equation (1).

$$V_L = \frac{V_b}{1-d_{Q1}} \tag{1}$$

Where, d_{Q1} = duty cycle of the gate pulse, V_{gQ1} during boost mode.

During higher irradiation conditions, the PV array generated power is used to operate the water pump and the excess power is fed to the backup battery simultaneously. Hence, in this mode, bidirectional DC-DC converter operates in buck mode for feeding power from PV array to backup battery with switch, Q_1 turned off. The gate pulse for switch Q_2 is generated with duty cycle calculated as per equation (2).

$$V_b = d_{Q2} * V_{PV} \tag{2}$$

Where, d_{Q2} = duty cycle of the gate pulse, V_{gQ2} during buck mode.

In both modes, gate pulse for the auxiliary switch, Q_a is generated with duty cycle of 10% for enabling the zero voltage switching (ZVS) conditions in order to avoid the switching losses [13]. The proposed system is simulated in MATLAB/Simulink software and the results are presented in the following section.

3. Simulation studies and results

Fig.3 shows the simulation diagram of proposed water pumping system. PV array is modelled using the classical equations of solar cells [14]. The PV array comprises of two series connected PV panels with the per panel open circuit voltage and short circuit current of 35.07 V & 6.48 A respectively.

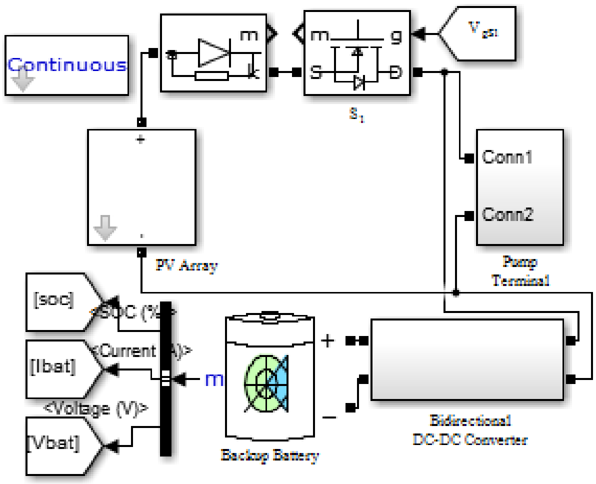

Fig. 3: Simulation Diagram of the Proposed Water Pumping System.

A lead acid battery of nominal voltage 36 V & capacity 100 Ah is considered as the backup battery in the proposed system. The initial state of charge of the battery is considered as 50 %. The battery model available in the library of MATLAB/Simulink is used for simulation.

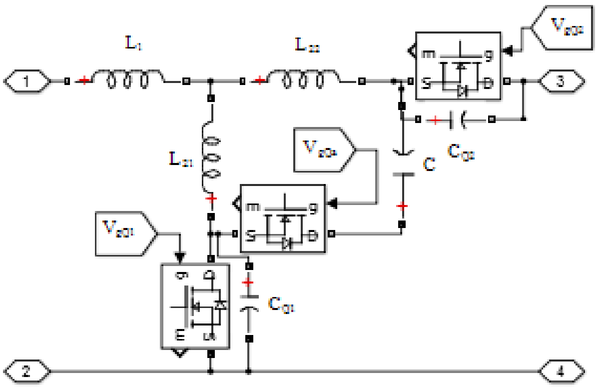

Fig. 4: Simulation Diagram of Bidirectional DC-DC Converter.

Simulation model of the bidirectional buck boost converter is constructed using inductors L_1, L_{21} and L_{22}, capacitor C, and MOSFET switches Q_1, Q_a & Q_2 as shown in Fig.4. The value of inductor, L_1 is 500 µH and two resonant inductors, L_{21} & L_{22} is 1.44 µH each and the capacitor is 44 nF which are designed as per formulae presented in literature [13].

The controller is constructed using pulse generators and selector switch from Simulink library as shown in Fig.5. In boost mode, the PV array is isolated from the system using the switch S_1. The stored energy in the backup battery operates the water pump. In this mode, switches Q_1 and Q_a operates with a duty cycle of 40 % and 10 % respectively and switch, Q_2 remains in off state. Gate pulses for switches during boost mode are shown in Fig.6 (a). In buck mode, the PV array is connected to the proposed water pumping system by closing the switch, S_1. During this mode, switches, Q_2 and Q_a operate with a duty cycle of 60 % and 10 % respectively and switch Q_1 remains in off state as shown in Fig.6 (b).

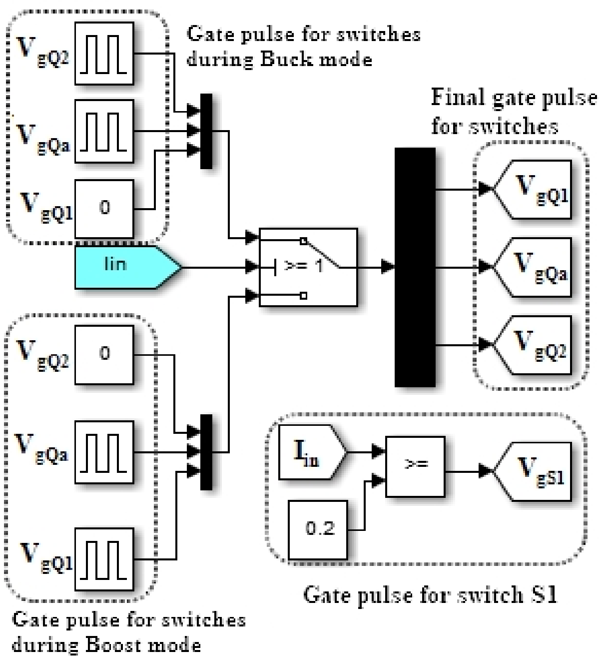

Fig. 5: Simulation Diagram of the Voltage Controller.

In order to observe the dynamic response of the system, it is operated in boost mode from 0 s to 0.3 s and in buck mode from 0.3 s to 0.7 s and the simulation results are shown in Fig.7. During boost mode, PV array is isolated from the system by turning off the switch, S_1 which is indicated by the PV array voltage, V_{PV} being equal to its open circuit voltage, V_{OC} of 70 V and PV array current, I_{PV} being equal to zero as shown in Fig.7 (a) & 7(b) respectively.

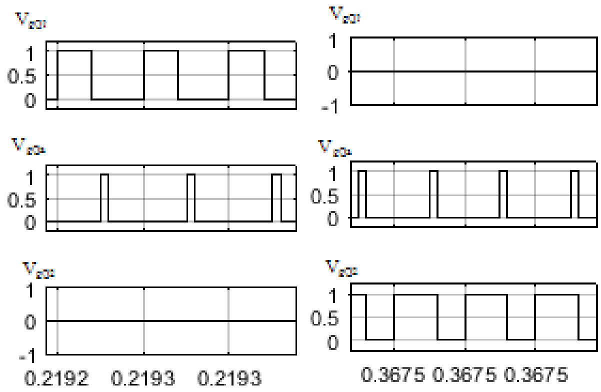

Fig. 6: Gate Pulses for Switches during (a) Boost Mode, (b) Buck Mode.

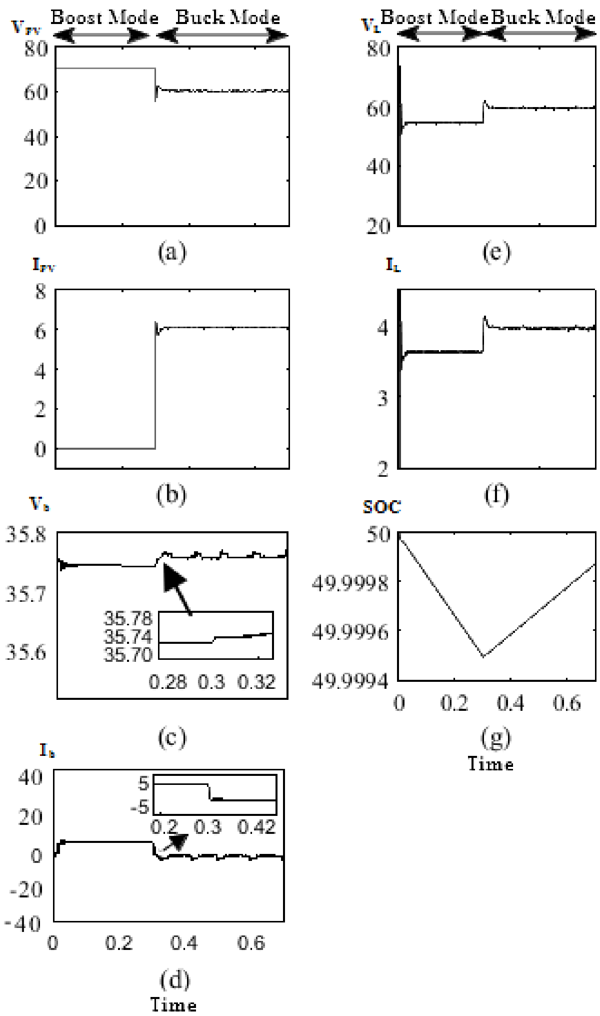

Fig. 7: Simulation Waveform of Proposed Water Pumping System (a) PV Array Voltage (b) PV Array Current (c) Backup Battery Voltage (d) Backup Battery Current (e) Water Pump Terminal Voltage (f) Water Pump Terminal Current (g) Battery SOC.

Fig.7 (c) & 7 (e) shows that the battery voltage, V_b of 35.7 V is increased to 53.3 V to drive the water pump and their corresponding currents are of 5.4 A and 3.6 A respectively are shown in Fig.7 (d) & 7 (f). Also decrease in battery SOC shown in Fig.7 (g) indicates the discharging of battery in this mode.

During buck mode, switch, S_1 is on and PV array power of 366 W generated at an irradiation of 770 W/m^2 is connected to the system. In this mode, approximately 243 W of PV power is utilized to drive the water pump and the remaining 110 W power is used to charge the backup battery through the bidirectional converter with 90% system efficiency. Fig.7 (a) & 7(c) shows that the PV array voltage, V_{PV} of 62.2 V is step down to 35.7 V by the bidirectional DC-DC converter to charge the battery in this mode. Also, the increase in battery SOC and negative battery current of 3.08 A indicates the charging of battery as shown in Fig.7 (g) & 7(d). A small scale laboratory prototype is designed and fabricated to justify the system behaviour and observed results are presented in the following section.

4. Experimental investigation of the proposed system

A hardware prototype of the bidirectional converter is fabricated in the laboratory using the components specified in Table 1 and tested in boost and buck mode separately and the results obtained in experimentation are shown in this section. Fig.8 shows the experimental test bench of the proposed system.

Table 1: Components Used for Hardware Prototype Fabrication

Sl. No.	Components	Specification
1	MOSFET, IRF 250N	100 V, 30 A
2	Driver, TLP 250	15 V, 0.01 A
3	Capacitor	44 nF, 100 V
4	Inductor	500 µH, 10 A
5	Inductor	1.44 µH, 10 A
6	Microcontroller, p18f45k20	-

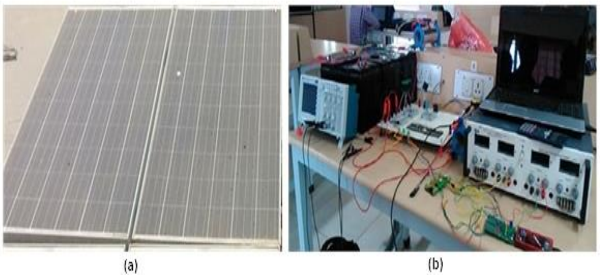

Fig. 8: Photograph of (a) PV Array and (b) Experimental Test Bench.

In boost mode, conventional dc supply of 44 W is connected in battery side to drive approximately 40 W resistive load connected at the water pump terminal/high voltage side of the bidirectional DC-DC converter and the gate pulses of 50 kHz switching frequency is provided to switches Q_1 and Q_a with the duty cycle of 47 % & 10 % respectively as shown in Fig.9. The input voltage, V_b of 32.1 V is boosted to 58.4 V to drive the load as shown in Fig.10 (a) & 10 (b).The waveforms of input & output voltage and current in boost mode is shown in Fig.10.

In buck mode, 54 W of PV array power is used to drive the load of approximately 28 W connected in the water pump terminal and the remaining 26 W of PV array power is fed to the another load of 24 W through the bidirectional DC-DC converter. The switches, Q_2 & Q_a are provided with the 50 kHz gate pulses of duty cycle 37.1% & 9.8 % respectively as shown in Fig.11. The waveforms of input & output voltage and current in this mode are provided in Fig.12 & 13 and it depicts that, PV array voltage of 60.5 V is fed directly to load connected in water pump terminal.

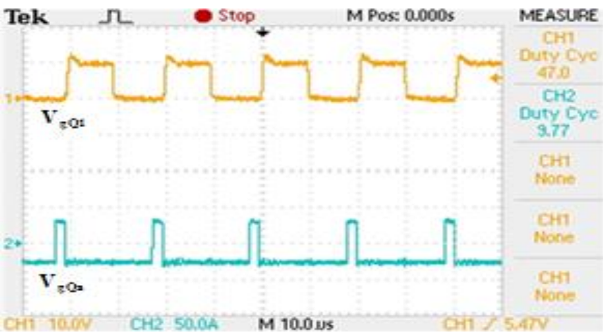

Fig. 9: Waveforms of Gate Pulses for the Switches Q_1 and Q_a in Boost Mode.

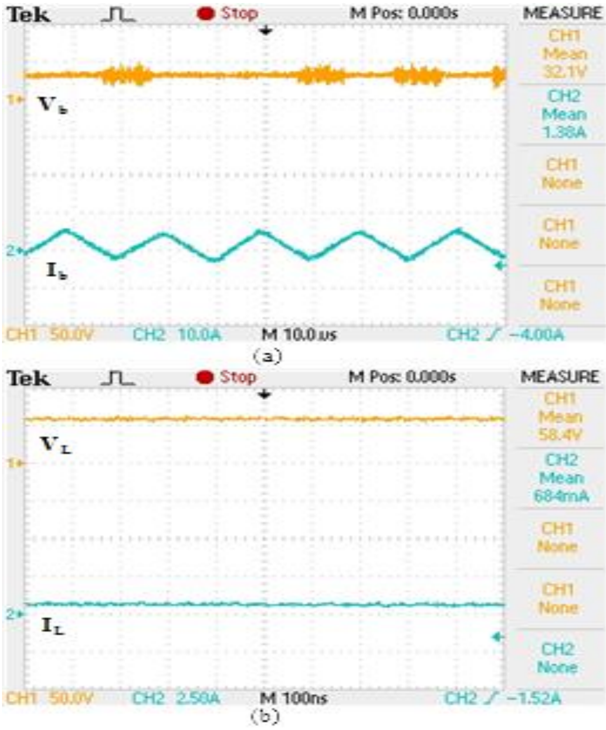

Fig. 10: Waveforms of (a) Battery Side Terminal Voltage & Current and (b) Water Pump Terminal Voltage & Current in Boost Mode.

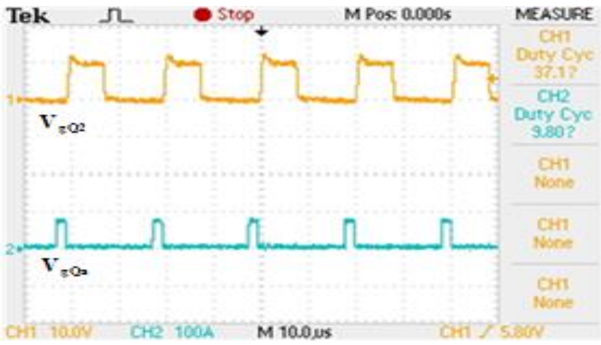

Fig. 11: Waveforms of Gate Pulses for Switches Q_2 & Q_a in Buck Mode.

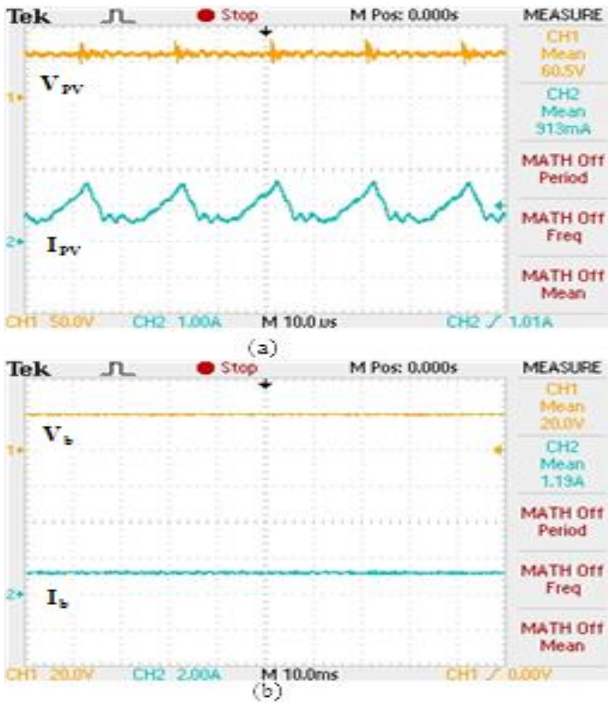

Fig. 12: Waveforms of (a) PV Array Voltage & Current, (b) Input Voltage & Input Current of Bidirectional Converter in Buck Mode.

Also, the PV array voltage of 60.5 V is bucked to 20 V and fed to the load in the battery terminal. From the experimentation results, efficiency of the bidirectional DC-DC converter is found to be approximately 90 % & 95 % in boost mode and buck mode respectively. From the simulation and experimentation of the proposed system, it is evident that, the results are well correlated with each other.

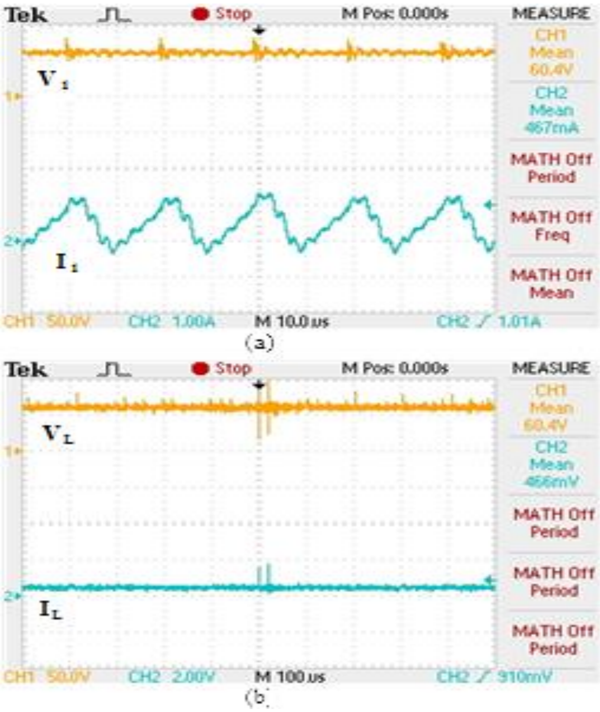

Fig. 13: Waveforms of (a) Voltage and Current at Battery Terminal (b) Voltage & Current at Water Pump Terminal in Buck Mode.

5. Conclusion

A PV fed water pumping system employing bidirectional buck boost converter with backup battery facility in a smart home is proposed in this paper. Irrespective of change in PV array power, the water pump is supplied with the uninterrupted power either by PV array or backup battery. The backup battery gets charged by the surplus PV array power using bidirectional converter operating in buck mode and discharges in boost mode to drive the load during low irradiance condition. The proposed system is a closed loop system which responds automatically to the variation in irradiation condition of PV array. Thus, autonomy operation of this system makes it smarter compared to the existing conventional systems. Simulation of the proposed system is carried out in MATLAB/Simulink software. The experimental prototype of the converter is fabricated and investigated in laboratory. Similarity of hardware result with the simulation result validates the efficacy of the proposed system.

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