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A Solar Powered Water Pumping System with Efficient Storage and Energy Management

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***Abstract*— This paper presents a standalone solar powered water pumping system with efficient storage and energy management. A single switch DC-DC converter feeding a dc water pump is fed by a photovoltaic (PV) cell. The converter is formed by combining a buck converter with a buck-boost converter. A battery is provided as a storage element as well as to maintain a steady dc-link voltage. The battery is protected from overcharging and over discharging for better and efficient energy management. With the Single-Switch Converter (SSC) topology, the converter is able to perform three tasks simultaneously, namely, Maximum Power Point Tracking (MPPT), battery charging, and driving the pump at constant flow rate. To verify the performance of this topology, a software simulation model is developed in MATLAB/Simulink.**

***Index Terms*— Battery, Maximum Power Point Tracking (MPPT), Photovoltaic (PV), Variable frequency control.**

I. INTRODUCTION

With the reserve of fossil fuels diminishing and rise in the global temperature, the need to look for sustainable energy resources has become indispensable. The sustainable energy not only reduces the consumption of fossil fuels but also prevents the rising temperature of the earth besides diminishing the various pollutants emitted by it [1].

Solar energy is clean, renewable and plentiful in the nature and the energy needs and costs have increased in recent years. But the output power from the photovoltaic (PV) system fluctuates under varying temperature and irradiation. So certain methods are to be adopted to harness the maximum power from the PV. This problem has been solved by the introduction of various Maximum Power Point Tracking (MPPT) methods [2]. MPPT techniques help in faster tracking of photovoltaic panel MPP which increases its efficiency.

Commonly used control algorithm is the Perturb and Observe (P & O) method and the Incremental Conductance (INC) algorithm [3], [4]. But these techniques have got some disadvantages along with the various advantages. Under varying atmospheric conditions, the power output tends to oscillate. So an efficient method should be adopted for the tracking of maximum power. A constant voltage (CV) method of MPPT is adopted in this project. The CV method needs the measurement of the PV array voltage V_{PV}.

The conventional topology uses a cascaded converter approach in which converters are combined to perform the task [5]. In such cases, the power loss is more due to repeated power processing as the energy flows from one stage to another. Also, a high number of power switches increases the converter cost. Moreover, the increased number of switches and its control circuitry makes the system more complex.

Due to the problems associated with cascaded converters, Single Switch Converter (SSC) topologies are developed [6]. Again the high voltage stress associated with this single switch as a result of sharing the same switch and lack of voltage control on the dc-link capacitor creates a new problem. A battery which serves as a storage element as well as to provide a constant dc link voltage is a solution to this problem.

Reference [4] shows the basic details of PV cell, PV module, PV array and their modeling are studied. Also, the behavior of PV modules at varying environmental conditions like solar irradiation and temperature are studied. A simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the solar energy that hits on the solar cell. The diode determines the Current Vs Voltage (I-V) characteristics of the solar cell.

Another challenge regarding the PV systems is the unavailability of power during night time and cloudy weather conditions. So, a storage element is necessary in such systems which can provide power to the load in the absence of PV power. In order to increase the life of the battery used, it need to be prevented from overcharging as well as over discharging.

In this paper, we propose a standalone DC-DC converter system with a single switch mainly for water pumping applications. The main objectives are maximum power point tracking, battery charging and output voltage regulation.

II. PROPOSED SYSTEM

The basic block diagram of the stand-alone PV-battery-powered water pumping system is shown in fig. 1. The PV module, which is providing the source power for the system, converts the solar energy falling on its surface to electrical energy. The DC-DC converter is formed by interleaving a buck converter with a buck-boost converter. In the front end, the buck converter performs the maximum power point tracking and in the rear end, the buck-boost converter regulates the output voltage. A battery is provided which stores energy and discharges its energy when the PV output power is not sufficient to drive the load.

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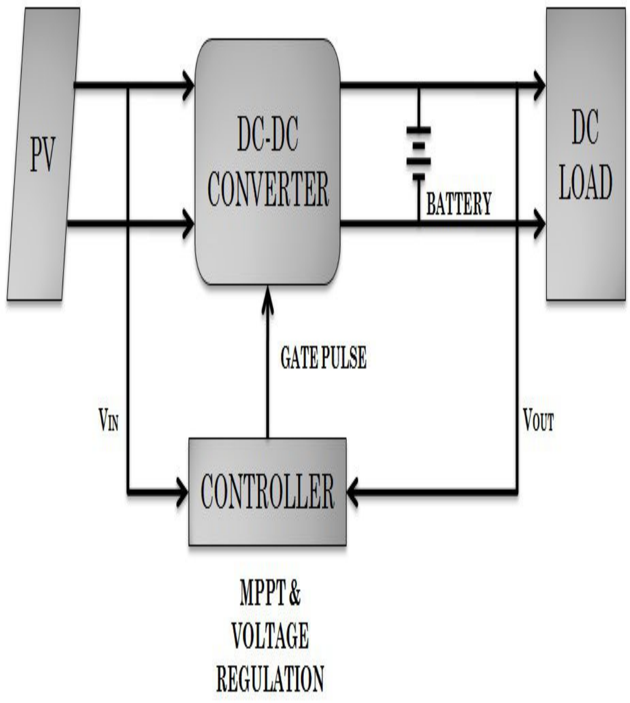

Fig. 1 Basic block diagram

A. Circuit Description

The proposed converter, shown in fig. 2 is derived through the integration of a boost converter into a buck converter. It consists of an input inductor L1 for battery charging and MPPT, a lead-acid battery as a storage element, capacitor C1 for absorbing the ac current ripple of the battery, output inductor L2 to supply the load, an output capacitor C2, dc motor pump as a load, four diodes (D1 to D4) and switch S which provides the current path during ON state of the switch.

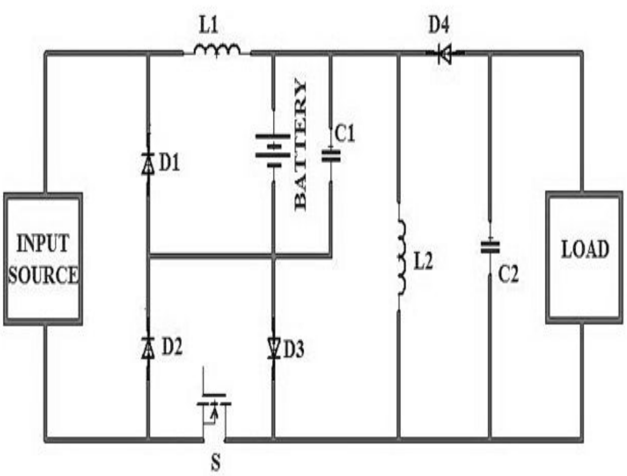

Fig. 2 Circuit diagram

B. Battery

The development of efficient power storage systems with high lifespan is essential for photovoltaic to become a stable mainstay of electricity – unaffected by the daily, seasonal and weather-related fluctuations in solar power generation.

When the power output from the PV is insufficient or unavailable, the battery supplies the load. A 12V rechargeable lead-acid battery is used. Battery stores energy in it when the PV power is more than required by the load and supplies energy to the load when PV power is insufficient.

The life span of the battery is yet another major concern. The battery is protected from the overcharging as well as over discharging. When the battery is in the discharging mode and the battery voltage reaches a minimum set value, the pump is turned off. Hence, the battery is protected from over discharging. Similarly, when the battery voltage reaches a set maximum value, it is controlled to protect the battery from overcharging.

C. Output Voltage Regulation

The second stage buck-boost converter performs the output voltage regulation by duty ratio control method. The load output voltage is sensed and is compared with the constant value, here it is 24V. The error signal generated is given to a Proportional Integral (PI) controller which adjusts the duty ratio. It is then compared with the ramp signal to produce the gate pulses. The output voltage is expressed as

$$V_O / V_D = D / (1 - D) \quad (1)$$

Thus, the output voltage regulation can be realized by adjusting the duty cycle of the switch with the output voltage feedback.

D. MPPT Control

The front end buck converter performs the MPPT using variable frequency control method. To achieve the pulse frequency modulation control, it is necessary to maintain two inductors in different conduction modes. The switching frequency has to stay within an upper bound and a lower bound to keep L1 in Discontinuous Mode (DCM) and L2 in Continuous Mode (CCM).

In this project, a constant voltage method of MPP tracking method is used to maintain the input operation point at or near the MPP. It provides a relatively simple and low cost approach for MPPT and shows better efficiency at PV cell temperatures. In this method, the PV panel voltage is regulated by comparing it with a reference voltage, V_{REF}, which is close to the MPP voltage, V_{MPP}.

The error signal obtained after comparing the PV panel voltage with the reference voltage is fed to a PI controller and it is tuned to obtain frequency signal which is then used to generate the ramp signal. This ramp signal is then compared with the fixed duty signal to produce the PWM pulses for triggering the switch. Thus the MPPT control is achieved and the PV panel used in this experiment is able to provide maximum power at 16.8V V_{MPP}.

III. Simulation Results

The Simulations are done in MATLAB SIMULINK Software. The MATLAB model of PV panel taking irradiation, operating temperature and module voltage as input is shown in fig. 3.

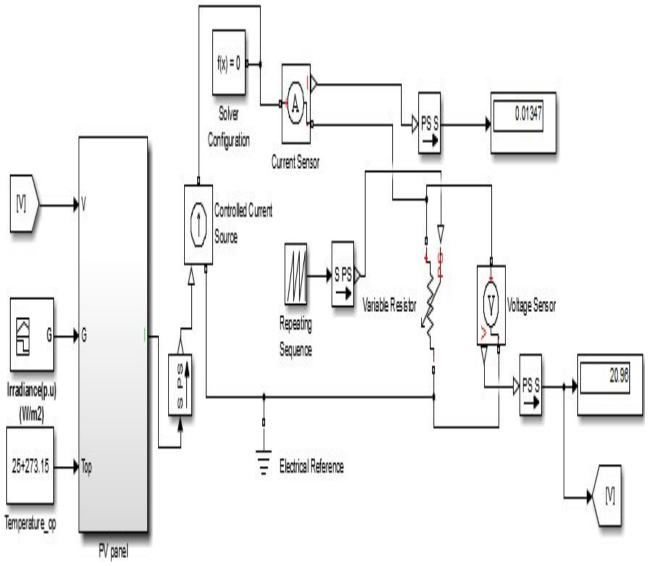

Fig. 3 PV MATLAB model

The I-V and P-V characteristic curves at different irradiation levels are shown in fig. 4 and fig. 5 respectively. Here the irradiation varies as 1000 W/m^2, 800 W/m^2 and 600 W/m^2. The output current decreases as the solar irradiance decreases.

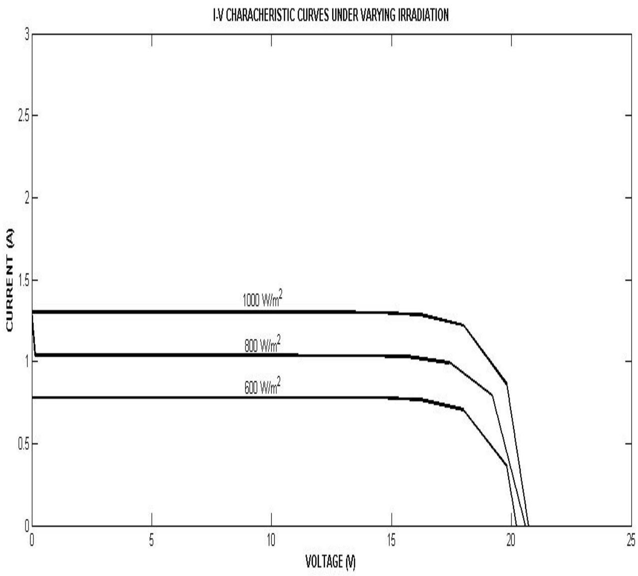

Fig. 4 I-V characteristic curves

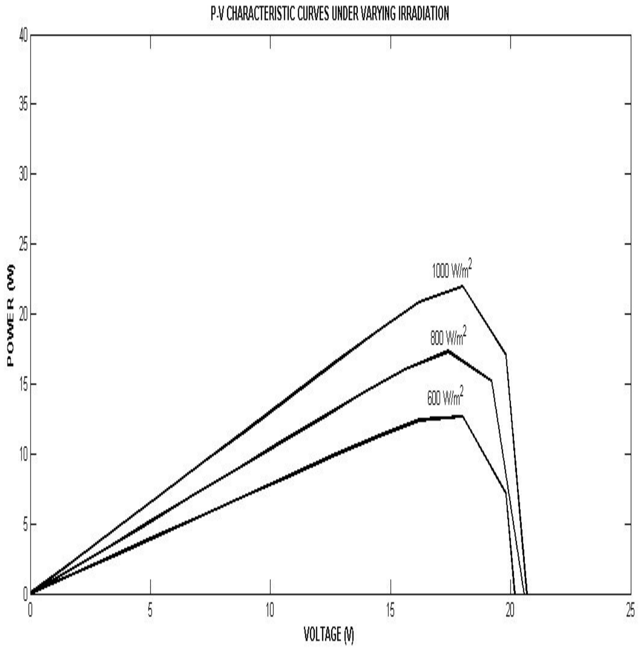

Fig. 5 P-V characteristic curves

The MATLAB circuitry of the proposed system is shown in fig. 6. All the five modes are simulated. Simulation results of Mode C are shown in the following waveforms. In this mode, the maximum power from the PV module is not enough to supply the load. This usually happens when the PV cells are shaded or under cloudy weather. The battery provides the extra energy required to the load. Here, a load power requirement of 26W is considered.

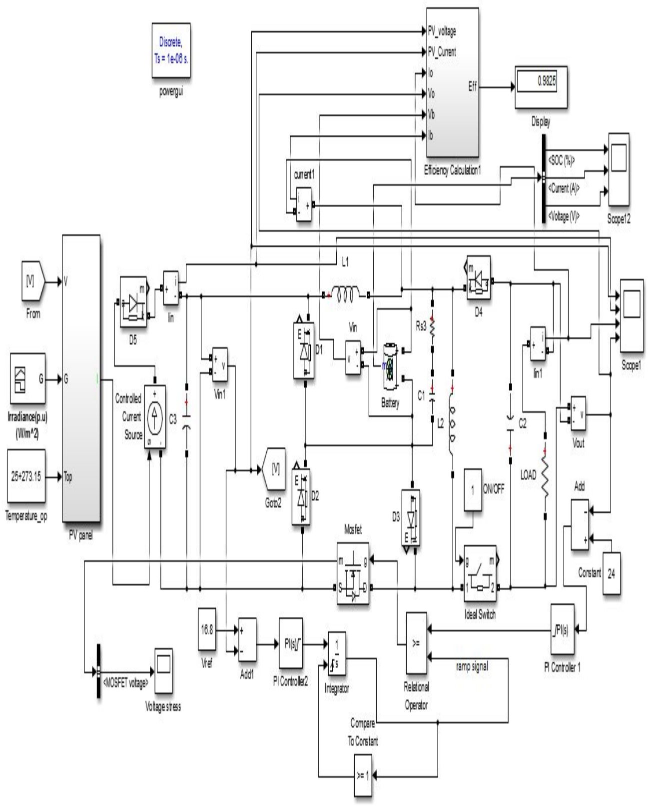

Fig. 6 MATLAB circuit of single switch converter

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The output voltage from PV is controlled to be V_{MPP} using MPPT control and is obtained as 16.8V. Fig. 7 shows the same. An efficiency of 98% is achieved in this mode of operation.

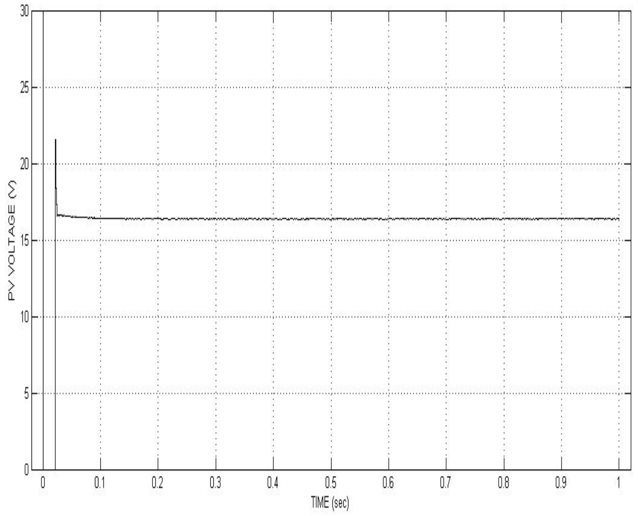

Fig. 7 PV voltage waveform

Fig. 8 shows the simulation results of State of Charge (SOC), current and voltage of the battery. The battery is in the discharging mode.

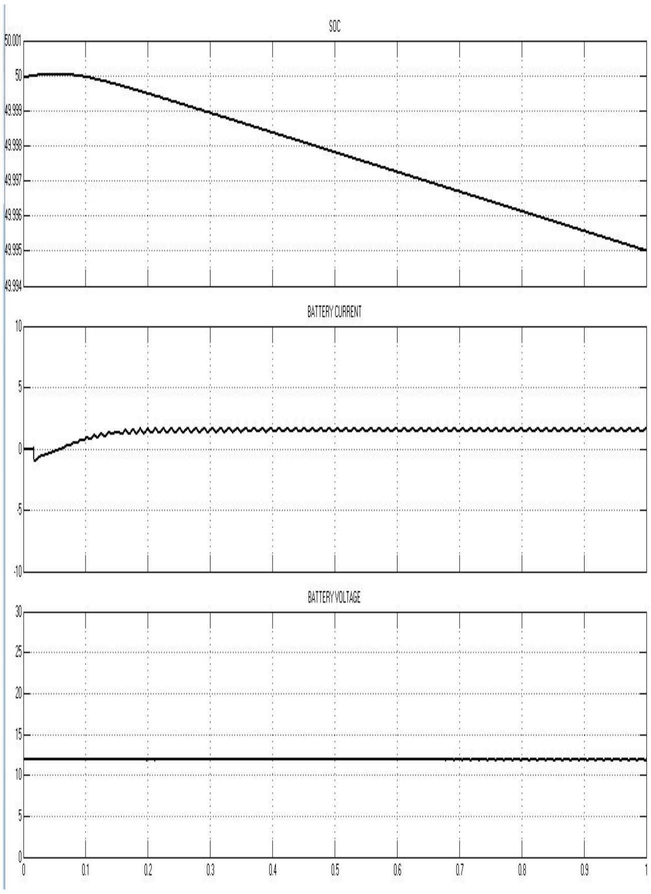

Fig. 8 Simulation results of battery

The output voltage is regulated and is obtained as 24V as shown in fig. 9.

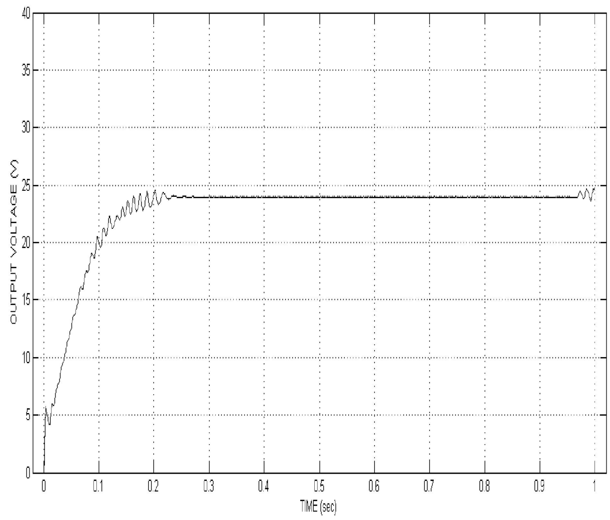

Fig. 9 Output voltage waveform

IV. CONCLUSION

A single-switch converter for a stand-alone PV-battery-powered water pumping system is simulated in steps. First the buck converter is simulated and then the buck-boost converter. Closed loop control of buck-boost converter is done to regulate the output voltage at 24V rated voltage. Then, the two converters are combined to form the single switch converter. PV panel is modeled and MPPT control is done to track the maximum power. A constant voltage method of MPPT is used. At maximum power point under STC, V_{MPP} = 16.8V and I_{MPP} = 1.18A are obtained. Thus, the main functions such as MPPT and output voltage regulation are achieved along with battery charging operation. An overall efficiency of 98% is achieved.

Battery serves as a storage element and supplies the load when the PV power is unavailable or insufficient. Also, the life of the battery is improved by protecting it from the adverse effects of overcharging and over discharging.

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