Modeling, Analysis and Control of Solar Water Pumping System

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Abstract: This paper presents a mathematical model of photovoltaic based pumping system and performs the analysis of photovoltaic pumping system using DC shunt motor.

In this analysis, different simulation has been performed to find out the I-V and P-V characteristics of system. A solar panel having several modules in series and parallel is designed and track the maximum power point in the panel. A DC-DC Buck-Boost converter is used with the aim of keeping constant voltage at the terminals of the motors irrespective of the load current for all realistic solar illuminations. Furthermore this controlled constant voltage is fed to the DC motors connected with the pump and investigate the change in the characteristics of DC motors and the pump under different environmental conditions of solar system. The results give an efficient model for solar energy based control of DC drives with water pumping system. The modelling and simulation has been done in Simulink software environment with MATLAB.

Keywords: Solar PV module, PV array, DC-DC buck-boost converter, Duty ratio, DC shunt motor, Centrifugal pump.

1. INTRODUCTION

Water resources are essential for satisfying human needs, protecting health, and ensuring food production, energy and the restoration of ecosystems, as well as for social and economic development and for sustainable development [1].

PV module is the basic power conversion unit of solar power generator system. The output characteristic of the PV module basically depends on the solar illumination and temperature of the PV module.

In this paper, the PV cells are designed which are connected into a no. of series and parallel combinations to form the PV module and PV array. These PV array then connected with the DC-DC buck-boost converter for the purpose of providing appropriate power for the pumping [2]-[8].

2. PROPOSED SYSTEM

The use of photovoltaic systems as a power source for water pumping consists of a single PV Array, a power electronic DC-DC buck -boost converter, DC Motor (*here the shunt motor is considered*) and a water pump (*here the centrifugal pump is considered*) (refer to fig.1). The size of the system is intended to be small; therefore it could be built in the lab in the future. The system including the subsystems will be simulated to validate the functionalities.

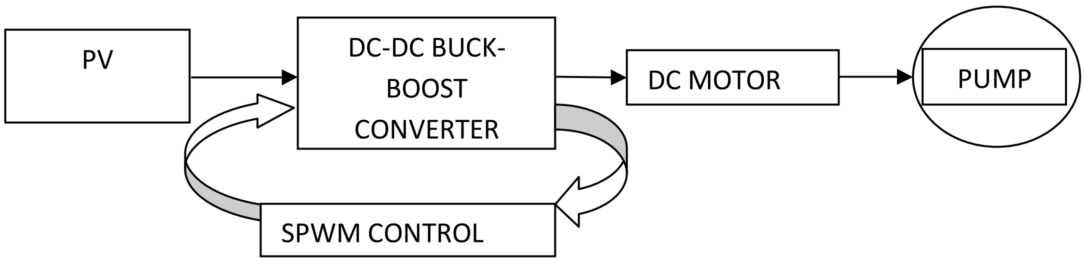

Fig.1 Proposed solar water pumping system

System Modelling and Design

A) PV Source:

A solar cell basically generates a voltage around 0.5V to 0.8V depending on the type of semiconductor. This voltage is too less to use for pumping. Therefore, numbers of cells are connected in series and parallel, to get the higher voltage and current ratings called PV module [2]. The equivalent circuit of PV cell is shown below in fig.2.

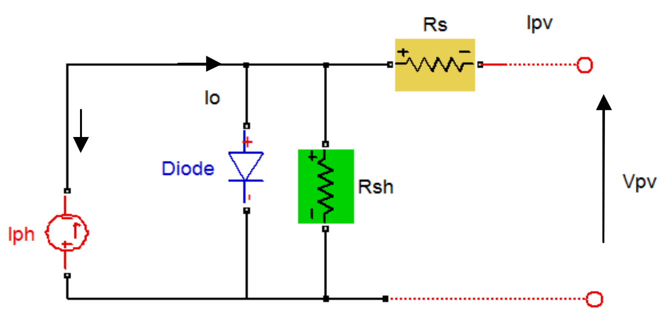

Fig.2 Basic PV cell model

The current source I_{ph} is the cell photon current and R_{sh} is shunt resistance which is usually very large, so for simplicity shunt resistance can be neglected.

The PV module can be made modeled by the following equations [3].

Module photo-current:

$$I_{ph} = [I_{sc} + K_i (T_{ak} - T_{rk})]*(\beta/1000) \quad \text{.........} \quad (1)$$

Module reverse saturation current:

$$I_{rs} = I_{sc} / [e^{(q*V_{oc} / N_s kAT_{ak})} - 1] \quad \text{.........} \quad (2)$$

Module saturation current is temperature dependent and is given by:

$$I_o = I_{rs} [\frac{T_{ak}}{T_{rk}}]^3 * [e^{q*E_{go}*\frac{1}{Bk}\{\frac{1}{T_{rk}} - \frac{1}{T_{ak}}\}}] \quad \text{.........} \quad (3)$$

PV Module output current:

$$I_{pv} = N_p * I_{ph} - N_p * I_o [e^{q*\{\frac{V_{pv} + I_{pv}*R_s}{N_s kAT_{ak}}\}} - 1] \quad \text{.........} \quad (4)$$

In this paper, PV module used has the following specifications (*refer to table.1*)

Table.1 PV module specifications

Rated power	36.0W
Voltage at max. power	16.56 V
Current at max. power	2.25Amp
Open circuit voltage (V_{oc})	21.24 V
Short circuit current (I_{sc})	2.55Amp
Number of series cells (N_s)	1
Number of parallel cells (N_p)	36

In this paper, the rated conditions of the DC shunt motor is 120V and 16A, so for this purpose the PV array can be formed by connecting several series and parallel modules (for specifications refer to table. 2).

Table.2 Specifications for PV array to meet the DC motor load

Design Voltage (V)	Design current (A)	N_s	N_p
120 V	16 A	8	8

B) DC-DC buck-boost converter with SPWM control technique:

A buck-boost converter circuit is a combination of the buck converter topology and a boost converter topology in cascade. The output to input conversion ratio is also a product of ratios in buck converter and the boost converter. Fig.3 shows a simplified schematic of the buck-boost power stage.

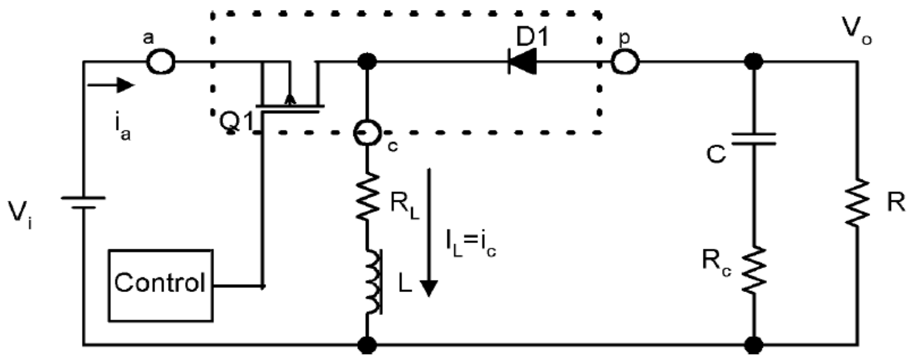

Fig.3 Buck-Boost converter schematic diagram

During normal operation of the buck-boost power stage, Q1 is repetitively switched on and off with the on- and off-times governed by the control circuit. This switching action gives rise to a train of pulses at the junction of Q1, D1, and L. Although the inductor, L, is connected to the output capacitor, C, only when D1 conducts, an effective L/C output filter is formed. It filters the train of pulses to produce a DC output voltage [4].

The ratio of output voltage to input voltage is given by:

$$\frac{V_o}{V_{in}} = D.\frac{1}{1-D} = \frac{I_a}{I_o} \quad \text{....... (5)}$$

Where, V_o and V_{in} are the output and input voltages, respectively. The term I_0 and Ia are the output and input currents, respectively. The output voltage is controlled by controlling the switch-duty cycle.

C) DC shunt motor:

A DC shunt motor has the armature and field circuit connected in parallel with the voltage supply (V). In this paper the effect of nonlinearity in the ferromagnetic material of motor is also included [5, 6]. The equivalent circuit may be shown below in fig.4:

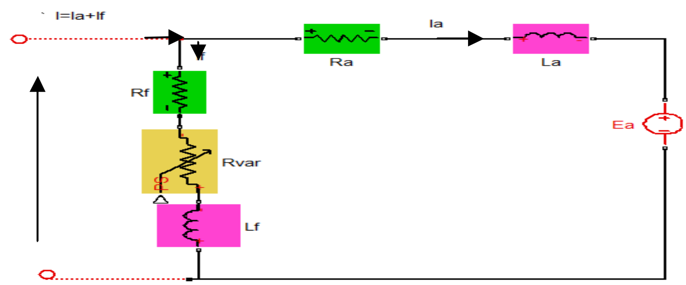

Fig.4 Equivalent circuit of DC shunt motor

The equation of field circuit is:

$$L_f \frac{dI_f}{dt} = [V - (R_f + R_{var}) * I_f] \qquad \text{...... (6)}$$

The equation of armature circuit is:

$$L_a \frac{dI_a}{dt} = [V - R_a * I_a - E_a] \qquad \text{...... (7)}$$

where, $E_a = K_a \phi \omega_m$ ...... (8)

$$J \frac{d\omega_m}{dt} = [K_a \phi I_a - T_{Load}] \qquad \text{...... (9)}$$

The $K_a \phi$ can be expressed in the form of I_f by the curve fitting of the data given in [7].

D) Centrifugal pump model:

Centrifugal pumps have relatively high efficiency and are capable of pumping a high volume of water.

The flow rate (Q) is directly proportional to the impeller speed, the head (H) is proportional to square of speed and the hydraulic power is proportional to the cube of the speed [8]. So, the equations of centrifugal pump can be written in the following form shown below:

$$Q = a\omega - b \qquad (10)$$

$$H = c\omega^2 - d\omega \quad \ldots\ldots \qquad (11)$$

$$P_h = C_1\omega^3 - C_2\omega^2 + C_3\omega \quad \ldots\ldots \qquad (12)$$

The pump load torque equation can be written in the form of equation found in literature [9].

$$T = 4.8 * 10^{-6}\omega^2 + 0.00019\,\omega + 0.092 \quad \ldots\ldots \qquad (13)$$

3. RESULTS AND DISCUSSION

The Matlab/simulink based model of solar water pumping system is shown below in fig. 5.

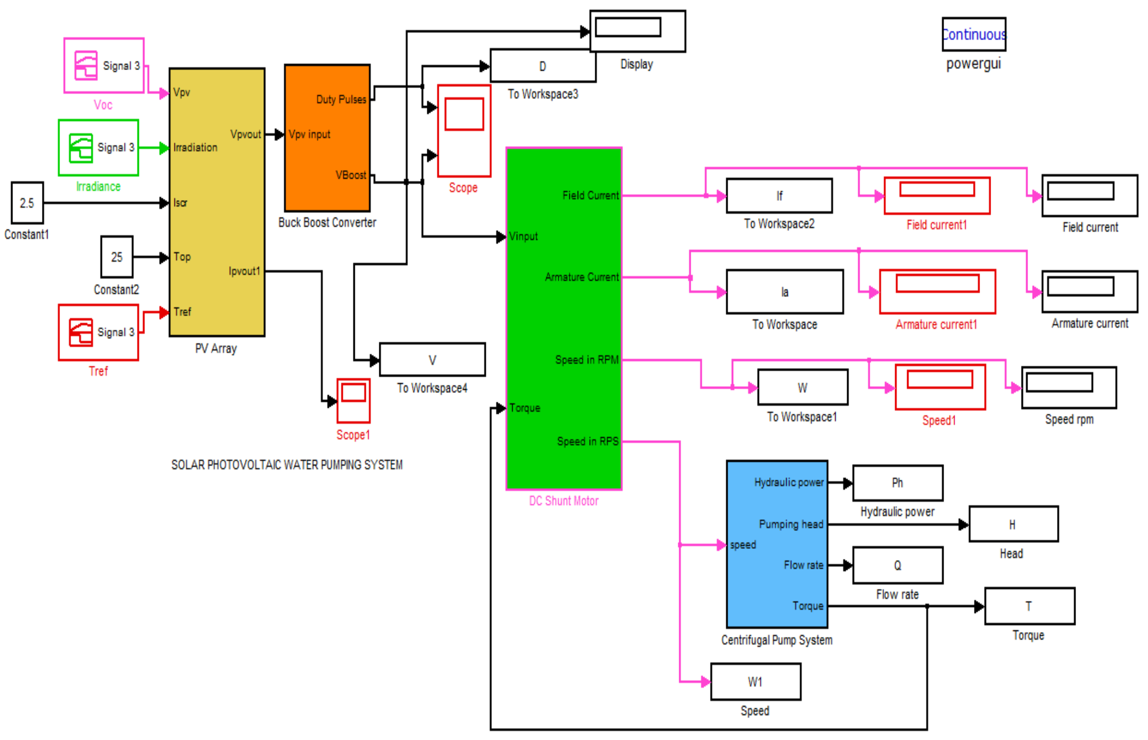

Fig. 5 Matlab / simulink model of PV water pumping system

It can be easily seen from the I-V and P-V characteristics of PV module (*refer to fig. 6*) that by increasing the irradiance level, the power level of solar module increases while the current capacity of module decreases.

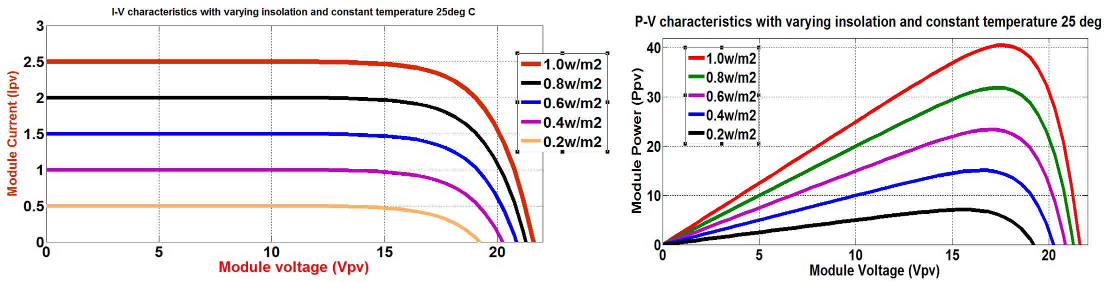

Fig.6 I-V and P-V characteristics of solar PV module at varying irradiance

The SPWM control based buck-boost converter waveforms are shown below in figure 7.. As the output from solar array is not constant, so to get the constant and controlled output the SPWM technique based buck-boost converter is used.

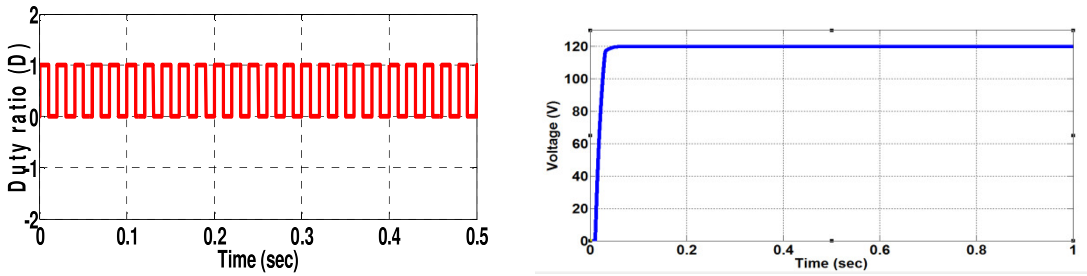

Fig.7 Duty ratio and output waveform of buck-boost converter

The DC shunt motor waveforms are shown below in figure 8 and it is clear from the figure that the motor performance is much better when they are fed with solar array at lower loads rather than when it is fed with constant voltage source.

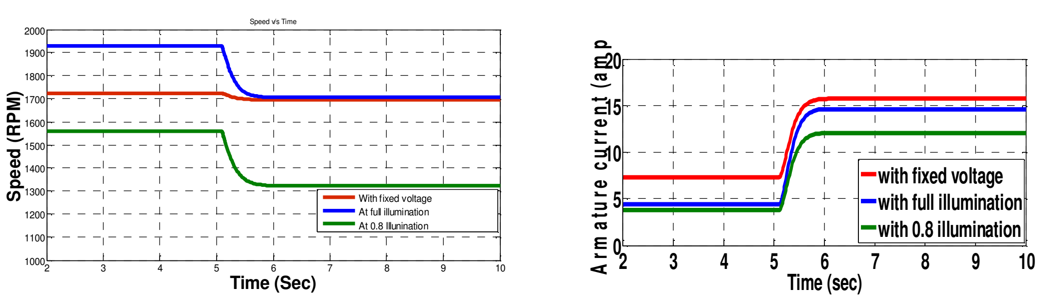

Fig.8 Speed and Armature current waveforms of DC shunt motor at different irradiation levels

The centrifugal pump characteristics are shown below in figure 9.

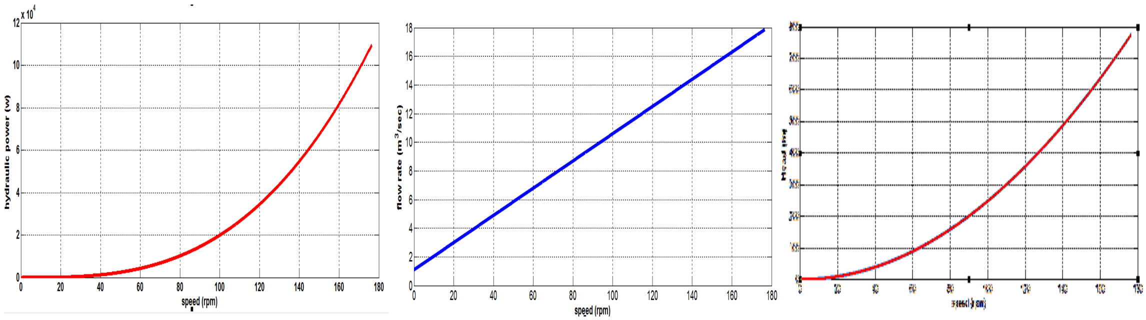

Fig.9 Power, flow rate (Q) & head (H) v/s speed characteristics of centrifugal pump

4. CONCLUSION

Water pumping is an important application of solar power. DC-DC buck boost converter helps in harnessing maximum output from the solar array by increasing the output voltage of solar array.

Present paper has proposed a novel method to realize SPWM technique based solar water pumping system. It can be seen that, by increasing the duty ratio of converter the output voltage of solar PV array can be increased and so the power level.By varying the duty ratio cycle of DC-DC buck-boost converter such that maximum power can be obtained from the solar array for the purpose of driving the DC motor. The proposed work contains the mathematical analysis of solar water pumping system and the Matlab/Simulation based results are obtained for the pumping system.

REFERENCES

[1] Khan, B.H., (2006), Renewable energy resources, Tata McGraw-Hill Publishing Company Limited, New Delhi, India.

[2] Pandiarajan N. and Ranganath Muthu. 2011. Mathematical modelling of Photovoltaic module with Simulink, IEEE. pp. 258-263.

[3] V. Badescu, "Dynamic Model of a Complex System Including PV cells, Electric Battery, Electrical Motor and Water Pump", Solar Energy, Vol. 28, pp. 1165-1181, 2003.

[4] "Power Electronics: Converters, Applications and Design", Mohan, Undeland and Robbins, Wiley, 1989.

[5] H. Suehrke, J. Appelbaum and B. Reshef.1997, Modelling a permanent Magnet DC motor/centrifugal pump assembly in a photovoltaic energy system. Solar Energy. 59: 37-42.

[6] H. M. Metwally and W. R. Anis,"Dynamic Performance of Directly Coupled Photovoltaic Water Pumping System Using D.C.Shunt Motor", Energy Convers.Mgm. Vol.37, No.9,pp.1407-1416, 1996.

[7] R.M.Swanson, Handbook of Photovoltaic Science and Engineering, edited by A. Luque and S.Hegedus, Wiley, West Sussex, England,2003.

[8] Taoufik Mhamdi, International conference on control, Engineering & Information Technology (CEIT'13) Proceedings Engineering & Technology – Vol.4,pp.117-121,2013

[9] Marityunjaya Kappali, ACEEE International Journal on Electrical and power Engineering, Vol.4,No.1,Feb2013