Solar PV Array Based BLDC Motor With Buck-Boost Converter FED Drive

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Abstract— Solar photovoltaic (SPV) array based water pumping is receiving wide attention now a days because the everlasting solar energy is the best alternative to the conventional energy sources. This paper deals with the utilization of a buck - boost converter in solar PV array based water pumping as an intermediate DC-DC converter between a solar PV array and a voltage source inverter (VSI) in order to achieve the maximum efficiency of the solar PV array and the soft starting of the permanent magnet brushless DC (BLDC) motor by proper control. Consisting of a least number of components and single switch, the buck-boost converter exhibits very good conversion efficiency. Moreover, buck–boost DC–DC converter topology is the only one allowing follow-up of the PV array maximum power point (MPP) regardless of temperature, irradiance, and connected load. A BLDC motor is employed to drive a centrifugal type of water pump because its load characteristic is well matched to the maximum power locus of the PV generator. The transient, dynamic and steady state behaviors of the proposed solar PV array powered buck-boost converter fed BLDC motor driven water pumping system are evaluated under the rapid and slowly varying atmospheric conditions using the sim-power- system toolboxes of the MATLAB/Simulink environment.

Keywords— *SPV array, Buck-boost converter, VSI, soft starting, BLDC motor, Centrifugal pump.*

I. INTRODUCTION

A continuous reduction in the cost of the solar photovoltaic (SPV) panels and the power electronics devices has encouraged the researchers and the industries to utilize the solar PV array generated power for different applications. Water pumping has gained a broad attention as a crucial and cost effective application of the solar PV array generated power. A maximum efficiency of the solar PV array is mostly achieved through a maximum power point tracking (MPPT) algorithm [1-3] using the DC-DC converters. Various DC-DC converters such as buck [3], boost [4], buck-boost [5], Cuk [6], SEPIC (Single Ended Primary Inductor Converter) [7] have been used for MPPT in different solar PV array based applications. The aforesaid non-isolated DC-DC converters are compared in [8] to find a best solution suiting an application with MPPT. It has been concluded that the best selection of DC–DC converter in the PV system is the buck– boost DC–DC converter since it is capable of achieving optimal operation regardless of the load value. On the other hand, when the buck and boost converter is used for MPPT, the MPP is tracked as if it is restricted to within the operation region. Besides that, due to the highest values of energy storage components, the Cuk and SEPIC converters contribute to their main drawback.

Due to a single switch, the DC-DC buck-boost converter possesses very good conversion efficiency. Its utilization is initiated in this paper in order to extract the maximum power available from the solar PV array and soft starting of the BLDC motor coupled to a centrifugal pump for water pumping. A centrifugal pump is selected because of its availability in a wide range of heads and flow rates, simplicity, low maintenance requirements and cost-effectiveness [3]. The BLDC motor having the merits of high efficiency, high reliability, high ruggedness, low EMI problems and excellent performance over a wide range of speed [9] is used to drive this centrifugal pump. The ratings of the solar PV array and the BLDC motor are selected such that the proposed system operates successfully under all the variations in the atmospheric conditions. The various performances are analyzed through the simulated results using MATLAB/Simulink environment. Simulated results verify the suitability of the proposed system for solar PV based water pumping.

II. PROPOSED SYSTEM CONFIGURATION

Fig.1 shows the configuration of the proposed solar PV based buck-boost converter fed BLDC motor drive for water pumping. From left to right, the proposed system consists of a solar PV array, a buck-boost DC-DC converter, a voltage source inverter (VSI), a BLDC motor and a centrifugal type of water pump.

III. OPERATION OF THE PROPOSED SYSTEM

As shown in Fig.1, the solar PV array generates the electrical energy and feeds the DC-DC buck-boost converter. The IGBT (Insulated Gate Bipolar Transistor) switch of the buck-boost converter is operated through an incremental conductance (INC) MPPT algorithm such that the operation of the solar PV array is optimized and the BLDC motor has a soft starting. The buck-boost converter is always operated in continuous conduction mode to reduce the stress on the components and semiconductor device. Further, the buck- boost converter feeds power to the VSI, supplying the BLDC motor coupled to a centrifugal pump.

Switching sequence for the VSI is provided by the electronics commutation of BLDC motor. Electronic commutation is a process of decoding the Hall Effect signals generated by the inbuilt encoder of the motor according the position of rotor. The design and the control of the proposed system are elaborated in the following sections.

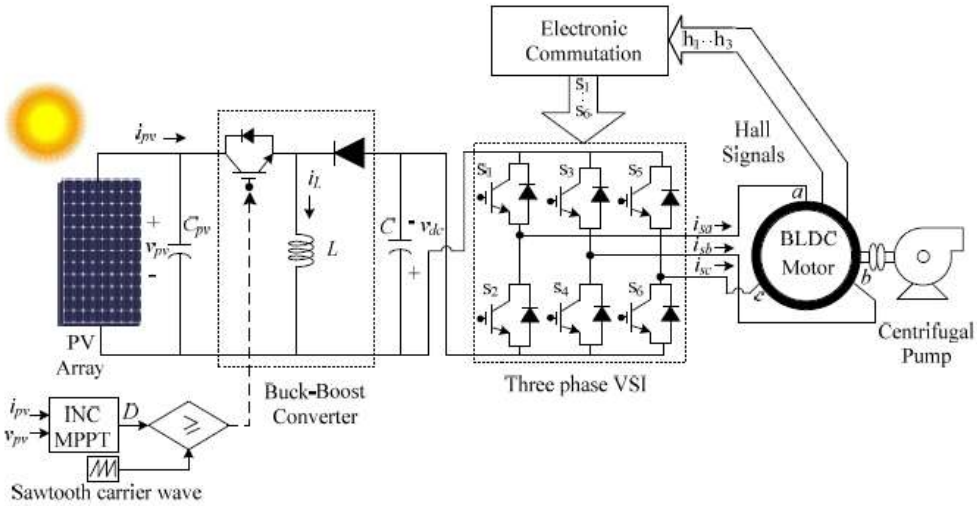


Fig.1 Configuration of the SPV array – buck-boost converter fed BLDC motor driven water pumping system.

IV. DESIGN OF THE PROPOSED SYSTEM

The various operating stages of the configuration shown in Fig.1 such as the solar PV array, the buck-boost converter and the centrifugal pump are designed such that a satisfactory operation is always accomplished under any kind of change in solar insolation level. A BLDC motor of 1.14 kW rated power is selected for a centrifugal water pump of 1 kW power rating. According to the selected power ratings, each stages of the proposed system are designed as follows.

A. Design of Solar PV array

A solar PV array of 1.5 kW peak power capacity, somewhat more than required by the motor, is selected so that the performance of the system is not affected by the losses associated with the converters and the motor. The parameters of the solar PV array are estimated at the standard solar insolation level of 1000 W/m^2. A PV module is formed by connecting 36 solar PV cells in series which reaches its maximum power at 77% of open circuit voltage and 90% of short circuit current, as suggested in [1]. Voltage of the solar PV array at MPP is selected in view of the DC voltage rating of the BLDC motor same as the DC link voltage of the VSI.

Table I summarizes the estimation of the various parameters to design a solar PV array of appropriate size and detailed data are repeated in Appendix.

B. Design of Buck-Boost Converter

The solar PV array voltage at MPP, $v_{pv} = V_{mpp} = 83.33$ V appears as the input voltage source whereas the DC link voltage of the VSI, v_{dc} appears as the output voltage of the buck-boost converter. The duty ratio, D of the buck-boost converter is estimated, using the input-output relationship as [10],

$$D = \frac{V_{dc}}{V_{dc} + v_{pv}} = \frac{60}{60 + 83.33} = 0.42 \qquad (1)$$

where Vdc = 60 V is an average value of the DC link voltage of the VSI. On the other hand, an average current flowing through the DC link, Idc is estimated as,

TABLE I. DESIGN OF SOLAR PV ARRAY

For a PV Module	
Open circuit voltage	13.6 V
Short circuit current	3.35 A
Voltage at MPP, V_m	0.77*13.6 = 10.47 V
Current at MPP, I_m	0.9*3.35 = 3 A
For a PV array	
Voltage at MPP, $V_{mpp} = v_{pv}$	83.33 V
Power at MPP, P_{mpp}	1500 W
Current at MPP, $I_{mpp} = i_{pv}$	P_{mpp}/V_{mpp} = 1500/83.33 = 18 A
Numbers of modules connected in series, N_s	V_{mpp}/V_m = 83.33/10.47 ≈ 8
Numbers of modules connected in parallel, N_p	I_{mpp}/I_m = 18/3 = 6

$$I_{dc} = \frac{P_{mpp}}{V_{dc}} = \frac{1500}{60} = 25\text{ A}$$

Addition of the two currents, *ipv* and *Idc* flows through the inductor, *L*. The design of inductor, *L* [10] and DC link capacitor, *C* is summarized in Table II, where *fsw* is the switching frequency of the switch of buck-boost converter; *IL* is an average current flowing through the inductor; Δ*IL* is an amount of ripple permitted in the current flowing through the inductor; Δ*Vdc* is the ripple permitted in the voltage across the DC link of VSI; *ωh* and *ωl* are the highest and lowest values of VSI output voltage frequencies respectively in rad/sec.; *f* is the frequency of VSI output voltage in Hz; *Ch* and *Cl* are the values of capacitors estimated corresponding to *ωh* and *ωl* respectively; *P* is the number of poles in the BLDC motor; *Nrated* is the rated speed of the motor and *N* is the minimum speed required to pump the water.

C. Design of Centrifugal Pump

A centrifugal water pump of 1 kW power rating is selected and is designed using its torque-speed characteristics as [3],

$$K_p = \frac{T_L}{\omega^2} = \frac{4.2}{(2*\pi*2600/60)^2} = 5.66*10^{-5} \qquad (3)$$

where *Kp* is a constant for selected centrifugal pump; *TL* is the torque required to drive the pump and *ω* is the rotational speed in rad/sec. The centrifugal pump is designed considering the rated values of torque as, *TL* = 4.2 Nm and speed of the BLDC motor as, *ω* = 272.27 rad/sec.

V. CONTROL OF THE PROPOSED SYSTEM

The controls of the proposed system viz. MPPT and Electronic commutation of BLDC motor are elaborated in the following sections.

A. Maximum Power Point Tracking (MPPT)

The MPPT technique is mostly used to optimize the efficiency in solar PV based applications. An INC type of MPPT technique [1-2] is used in this paper because of its high precision of tracking even under the rapid change in the atmospheric conditions. The perturbation size is wisely selected such that the oscillation around the peak point is avoided and the soft starting of the BLDC motor is ensured under all the possible variation in the solar insolation level.

B. Electronic Commutation

The switching signals for the VSI are generated through the electronics commutation of the BLDC motor [9]. According to the angular position of the rotor, the encoder provides 3 Hall Effect signals. These Hall Effect signals are logically converted into 6 switching pulses used to operate the 6 IGBT switches of the VSI. Various parameters and ratings of the BLDC motor, selected for the proposed system are indicated in Appendix.

VI. RESULTS AND DISCUSSION

The performance of the proposed solar PV powered buckboost converter fed VSI-BLDC motor-pump system is simulated in the MATLAB/Simulink environment using the Sim-power-system toolbox. To elaborate the dynamic performance of the proposed system, the solar insolation level is varied as indicated in Table III. The starting, dynamic and steady state performances are evaluated using the simulated results as shown in Figs. 2-4. These results verify the satisfactory performance of the proposed system even under the rapid and slow change in weather condition.

A. Performance of INC-MPPT Under Dynamic Condition

An excellent tracking performance by the INC-MPPT technique under the dynamically changing weather condition is verified as shown in Fig. 2(a). Proper selection of the perturbation size has avoided the oscillation around the peak power point. Fig. 2(a) shows that the peak power point is tracked instantaneously under all types of variation in solar insolation level. On the other hand, tracking time is intentionally increased at the starting so that the BLDC motor
has a soft starting.

B. Performance of Buck-Boost Converter Under Dynamic Condition

As shown in Fig. 2(b), the buck-boost converter is always operated in its continuous conduction mode. Operating the converter in continuous conduction mode reduces the stress on the components. The inductor current *iL* is almost ripple free. The output voltage, *vdc* which is nothing but the DC link voltage of VSI comprises 20% of the voltage as a ripple. These two converter indices follow the variation in the weather condition and vary in proportion to the solar insolation level as shown in Fig. 2(b).

TABLE II. DESIGN OF BUCK-BOOST CONVERTER

Para-meter	Expression	Design data	Value	Selected value
L	$\frac{D*v_{pv}}{f_{sw}\Delta I_L}$	$D = 0.42$ $v_{pv} = 83.33$ V $f_{sw} = 20$ kHz $I_L = 43$ A $\Delta I_L = 1\%$ of I_L	4.07 mH	5 mH
$^*C$	$\omega_h = 2*\pi*f = \frac{2*\pi*N_{rated}*P}{120}$ $\omega_l = 2*\pi*f = \frac{2*\pi*N*P}{120}$ $C_h = \frac{I_{dc}}{6*\omega_h*\Delta V_{dc}}$ $C_l = \frac{I_{dc}}{6*\omega_l*\Delta V_{dc}}$	$P = 4$ N_{rated}=2600 rpm N=1100 rpm I_{dc}=25 A $V_{dc} = 60$ V ΔV_{dc}=20% of V_{dc}	C_h=638 µF C_l =1507 µF	1500 µF

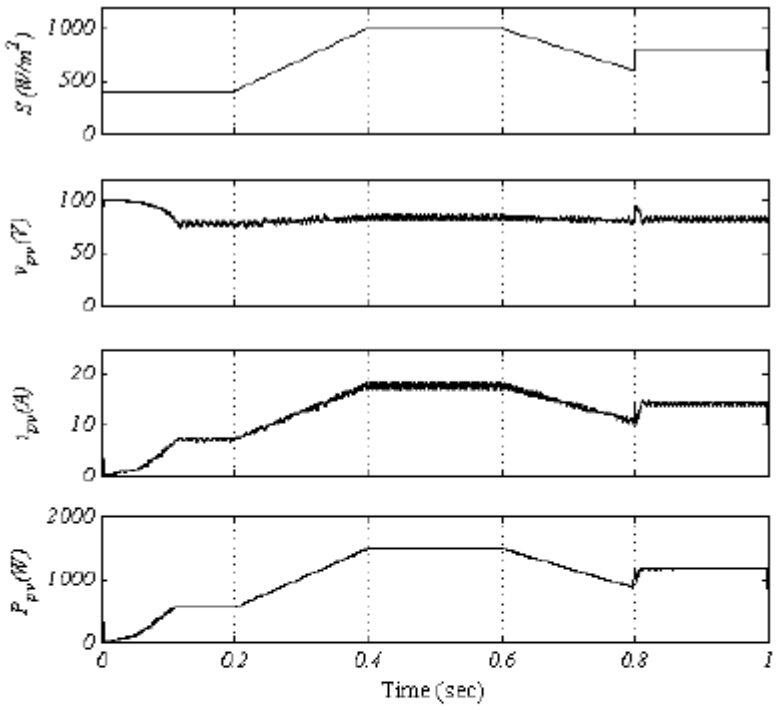
* 6th harmonic component of the motor voltage appears on the DC link of VSI

TABLE III. DYNAMIC VARIATION IN SOLAR INSOLATION LEVEL

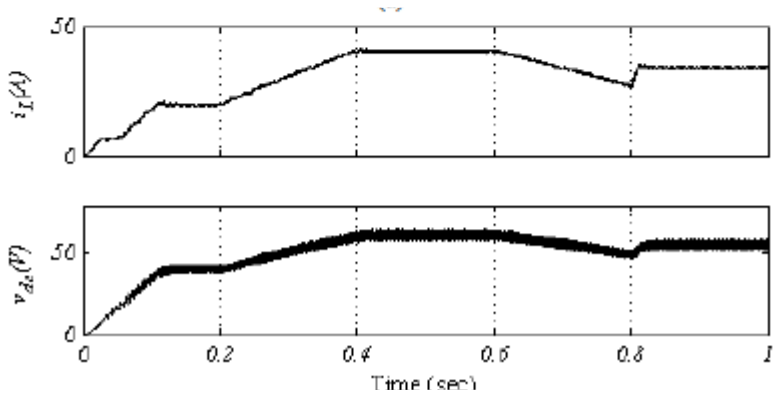
S. No.	Solar Insolation Level, *S* (W/m^2)	Duration (sec.)
1	400	0.0 - 0.2
2	Slowly increasing from 400 to 1000	0.2 - 0.4
3	Maintained at 1000	0.4 - 0.6
4	Slowly decreasing form 1000 to 600	0.6 – 0.8
5	Rapidly increasing from 600 to 800	0.8 – 1.0

C. Performance of BLDC Motor–Pump Under Dynamic Condition

As the solar insolation level alters, the various BLDC motor–pump indices such as the back EMF, *ea*, the stator current, *isa*, the speed, *N*, the electro-magnetic torque developed, *Te* and the load torque, *TL* vary in proportion to the solar insolation level as shown in Fig. 2(c). Two important facts are observed from the simulated results. First, the stator current, *isa* at the starting is controlled such that it takes time to reach its steady state value and hence the BLDC motor has a soft starting. Second, the BLDC motor develops the electromagnetic torque, *Te* equal to the torque required to drive the pump, *TL* under all variations in solar insolation level which manifest the stable operation of the proposed system regardless of the weather condition.



2(a)



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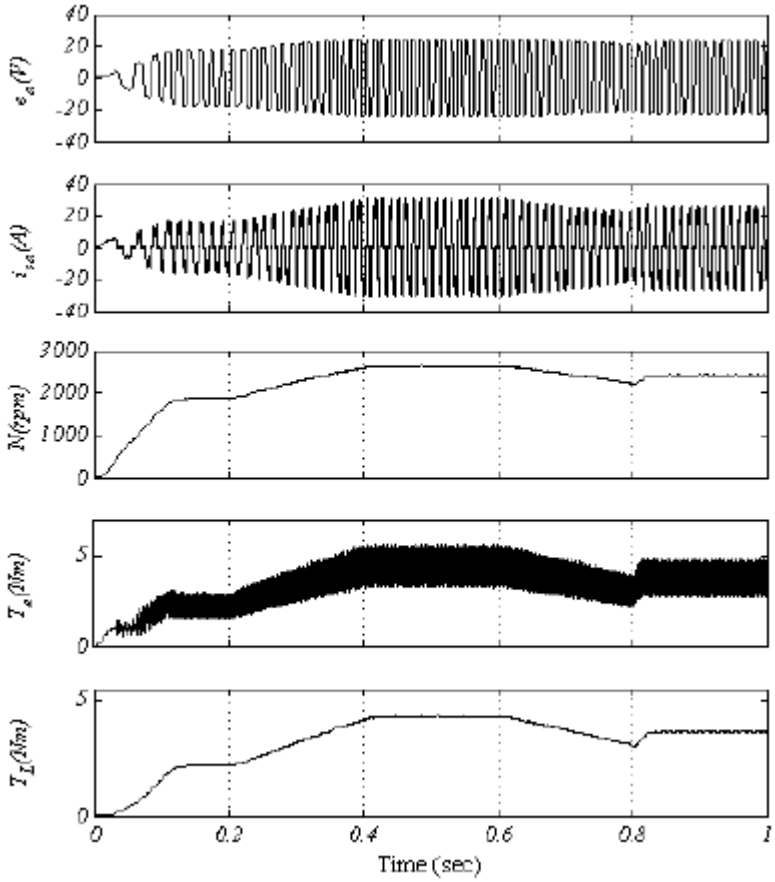

2(c)

Fig.2 Performance of SPV array - buck-boost converter fed VSI-BLDC motor pump system under varying solar insolation level conditions, (a) SPV array variables, (b) Buck-boost converter variables, (c) BLDC motor-pump variables,

However, a small pulsation in *Te* results from the electronic commutation of the BLDC motor. Besides these, the BLDC motor attains a speed higher than 1100 rpm, a minimum required speed to pump the water, regardless of the solar insolation level.

D. Performance of BLDC Motor–Pump at 1000 W/m2

The starting and steady state behaviors of the BLDC motor–pump at the standard solar insolation level of 1000 W/m2 are shown in Fig. 3. All the motor indices increase and reach their rated values under steady state condition. Soft starting along with the stable operation of the motor–pump is observed and hence the successful operation of the proposed system is verified.

E. Performance of BLDC Motor–Pump at 200 W/m2

The satisfactory performance of the BLDC motor–pump is verified at the minimum solar insolation level of 200 W/m2 also as shown in Fig. 4. The BLDC motor attains a higher speed than 1100 rpm, a minimum speed required to pump the water, under this minimum solar insolation level also. Moreover, the soft starting and stable operation of the BLDC motor–pump contribute to the successful operation of the proposed system.

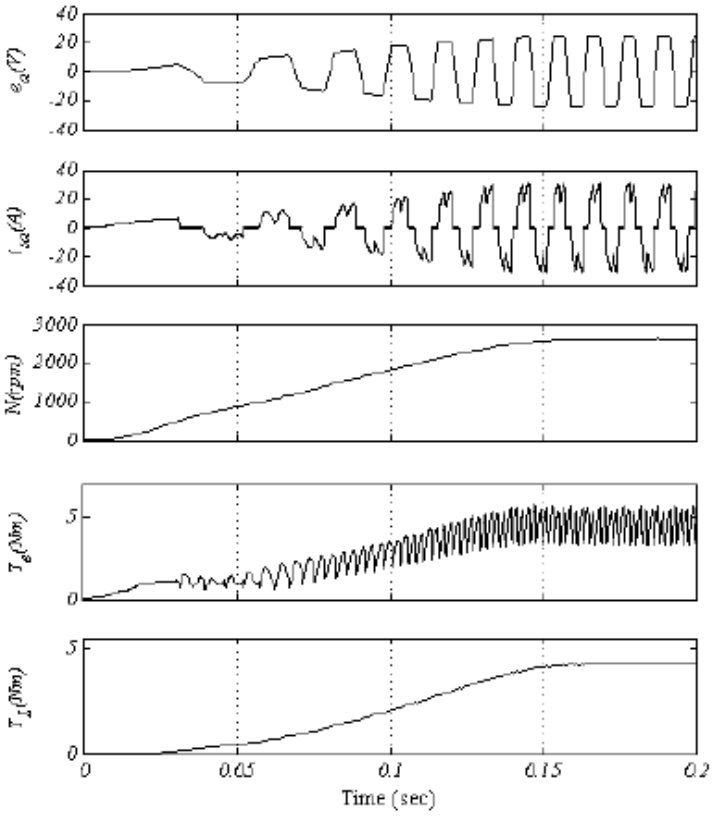

Fig 3. Performance of the BLDC motor – pump system at 1000 W/m²

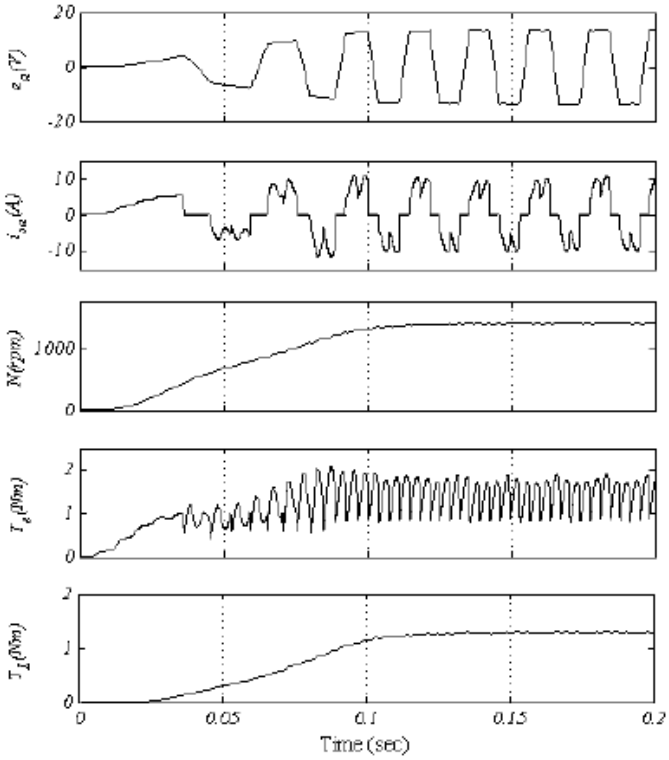

Fig 4. Performance of the BLDC motor – pump system at 200 W/m²

F. Efficiency Estimation of BLDC Motor–Pump System

A very good efficiency is obtained for the proposed water pumping system. Table IV and Fig. 5 show the efficiency estimation of the BLDC motor-pump system and its graphical representation respectively, subjected to the variation in atmospheric condition, where *Pm* and η are the mechanical power output and efficiency of the BLDC motor.

VII. CONCLUSIONS

The transient, dynamic and steady state behaviors of the proposed solar PV array based buck-boost converter fed BLDC motor have been validated for water pumping. The proposed system has been modeled, designed and simulated in MATLAB/Simulink environment. A DC-DC buck-boost converter provides the flexibility of increasing and decreasing the voltage level and hence does not possess a limited region of MPPT. Taking the advantages of very good conversion efficiency of buck-boost converter, the BLDC motor and centrifugal pump, a suitable water pumping system based on solar PV array has been developed. The proposed system is designed brilliantly, such that the performance is not affected by the weather condition and efficiency limitations of the converters and motors. Using the simulated results, a buckboost converter with the BLDC motor is proved as a suitable combination for solar PV based water pumping. Compatibility of the proposed system regardless of the weather condition has been demonstrated using the MATLAB based simulation results.

TABLE IV. EFFICIENCY ESTIMATION OF THE BLDC MOTOR – PUMP SYSTEM

S (W/m^2)	P_{pv} (Watt)	P_m (Watt)	η (%)
200	254	198	78
400	551	440	80
600	859	680	79
800	1172	938	80
1000	1488	1190	80

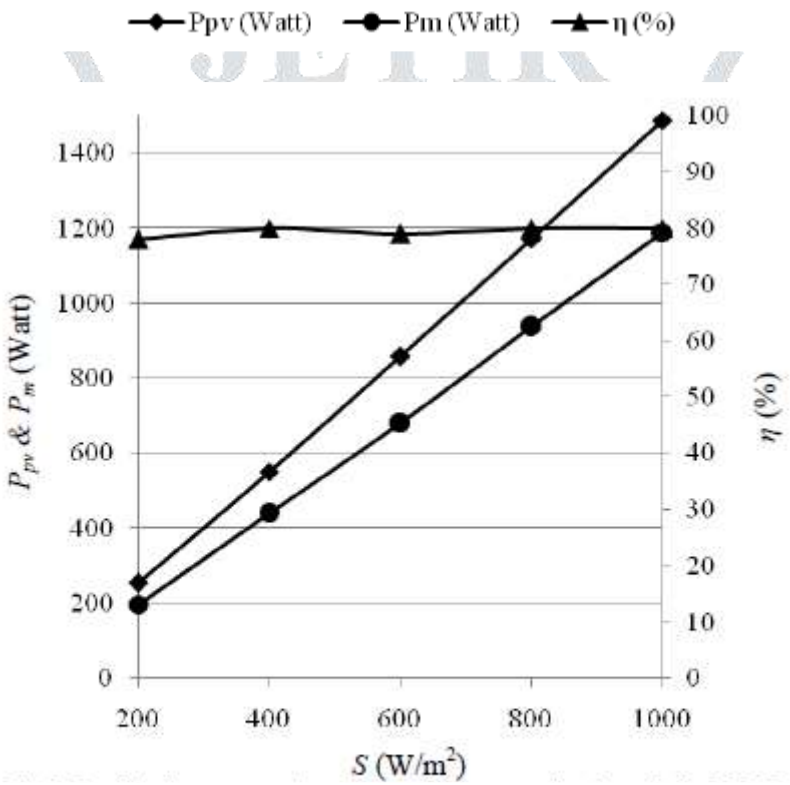

Fig.5 Graphical representation of the efficiency estimation of the BLDC motor – pump system

APPENDIX

A. Selected Parameters of Solar PV Array

Open circuit voltage, *Voc* = 109 V; Short circuit current, *Isc* = 20 A; Maximum power, *Pmpp* = 1.5 kW; Voltage at MPP, *Vmpp* = 83.33 V; Current at *MPP*, *Impp* = 18 A; Numbers of cells connected in series in a module, *Nss* = 36; Numbers of modules connected in series, *Ns* = 8; Numbers of modules connected in parallel, *Np* = 6.

B. Parameter Selection for Design of Buck-Boost Converter

Switching frequency, *fsw* = 20 kHz; Inductor, *L* = 5 mH; Capacitor, *C* = 1500 μF.

C. Parameter Selection for Design of Buck-Boost Converter

Stator phase/phase resistance, *Rs* = 0.13 Ω; Stator phase/phase inductance, *Ls* = 0.41 mH; Torque constant, *Kt* = 0.18 Nm/Apeak; Voltage constant, *Ke* = 18.5 VpeakL-L/krpm; Rated current, *Israted* = 23.82 A; Rated torque, *Trated* = 4.2 Nm; Rated speed, *Nrated* = 2600 rpm @ 60 V DC; Rated power, *Prated* = 1.14 kW; No. of poles, *P* = 4; Moment of inertia, *J* = 3.5 kg.cm2; Constant, *Kp* = 5.66*10-5.

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