International Journal of Advanced Science and Technology
Vol.120 (2018), pp.73-84
http://dx.doi.org/10.14257/ijast.2018.120.06

Analysis of Solar Photovoltaic Source Fed BLDC Motor Drive with Double Boost Converter for Water Pumping Application in Irrigation System

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Abstract

In this paper, analysis of solar power fed Brushless DC motor (BLDC) motor drive with a double boost converter is presented for water pumping application in irrigation system. In the current scenario, the usage of renewable PV source is increasing gradually, due to the encouragement of the government for use of alternative and environmentally friendly energy sources by providing subsidies for the installation in the initial states. In the agricultural sector, the water pump system requires a 3-ϕ power supply, for that we need a separate transmission line and transformers to meet the load demand. In this paper, a solar power fed BLDC motor with double boost converter is presented which reduces the converter switch stress by increasing the voltage transfer gain ratio. An MPPT controller is required to extract maximum power from the high penetrating renewable PV source. An Adaptive Neuro-Fuzzy Inference System (ANFIS) based MPPT controller is implemented in the PV system with the rating 1.2 kW, and the obtained results are compared to the conventional P&O MPPT controller. The simulation is carried out in the MATLAB/Simulink software.

Keywords: *ANFIS MPPT; BLDC motor; Double Boost converter; PV system; VSI*

1. Introduction

The usage of solar energy increases drastically in the recent decade, the total grid-tied installed solar energy capacity is 23,022.83 MW, as of 30th June 2018. The total grid-tied installed capacity in India is reached 71,187.12 MW [1,2]. The economy of the nation depends on the agricultural sector, which intern depends on the availability of water resource to the field [3,4]. So, many researchers are focusing on the solar power fed water pumping drive applications for effective irrigation pumping application [5].

Authors in [6], dispense a literature survey on solar PV water pumping system current status. The detailed information of solar PV water pumping system, its mechanisms and advantages are illustrated with a summarization of factors affecting the performance of the developed system. The effective utilization of alternative green energy sources, different optimization methods are illustrated with numerical data.

Received (May 15, 2018), Review Result (July 23, 2018), Accepted (August 5, 2018)
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ISSN: 2005-4238 IJAST

An integrated PV, wind and hydroelectric power station based water pumping system is developed in [7], the authors developed a mixed integer mathematical model of proposed hybrid water pumping system and introduced an optimization method to denigrate the encounter of renewable energy sources on the national conventional power system network and to inspect the impact of specific parameters on energy exchange with the grid.

Authors in [8], scrutinized a PV fed water pumping system in the agricultural sector, a vector controlled method is used to control the BLDC motor for water pumping applications and for extracting maximum solar power under distinct solar irradiation level, P&O algorithm is used. The entire system performance is analyzed in MATLAB/Simulink environment by considering the contrasting solar irradiation data and a constant DC link voltage is fed to the VSI, by connecting battery bank across the DC link capacitor.

In [9], the authors proposed a dual MPPT controller for dual PV source fed water pumping system. In this system, a 3-ϕ open-end winding induction motor coupled to a centrifugal pump is used and it is connected to the two level 3-ϕ inverter. As different PV sources are used for power supply, it provides different levels of voltages. The inverter is controlled by PWM techniques along with v/f control, in addition to the proposed dual MPPT techniques.

A back stepping control algorithm is proposed in [10], to control the centrifugal water pump system fed with the solar PV and grid-tied system. The following are the main objectives of the proposed controller, (i) to control the water flow rate by tracking the reference signal, (ii) regulating the rotor flux, (iii) regulation of DC link to obtain maximum power and (iv) power factor correction. In order to do the system performance evaluation, the whole system is developed in the park- coordinates.

A solar PV fed water pumping system using switched reluctance motor drive with dual output buck-boost converter has been implemented in [11], the main advantage of the proposed dual output converter is it able to optimize the PV array power and to provides the soft starting to the reluctance motor. During the continuous current mode operation, the implemented system reduces the current and voltage stress on the converter components and slashes the electromagnetic interference.

A single stage PV fed BLDC motor drive centrifugal pump system is implemented in [12]. The entire system is implemented in MATLAB/Simulink model by considering the 4 kW PV system with INC method as maximum power point tracking algorithm and BLDC motor is controlled by the Hall sensor signals. The performance analysis is done in both simulation and experimentally by considering the different solar irradiation data levels.

A detailed literature review is done in this section by considering the all the aspects in designing the solar PV fed water pumping system in the irrigation sector. From the literature review, many solar power fed water pumping systems have been implemented by considering the interfacing or connecting power electronic converters, PV array modeling, different types of motors (BLDC, switches reluctance), different control and MPPT control techniques.

A solar power fed water pumping system requires a DC-DC converter, to obtain maximum and constant DC power from the high penetrating PV source and a voltage source inverter (VSI) for the BLDC motor, to transfer power from the PV source to the water pump[13]. A double boost DC-DC converter is considered in this paper, which provides the high voltage transfer gain compared to the conventional boost converter [14-16].

In this proposed solar power fed BLDC motor drive water pumping system, a 1.2 kW PV source is considered with a double boost converter, the maximum power extraction is regulated by the ANFIS based MPPT controller to maintain constant DC power, then the hall effect based VSI is placed between the DC-DC converter and BLDC motor. In order

to analyze the performance of the entire system a constant 1000W/m^2 irradiation level is considered with the temperature of 25^{o}C.

This paper is divided into 5 sections to explain the system design and performance. In section-1, introduction to the renewable energy sources. In Section-2, explained about the proposed PV fed BLDC motor water pump design with a double boost converter. Section-3, explains the proposed PV fed water pumping system control with different ANFIS system. Final simulation and results discussion are explained in section-4 followed by a conclusion section.

2. Proposed PV Fed Water Pumping System Design

Figure 1 illustrates the solar PV fed water pumping system with the considered 1.2 kW PV array, developed double boost power converter, P&O MPPT controller to extract maximum power, a 3-phase VSI with hall signal control connected to BLDC motor with centrifugal water pumping system.

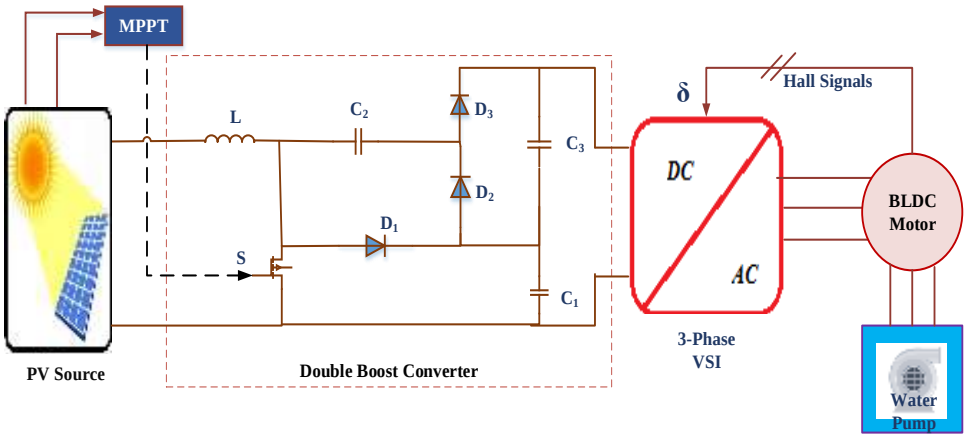

Figure 1. Block Diagram of Proposed PV Fed Water Pump Application

2.1. PV System

A SunPower SPR-305-WHT PV panel is considered to design a 1.2 kW PV system, the detailed specifications of the PV module are listed in Table 1. Figure 2 shows the equivalent circuit of a PV cell [17,18].

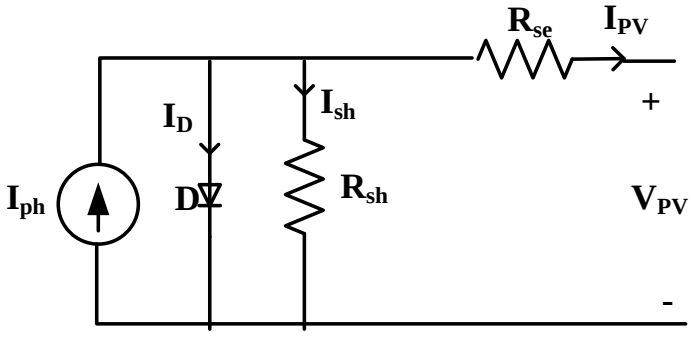

Figure 2. PV Cell Equivalent Circuit

In order to analyze the system, a constant 1000 W/m^2 PV irradiation is considered without any shading effect on the PV panels in MATLAB as shown in illustrated. 3. Figure 4 represents the Sun Power SPR-305-WHT 1.2 kW PV Module I-V and P-V characteristics at 25^{0}C with different solar irradiation levels from 0.25 kW/m^2 to 1 kW/m^2.

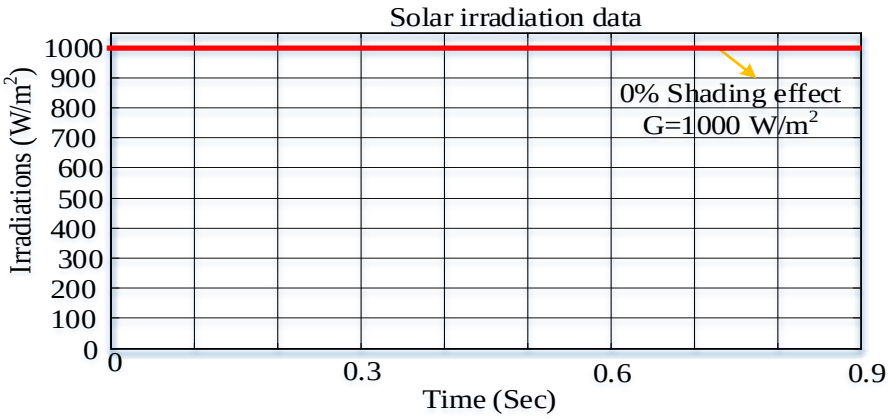

Figure 3. Solar Irradiation Data

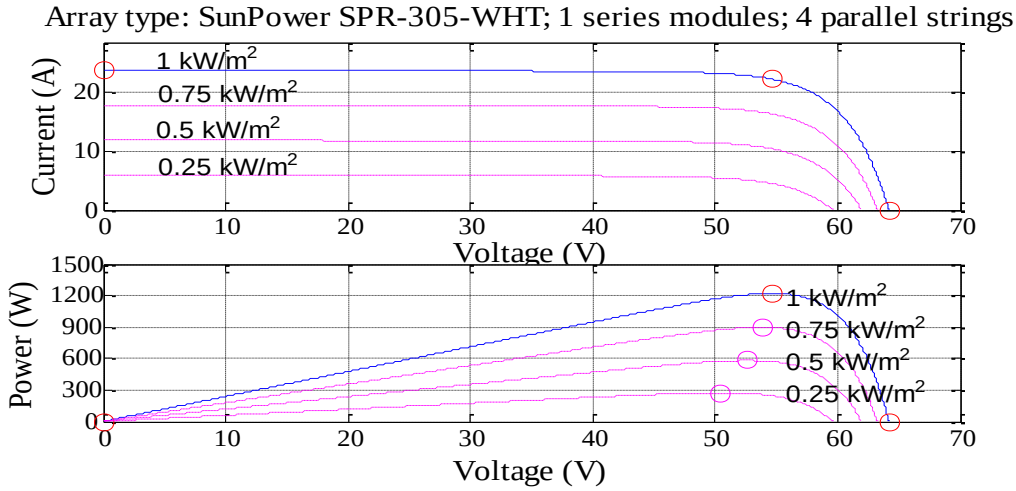

Figure 4. 1.2 kW SPR-305-WHT Model P-V and I-V Characteristics

Table 1. Specifications of SunPower SPR-305-WHT 1.2 kW PV Module

Parameter Description	Rating
Maximum power (P_{MP})	1.2 k W
Maximum current (I_{MP})	5.58 A
Maximum voltage (V_{MP})	54.7 V
Short circuit current (I_{SC})	5.96 A
Temperature (T)	25^0 C
Open circuit voltage (V_{oc})	64.2 V
Number of cells per module	96
Parallel strings	4
Series-connected modules per string	1
Series resistance (R_s)	0.037998
Parallel resistance(R_p)	993.51
Solar irradiation (G)	1000 W/m^2

2.2. Double Boost Converter

In order to extract maximum power from the high penetrating renewable PV source and to step-up the low voltage renewable energy source voltage to required level voltage to meet the load demand, a high step-up DC-DC converter is required. In this section, a

double boost converter is developed to achieve the proposed target in the solar powered water pumping system.

The double boost DC-DC converter is the combination of conventional boost and the switched capacitor. The double output voltage is achieved by this double boost converter without operating it in extreme duty cycle [19].

The schematic diagram of the double boost converter is shown in Fig. 5. It consists of a single switch (S), a single inductor (L), three capacitors (C_1, C_2, and C_3) and three diodes (D_1, D_2 and D_3) as the circuit arrangement is shown in the schematic diagram. The voltage transfer gain of the double boost converter is given in Eq. 1.

$$\text{Voltage Transfer Gain, } M = V_0/V_s = 2/(1\text{-}D) \quad (1)$$

It operates in two modes based on switch (S) condition in charging and discharging mode of the inductor (L) as explained in the following subsections.

Mode-I: Switch (S) is ON

Mode-I is a discharging mode, in this mode, an inductor (L) is charged by the supply voltage (V_S) through a switch (S) and capacitor (C_2) is charged by a capacitor (C_1) through the diode (D_2) and switch (S) as shown in the Fig. 6. In this mode capacitors (C_1 and C_3) are in discharging mode through the load. The current flow diagram of Mode-I is shown in Figure 6.

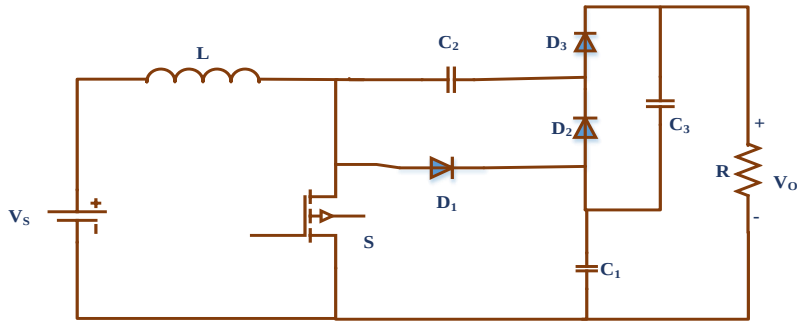

Figure 5. Schematic diagram of Double Boost Converter

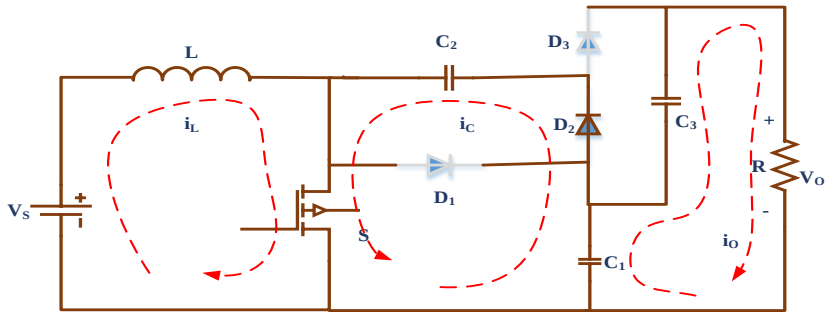

Figure 6. Mode-1: ON state, Double Boost Converter

Mode-II: Switch (S) is OFF

Mode-II is a charging mode, in this mode, the capacitor (C_1) is in charging mode, through supply voltage (V_S), inductor voltage (V_L) and diode (D_1). The capacitors (C_1 and C_3) are in charging mode through supply voltage (V_S), a capacitor (C_2) and diode (D_3). The current flow diagram of Mode-II is shown in Figure 7.

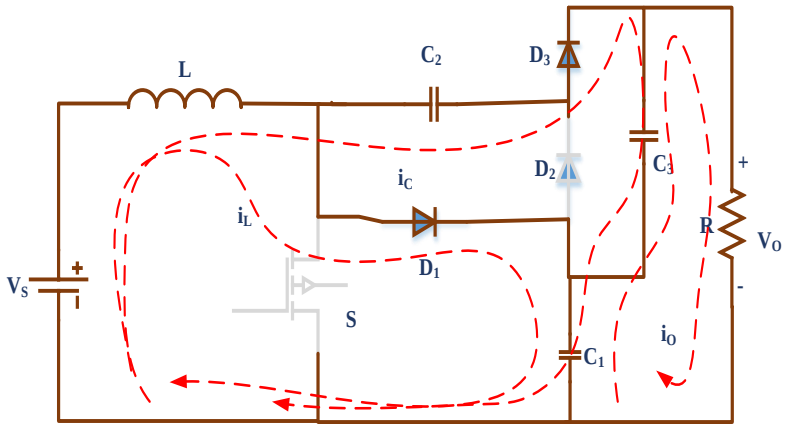

Figure 7. Mode-2: OFF state, Double Boost Converter

The above section gives the detailed operation of the developed single switch double boost DC-DC power converter in both ON and OFF switching conditions and twice the voltage transfer gain is achieved for step-up the low voltage renewable energy sources to the desired level to meet the load demand and to extract maximum power from the renewable energy sources.

3. Proposed PV Fed Water Pumping System Control

3.1. ANFIS MPPT Controller

In literature a various number of MPPT control techniques are available, each control techniques is having its own performance characteristics. Among them, PI, P&O, INC, Fuzzy, NN and ANFIS are the most popular methods in renewable energy system [20-22]. In this, the P&O method is the most commonly used method, due to its simple structure and easy to implement. In this paper, ANFIS based MPPT controller is used for the proposed system and the obtained results are compared to the conventional P&O based MPPT method.

ANFIS is a combination of neural network and fuzzy logic system. The architecture of the 5 layers ANFIS based MPPT model is shown in Figure 8. The control structure of ANFIS based MPPT model is shown in Figure 9 with two inputs V_{PV} and I_{PV} and one output *i.e.*, duty cycle (§) to operate the converter with maximum power extraction point. Each input port is having three membership functions; from Figure 9 nine rules are derived to generate the duty cycle to operate its maximum power extraction point.

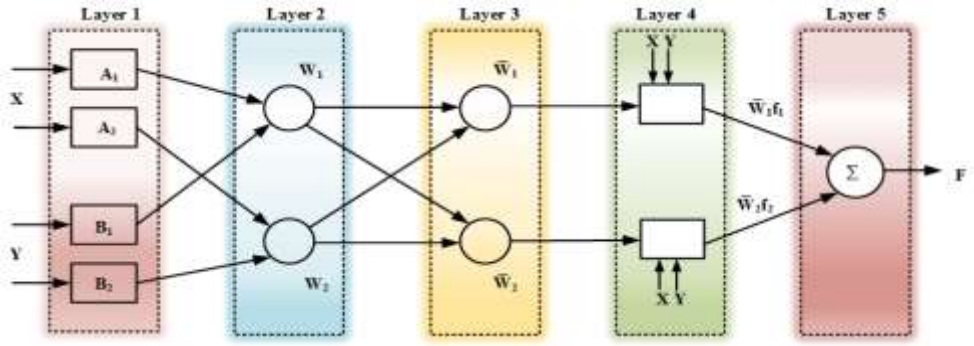

Figure 8. Architecture of 5 Layer ANFIS Model

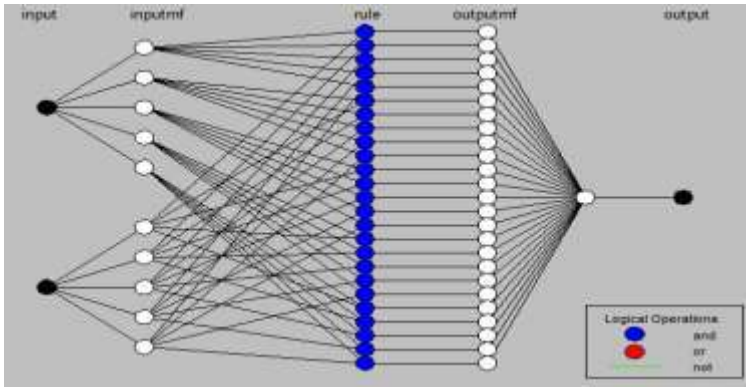

Figure 9. Control Structure of ANFIS Model

The above sub-section gives the basics of maximum power extraction concepts and the list of MPPT control techniques available in the literature to extract maximum power. In this proposed system, ANFIS based MPPT controller is used to extract maximum power and the detailed explanation of the MPPT technique is presented.

3.2. Hall Effect Controller for VSI

In BLDC motor, electronic commutation is generally used for commutating the current flow through the windings. In order to energize the next winding sequence, Hall Effect signals are used, which are generated by the inbuilt encoder by sensing the rotor position. Based on the sensed rotor position three hall signals will be generated and used for the six switch VSI control. Table 2. show the electronic commutation of BLDC motor switch states at different rotor positions with hall signals.

Table 2. BLDC motor Hall Signals for Electronic Commutation

Degree, ɵ	Hall sensor signals			VSI switching states					
	H_1	H_2	H_3	S_1	S_2	S_3	S_4	S_5	S_6
NA	-	-	-	-	-	-	-	-	-
0-60	-	-	*	-	-	-	*	*	-
60-120	-	*	-	-	*	*	-	-	-
120-180	-	*	*	-	*	-	-	*	-
180-240	*	-	-	*	-	-	-	-	*
240-300	*	-	*	*	-	-	*	-	-
300-360	*	*	-	-	-	*	-	-	*
NA	*	*	*	-	-	-	-	-	-
Where,	NA= Not Applicable			* = 1			- = 0		

4. Simulation Result and Discussion

To validate the proposed PV source fed water pump system with double boost converter topology, a MATLAB/Simulink model is developed and performance analysis is carried out in simulation by considering the constant solar irradiation data without any shading effect on it. Two different MPPT control techniques (P&O and ANFIS) are considered for extracting maximum power and the obtained results are compared.

Figure 10 shows the 1.2 kW PV system output voltage, current and power waveform. The PV system output voltage is 54V and power is 1200W.

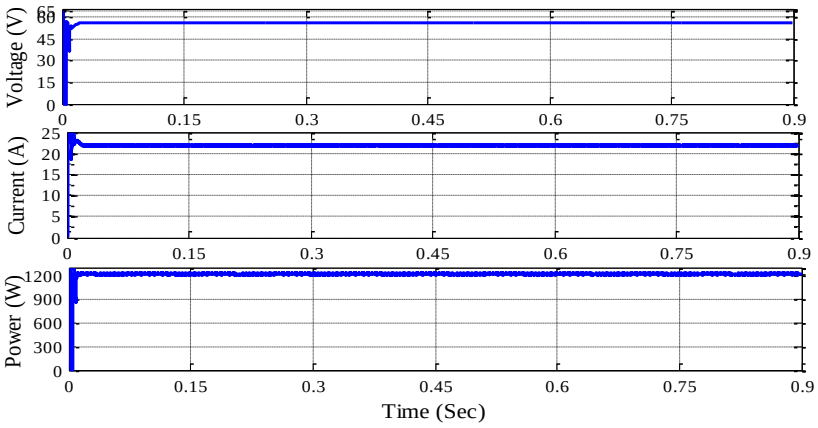

Figure 10. 1.2 kW PV System Output Voltage, Current and Power Waveforms

The DC link output voltage, current, and power with two different MPPT control techniques are presented in Figure 11. From the waveform, the ANFIS based system gives better results compared to the P&O based MPPT system. The obtained power from the system with ANFIS MPPT is 1104 W and from P&O based MPPT system is 1032 W.

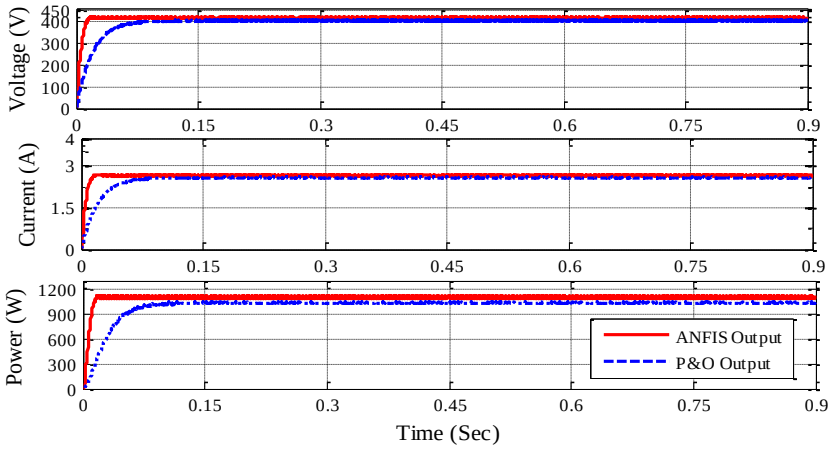

Figure 11. DC Link Output Voltage, Current and Power Waveforms

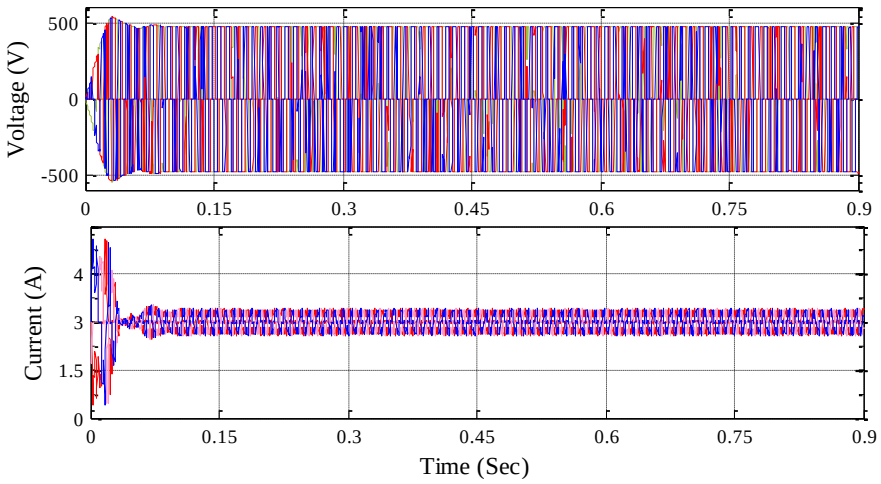

Figure 12. Voltage Source Inverter output Voltage and Current

Figure 12 shows the voltage source inverter output voltage and current which is 432.6V and 0.32A respectively. Figure 13 shows the stator back EMF of 240.6V and current of 0.32A. The Hall Effect signals for the electronic commutation in the voltage source inverter are shown in Figure 14.

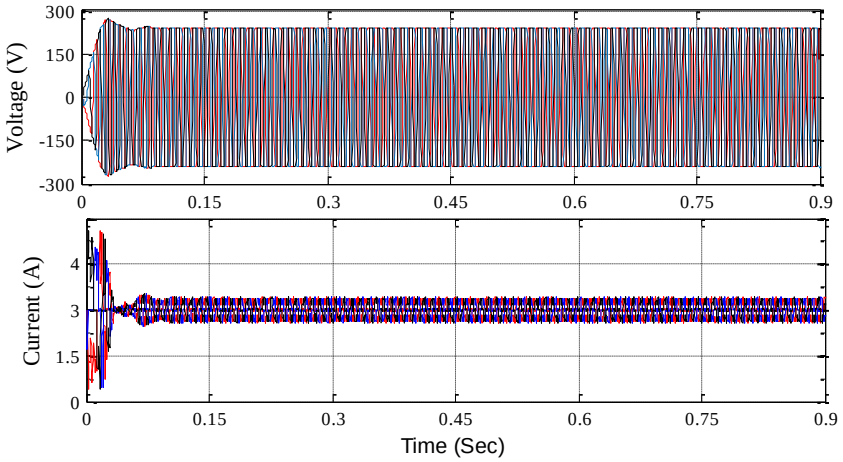

Figure 13. Stator Back EMF and Current Waveform

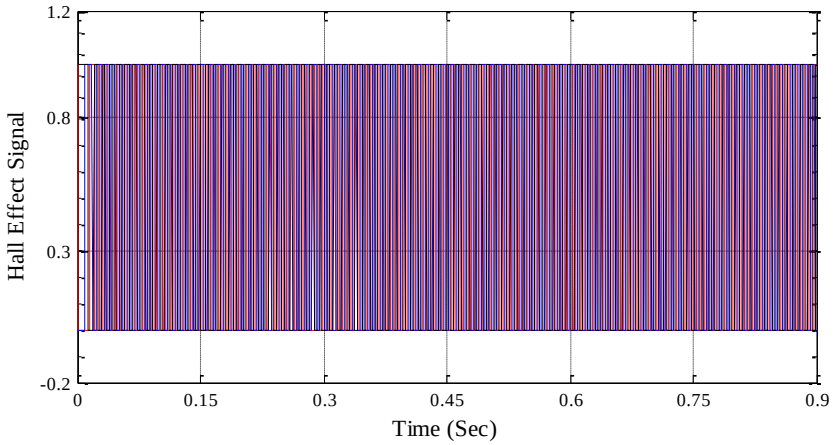

Figure 14. Hall Effect Signal

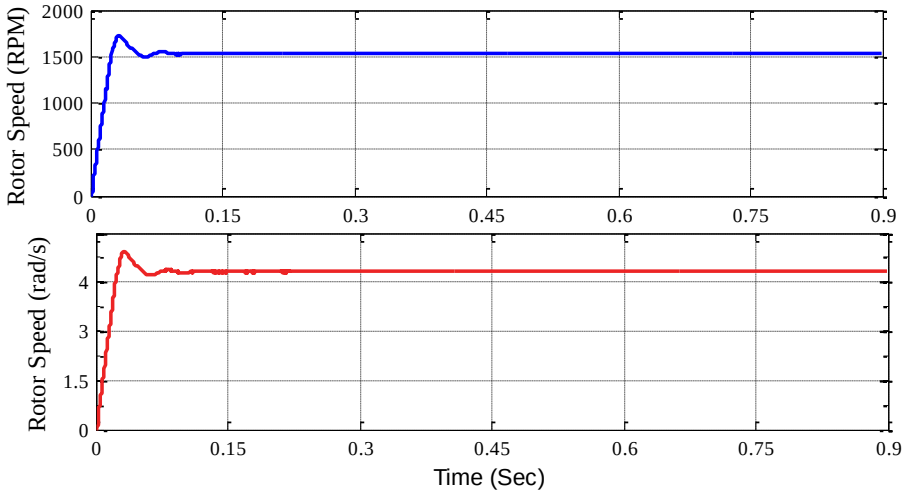

Figure 15. BLDC Motor Speed in RPM and in rad/sec

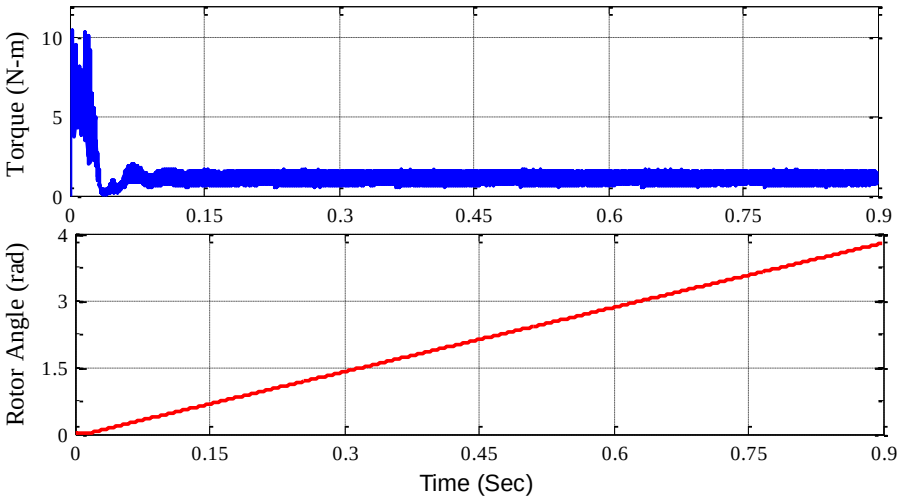

Figure 16. Torque and Rotor Angle of BLDC motor for Water Pump Application

Figure 15 gives the BLDC motor speed in RPM and rad/sec and the BLDC torque and rotor angle of the system is shown in Figure 16. From the performance analysis done in MATLAB/Simulink, PV fed BLDC motor different performance characteristics are presented in the simulation and result in the analysis section. The DC link voltage, current, and power values are tabulated with different MPPT techniques.

Table 3. Double Boost Converter DC link Voltage, Current and Power Comparison

Double Boost Converter DC link Voltage, current and power comparison				
	Voltage (V)	Current (A)	Power (W)	Efficiency
P&O MPPT	422	2.44	1032	86%
ANFIS MPPT	434	2.54	1104	92%

As illustrated in Table 3, the obtained DC link voltage, current and power outputs are listed with P&O and ANFIS based MPPT control techniques. In P&O, the obtained voltage, current and power are 422 V, 2.44 A, and 1032 W respectively, which is 86 % of the considered system rating. Similarly, in ANFIS based MPPT controller system, the proposed system gives the DC link voltage, current and power are 434 V, 2.54 A, and 1104 W respectively, which is 92 % of the considered system rating. From the comparison, the proposed PV fed water pumping system with double boost DC-DC converter and ANFIS based MPPT controller gives the greater efficiency of 92 %, which is more than the compared conventional P&O MPPT technique.

5. Conclusion

In this paper, PV source fed BLDC motor with double boost converter is designed and performance analysis has been done in MATLAB/ Simulink model. In boost converter max voltage gain is obtained by operating at its maximum duty cycle with high switching stress, this stress can be reduced by using a double boost converter. A water pump system with PV fed BLDC motor performance has been analyzed and discussed in this paper. In order to extract maximum power from the PV source, ANFIS based MPPT controller is used and the obtained results are compared with the most commonly used P&O MPPT method. From the results, ANFIS based MPPT system gives the better results with the efficiency of 92% compared to the P&O method with the efficiency of 86%. From the

developed system simulation analysis, ANFIS based MPPT water pump system with PV fed BLDC motor gives the better results.

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