SPV Based Landsman Converter with Fuzzy Logic Based BLDC Motor Drive for Water Pumping Applications

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Abstract : In this paper Fuzzy controller based for single array fed BLDC motor for water pumping applications is presented. Of the various renewable energy sources, Solar Photovoltaic is one among the cheapest and widely used. Maximum Power Point Techniques are used to extract the maximum power from a PV module and the fuzzy based MPPT technique has been found to provide better results for randomly varying atmospheric conditions as compared to other methods. The primary function of a DC– DC Landsman converter is to optimize the power output of SPV array and it also provides the safe and soft starting of the BLDC motor with an appropriate control. Amongst various DC–DC converters, Landsman converter meets the desired performance of proposed water pumping system. The starting, dynamic and steady-state behaviors of the SPV array fed BLDC motor driven water pump are presented to demonstrate the novelty of the proposed system. Induction Motors have been in use for years and now are being replaced by Brushless DC Motors owing to their advantages. The main advantages are higher efficiency and noiseless operation. The performance of the drive is analyzed for wide range of operations. Further to add to its features minimal rule based fuzzy logic speed controller is introduced. The performance characteristics of the proposed drive system are obtained for different operating conditions. Thetotal system performance can be evaluated by using MATLAB/SIMULINK software.

I. Introduction

Nonconventional sources of energy are gaining attention on account of dwindling fossil fuels. Using solar energy in coordination with conventional sources of energy will be more promising. The drastic reduction in the cost of power electronic devices and annihilation of fossil fuels in near future invite to use the solar photovoltaic (SPV) generated electrical energy for various applications as far as possible [1]. The water pumping, a standalone application of the SPV array generated electricity is receiving wide attention now a days for irrigation in the fields, household applications and industrial use.

The BLDC motor has high reliability, high efficiency, high torque/inertia ratio, improved cooling, low radio frequency interference and noise and requires practically no maintenance. To optimize the operating point of the SPV array in order to get maximum possible power output by means of the superior maximum power point tracking (MPPT) technique. A converter acts as an interface between the SPV array and Voltage Source Inverter (VSI) feeding the BLDC motor [2]. The starting inrush current of BLDC motor is restricted within the permissible range by appropriate control of Landsman converter through MPPT algorithm.

Investigating the various non-isolated DC–DC converters viz. buck, boost, buck–boost, Cuk and single-ended primary inductor converter for photovoltaic applications, although not based on water pumping, it is concluded that the best selection of DC–DC converter in the PV system is buck–boost converter, allowing an unbounded region for MPPT. On the contrary to it, a buck–boost converter always calls for a ripple filter at its both input and output for coveted operation of the overall system, resulting in an associated circuitry [3-7]. A Landsman converter, one of the topology of a DC–DC buck–boost converter, capable to overcome the aforementioned limitations of various previously used converters in SPV array fed water pumping, is adapted in this work. This converter is apparently derived by a CSC or topological transformations on a DC–DC boost converter. A small input inductor of the Landsman converter, as shown in Fig.1, acts as an input-ripple filter, eliminating the external ripple filtering. This inductor also damps the oscillation occurred, due to the snubbed elements of insulated gate bipolar transistor (IGBT) module, in the current through the module.

In this paper, fuzzy logic controller (FLC) is used for the control of the speed of the BLDC motor. The speed controllers are the conventional PI controllers and current controllers are the P controllers to achieve high performance drive. Fuzzy logic can be considered as a mathematical theory combining multi-valued logic, probability theory, and artificial intelligence to simulate the human approach in the solution of various problems by using an approximate reasoning to relate different data sets and to make decisions [8].

The Landsman converter is designed to operate always in continuous conduction mode (CCM) irrespective of the variation in irradiance level, resulting in a reduced stress on its power devices and components. The speed of BLDC motor is controlled by variation in the DC-link voltage. No additionalphase current sensors, additional control or associated circuitry are imposed unlike for the speedcontrol [9-13].The motor always attains the required speed to pump the water irrespective of the atmospheric variation. By using fuzzy logic controller for BLDC motor the various performances of the proposed water pumping system are analyzed through simulated results in MATLAB/SIMULINK software.

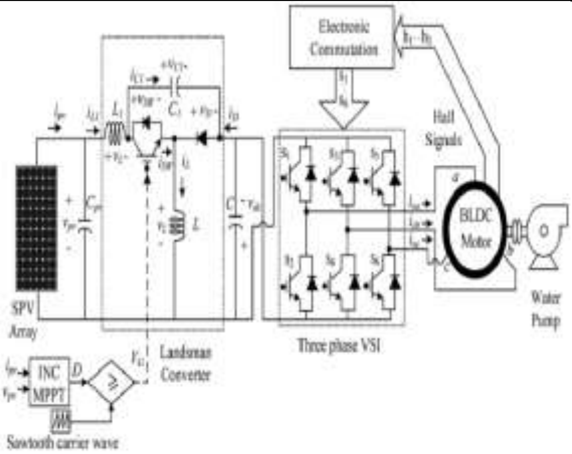


Fig.1. Configuration of SPV array – Landsman converter fed BLDC motor driven water pumping system

II. CONFIGURATION AND OPERATION OF PROPOSED SYSTEM

Fig.1 illustrates the detailed configuration and operation of the proposed SPV array-based BLDC motor driven water pumping system using the Landsman converter. The proposed system consists of an SPV array, Landsman converter, VSI and the BLDC motor with a water pump coupled to its shaft. The Landsman converter, acting as an interface between the SPV array and the VSI, is operated by the execution of INC-MPPT algorithm in order to extract the maximum power available from the SPV array. The VSI, operated through the electronic commutation, feeds the BLDC motor pump. The motor has three inbuilt low-cost Hall-effect position sensors, generating a particular combination of three Hall signals according to the rotor position.

III. OPERATING PRINCIPLE OF LANDSMAN CONVERTER

The Landsman converter is designed to operate in CCM irrespective of the variation in irradiance level. The circuit operation is divided into two modes as shown in Figs.2a, b, and the associated waveforms are shown in Fig. 2 c.

Mode I – when switch is ON

When the switch is on, VC_1,the voltage across intermediate capacitor C1 reverse biases the diode, resulting in a circuit configuration shown in Fig.2a. The inductor current I_L flows through the switch. Since $VC_1$is larger than the output voltage V_{dc}, C_1 discharges through the switch, transferring energy to the inductor L and the output. Therefore, V_{c1} decreases and I_L increases, as shown in Fig.2c. The input feeds energy to the input inductor L_1.

Mode II – when switch is OFF

When the switch is off, diode is forward biased, resulting in a circuit configuration as shown in Fig. 2b. The inductor current I_L flows through the diode. The inductor L transfers its stored energy to output through the diode. On the other hand, C_1 is charged through the diode by energy from both the input and L_1.Therefore, vc1increases and I_L decreases, as shown in Fig.2c.

Current ripple in input inductor L1

The ripple in input current, that is the current through L_1, IL_1iscalculated by considering its waveform as shown in Fig.2c for CCM of operation, assuming that all of the ripple component iniL1flows through C1. The shaded area in the waveform of vc1represents an additional flux ΔΦ. Therefore, the peak-to-peak current ripple DIL1is written as

$$\Delta I_{L_1} = \frac{\Delta\Phi}{L_1} = \frac{1}{L_1}\frac{1}{2}\frac{\Delta V_{C_1}}{2}\frac{T}{2} \qquad (1)$$

From Fig.2c during switch off, the current through C1 is as

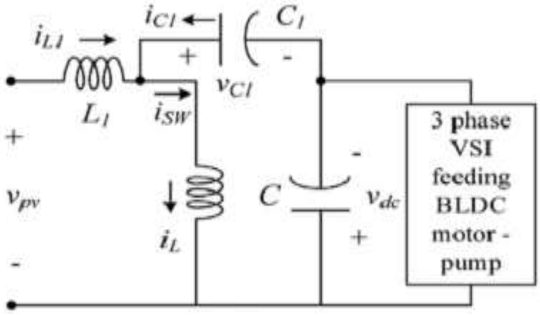
$$i_{C_1} = I_{L_1} = C_1 \frac{\Delta V_{c_1}}{(1-D)T} \qquad (2)$$

Where D is the duty ratio and T is the switching period. The voltage ripple content in $vc_1$is estimated from (2) as

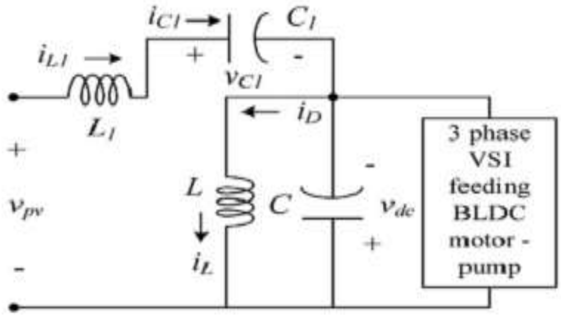
$$\Delta V_{C_1} = \frac{I_{L_1}}{C_1}(1-D)T \qquad (3)$$

Therefore, substituting DVC1from (3) into (1) gives

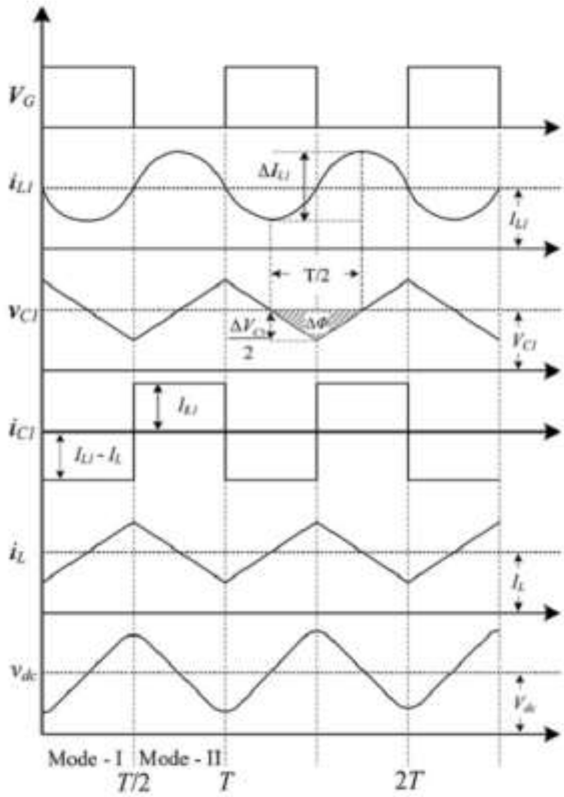
$$\Delta I_{L_1} = \frac{1}{L_1}\frac{1}{2}\frac{I_{L_1}}{2C_1}(1-D)T\frac{T}{2} \qquad (4)$$



(a)



(b)



(c)

Fig.2 Operation of the Landsman converter a Mode I b Mode II c Waveforms

$$\Delta I_{L_1} = \frac{1}{8L_1C_1}\frac{I_{L_1}(1-D)}{f_{SW}^2} \tag{5}$$

It is normalized as

$$\frac{\Delta I_{L_1}}{I_{L_1}} = \frac{1}{8L_1C_1}\frac{(1-D)}{f_{SW}^2} \tag{6}$$

Where $f_{SW} = 1/T$ is the switching frequency. From the input–output relationship, it is obvious that

$$I_{L_1} = \frac{D}{1-D} I_{dc} \tag{7}$$

whereI_{dc} is the output current of Landsman converter

Therefore, substituting $I_{L1}$from (7) into (5) and rearranging the terms, it gives

$$L_1 = \frac{DI_{dc}}{8 f_{SW}^2 C_1 \Delta I_{L_1}} \quad (8)$$

IV. DESIGN OF PROPOSED SYSTEM

The configuration of the proposed system presented in Fig.1 has various stages viz. SPV array, Landsman converter, BLDC motor and a water pump. These stages are designed such that the operation and performances remain satisfactory and are not deteriorated even by the sudden atmospheric disturbances. A BLDC motor is selected to drive a water pump of 5.8 kW.

A. Design of SPV array

To ensure the successful operation even at the minimum solar irradiance of 200 W/m2 and considering the losses associated with converters and motor pump, an SPV array of 6.8 kW peak power rating is selected and designed for the proposed system. An array of the required size is made by using HBL Power System Ltd. make SPV module, HB-12100 with peak power capacity of 100 W. The maximum voltage of SPV array is selected as 289 V. The electrical specifications of HB-12100 and designed SPV array at 1000 W/m2 are estimated in Table.1.

TABLE 1 DESIGN OF SOLAR PV ARRAY

HB-12100 SPV module	
number of cells in a module	36
open-circuit voltage, V_o	21 V
short-circuit current, I_s	7.1 A
voltage at MPP, V_m	17 V
current at MPP, I_m	6 A
Design of SPV array	
voltage at MPP, $V_{mpp} = v_{pv}$	289 V
power at MPP, $P_{mpp} = p_{pv}$	6800 W
current at MPP, $I_{mpp} = i_{pv}$	$P_{mpp}/V_{mpp} = 6800/289 = 23.53$ A
numbers of modules connected in series, N_s	$V_{mpp}/V_m = 289/17 = 17$
numbers of modules connected in parallel, N_p	$I_{mpp}/I_m = 23.53/6 = 4$
open-circuit voltage, V_{oc}	$N_s \times V_o = 17 \times 21 = 357$ V
short-circuit current, I_{sc}	$N_p \times I_s = 4 \times 7.1 = 28.4$ A

B. Design of Landsman converter

The Landsman converter is designed to operate in CCM irrespective of the operating conditions. Following the atmospheric variation, the converter automatically operates either in buck mode or boost mode. The estimation of the parameters of Landsman converter is summarized in Table 3.2, where C is the output capacitor at the DC link of VSI, ΔIL is the permitted current ripple in IL, ΔV_{dc} is the permitted voltage ripple in V_{dc}, ωh and ωl are the highest and lowest values of VSI output voltage frequencies, respectively, in rad/s, f isthe frequency of VSI output voltage in Hz, Ch and Cl are the capacitors estimated corresponding to ωh and ωl, respectively, P is the number of poles in the BLDC motor, N_{rated} is the rated speed of the motor and N is the minimum speed required to pump the water.

TABLE 2 DESIGN OF LANDSMAN CONVERTER

Parameter	Expression	Design data	Value	Selected value
D	$\frac{V_{dc}}{V_{dc}+V_{mpp}}$	$V_{dc}=310$ V, $V_{mpp}=289$ V	0.52	0.52
C_1	$\frac{D \times I_{dc}}{f_{SW} \Delta V_{C_1}}$; $I_{dc}=P_{mpp}/V_{dc} V_{C_1}=V_{mpp}+V_{dc}$	D=0.52, $P_{mpp}=6800$ W, $V_{dc}=310$ V, $f_{SW}=20$ kHz, $V_{mpp}=289$ V, $\Delta V_{C_1}=20\%$ of V_{C_1}	4.76 µF	5 µF
L_1	$\frac{D \times I_{dc}}{8 \times f_{SW}^2 \times C_1 \times \Delta I_{L_1}}$; $I_{L_1}=I_{mpp}$	D=0.52, $P_{mpp}=6800$ W, $V_{dc}=310$ V, $f_{SW}=20$ kHz, $C_1=5$ µF, $I_{mpp}=23.53$ A, $\Delta I_{L_1}=3\%$ of I_{L_1}	0.99 mH	1 mH
L	$\frac{D \times V_{mpp}}{f_{SW} \Delta I_L}$; $I_{dc}=P_{mpp}/V_{dc}$, $I_L=I_{mpp}+I_{dc}$	D=0.52, $V_{mpp}=289$ V, $f_{SW}=20$ kHz, $P_{mpp}=6800$ W, $V_{dc}=310$ V, $I_{mpp}=23.53$ A, $\Delta I_L=3\%$ of I_L	5.46 mH	6 mH
C	$\omega_h=2 \times \pi \times f = \frac{2 \times \pi \times N_{rated} \times P}{120}$; $\omega_l=2 \times \pi \times f = \frac{2 \times \pi \times N \times P}{120}$; $C_h=\frac{I_{dc}}{6 \times \omega_h \times \Delta V_{dc}}$; $C_l=\frac{I_{dc}}{6 \times \omega_l \times \Delta V_{dc}}$; $I_{dc}=P_{mpp}/V_{dc}$	P=6, $N_{rated}=3000$ rpm, N=1100 rpm, $V_{dc}=310$ V, $P_{mpp}=6800$ W, $\Delta V_{dc}=4\%$ of V_{dc}	$C_h=312.7$ µF $C_l=853$ µF	1000 µF

C. Design of water pump

A water pump is coupled to the shaft of BLDC motor, acting as a load. This pump is designed by its power–speed characteristics as

$$K_p = \frac{P_m}{\omega^3} = \frac{5800}{(2 \times \pi \times 3000/60)^3} = 1.87 \times 10^{-4}\ \mathrm{W/(rad/s)^3} \quad (9)$$

Where Kp is proportionality constant, Pm is the rated power and ω is the rated speed of selected BLDC motor.

V. CONTROL OF PROPOSED SYSTEM

There are two control methodologies used in the proposed system at two different stages, one for MPPT of SPV array and another for BLDC motor operation as elaborated in the subsequent sections.

A. INC-MPP tracking

An INC-MPPT technique is applied to track the optimum operating point of SPV array. This technique states that the power slope of the PV array is null, positive and negative, respectively, at MPP ($dp_{pv}/dv_{pv} = 0$), left of MPP and right of MPP. Due to this fact, the MPP can be found in terms of INC as

$$p_{\mathrm{pv}} = v_{\mathrm{pv}} \times i_{\mathrm{pv}} \tag{10}$$

$$\frac{\partial p_{\mathrm{pv}}}{\partial v_{\mathrm{pv}}} = i_{\mathrm{pv}} + v_{\mathrm{pv}} \times \frac{\partial i_{\mathrm{pv}}}{\partial v_{\mathrm{pv}}} = 0 \tag{11}$$

$$\frac{\partial i_{\mathrm{pv}}}{\partial v_{\mathrm{pv}}} = -\frac{i_{\mathrm{pv}}}{v_{\mathrm{pv}}} \text{ at MPP} \tag{12}$$

$$\frac{\partial i_{\mathrm{pv}}}{\partial v_{\mathrm{pv}}} > -\frac{i_{\mathrm{pv}}}{v_{\mathrm{pv}}} \text{at the left of MPP} \tag{13}$$

$$\frac{\partial i_{\mathrm{pv}}}{\partial v_{\mathrm{pv}}} < -\frac{i_{\mathrm{pv}}}{v_{\mathrm{pv}}} \text{at the right of MPP} \tag{14}$$

To implement the INC-MPPT algorithm, the direct duty ratio control is adapted in view of the simplicity. This method obviating the proportional integral (PI) controller directly uses duty ratio as the control parameter. The direct duty ratio perturbation offers very good stability characteristics and high energy utilization efficiency due to the low impact of noise and the absence of oscillation. Moreover, higher perturbation rates up to the PWM rate can be used without losing the global stability of the system.

An excellent tracking performance under dynamic condition with negligible oscillations around optimum operating point is achieved. Optimally selecting the initial value of duty ratio and its perturbation size offer soft starting of BLDC motor by slowly increasing the DC-link voltage of VSI.

B. Electronic commutation of BLDC motor

An electronic commutation of BLDC motor stands for commutating the currents flowing through windings of BLDC motor in a predefined sequence using a decoder circuit. Three inbuilt low-cost Hall sensors generate three Hall signals according to the rotor position at an interval of 60°. These Hall signals are then converted, using a decoder circuit, into the six switching pulses tope rate the VSI feeding a BLDC motor. In this manner, fundamental frequency switching of VSI is obtained, resulting in are reduced switching loss. Table 3 shows the switching states of VSI for each particular combination of Hall signal states. It is perceptible that only two switches conduct at a time, resulting in120° conduction mode of operation of VSI and hence the reduced conduction losses.

Table.3. Switching states for electronic commutation of BLDC motor

θ, deg	Hall signals			Switching states					
	h_3	h_2	h_1	S_1	S_2	S_3	S_4	S_5	S_6
NA	0	0	0	0	0	0	0	0	0
0–60	1	0	1	1	0	0	1	0	0
60–120	0	0	1	1	0	0	0	0	1
120–180	0	1	1	0	0	1	0	0	1
180–240	0	1	0	0	1	1	0	0	0
240–300	1	1	0	0	1	0	0	1	0
300–360	1	0	0	0	0	0	1	1	0
NA	1	1	1	0	0	0	0	0	0

VI. MATLAB/SIMULINK RESULTS

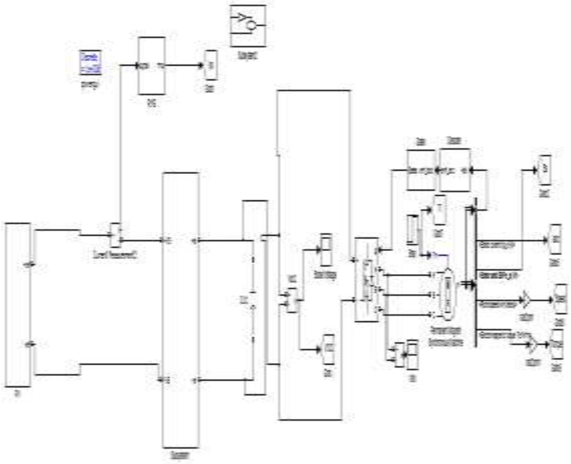


Fig.3.MATLAB/SIMULINK circuit of SPV array–Landsman converter fed BLDC motor drive

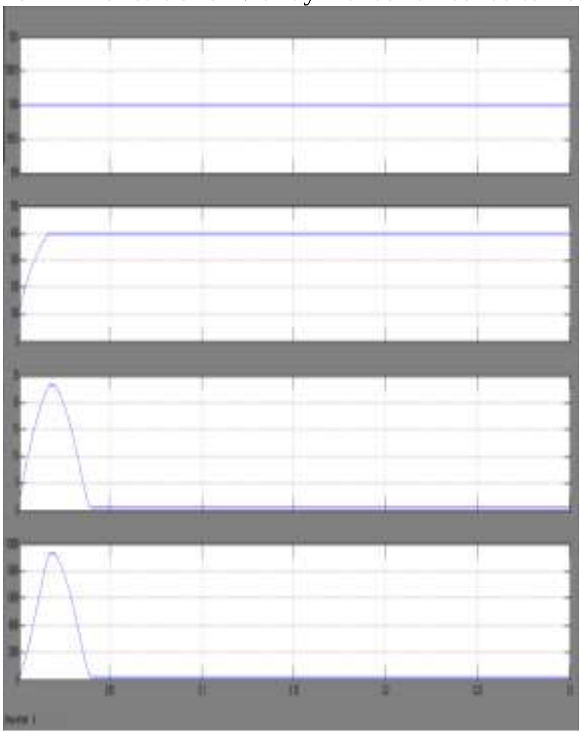


Fig4. Simulation model of Speed, PV voltage, PV current and Power

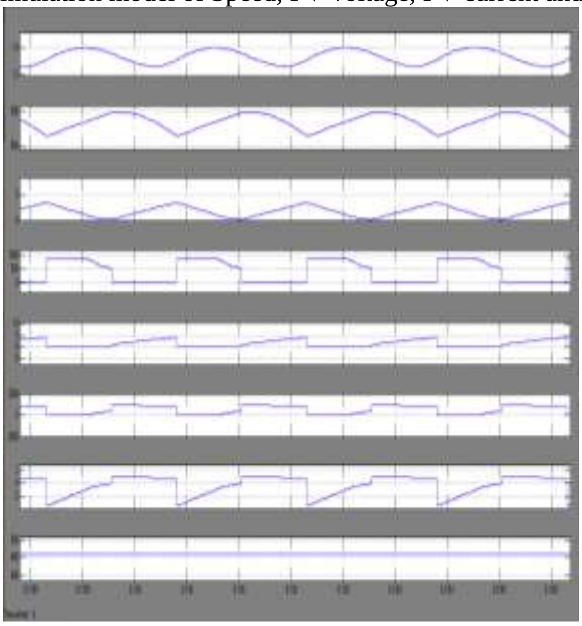


Fig.5.Simulation waveform for Load Current 1, Capacitor voltage 1, Load current, Switch voltage, Switch current, Diode voltage, Diode current, DC voltage

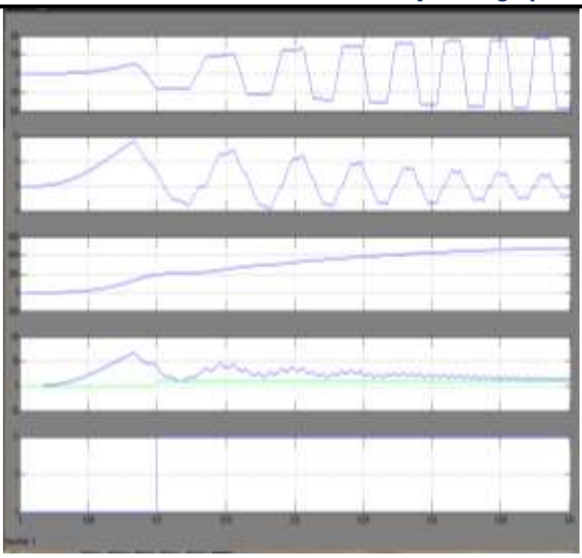


Fig.6.Simulation waveform for Back EMF, Stator current, Speed, Electromagnetic torque, Load torque

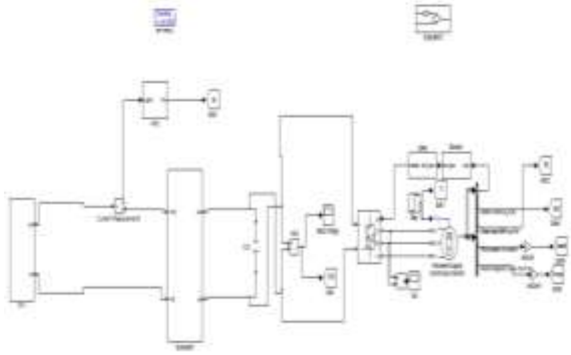


Fig.7.MATLAB/SIMULINK circuit of SPV array–Landsman converter fed BLDC motor drive

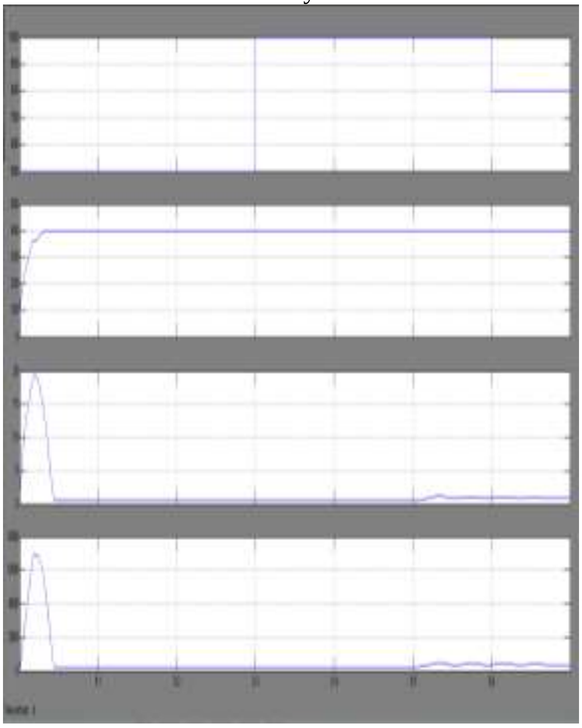


Fig.8.Simulation waveform for Speed, PV voltage, PV current and Power.

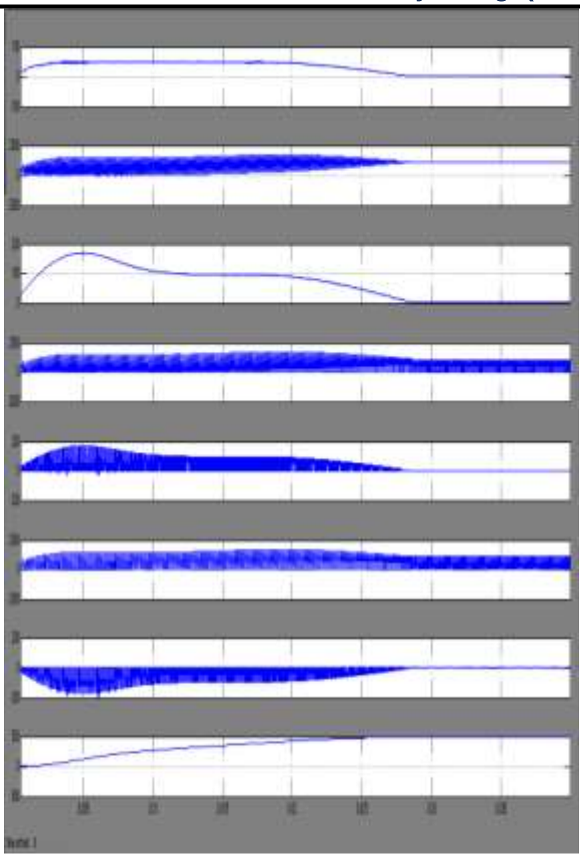


Fig.9. Simulation waveform for Load current 1, Capacitor voltage 1, Load current, Switch voltage, Switch current, Diode voltage, Diode current and DC current

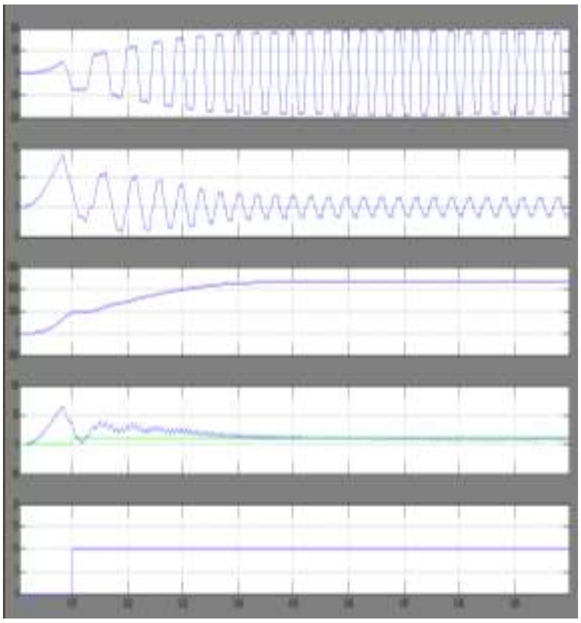


Fig.10. Simulation waveform for Back EMF, Stator current, Speed, Electromagnetic torque and Load torque.

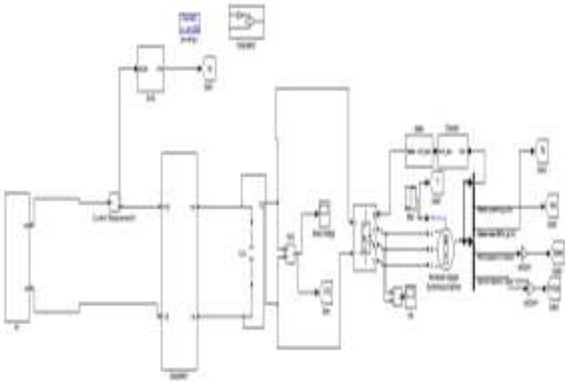


Fig.11.MATLAB/SIMULINK circuit of SPV array–Landsman converter fed BLDC motor drive with fuzzy logic controller

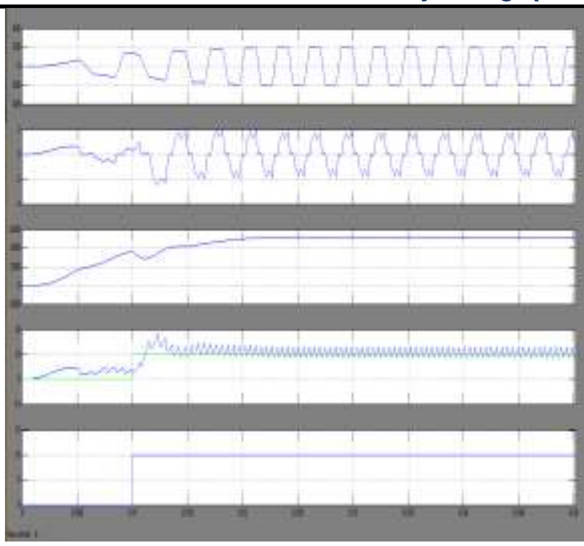


Fig.12.Simuation waveform for Back EMF, Stator current, Speed, Electromagnetic torque and Load torque

VII. CONCLUSION

In this paper A solar PV array-based BLDC motor driven water pump employing Landsman converter has been proposed, and its starting, dynamic and steady-state behaviors have been analyzed through simulation and implementation on the developed system. The utilization of Landsman converter has eliminated external filtering requirement and has also contributed to damp the oscillations occurred in the module current due to snubber elements. The speed control of BLDC motor by variable DC-link voltage has completely eliminated the additional phase current sensing, DC-link voltage sensing, additional control and associated circuitry. The fuzzy logic controller is implemented to proposed circuit to attain better performance regarding good speed and reduction of torque ripples. The Landsman converter with fuzzy based BLDC motor is hence proved as a compatible and suitable combination for SPV array-based water pumping with better speed control.The future development of the project is hybrid renewable energy system and hybrid fuzzy logic controller.

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