Simulation and Modeling of a Constant Voltage Controller Based Solar Powered Water Pumping System

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Abstract. In this paper the performance of a squirrel cage induction motor driving a water-pump load is investigated. The induction motor is fed through a Photovoltaic (PV) array. The PV array and the drive is designed and simulated in a Simulink/MATLAB environment. For tracking of maximum power point of PV array a constant voltage controller (CVC) is also presented. The performance of directly connected and constant voltage controller fed water pumping system is compared for different operating conditions. The system with constant voltage controller is found to have better performance as compared to directly connected system.

Keywords: centrifugal pump, constant voltage controller, induction motor, PV array.

1 Introduction

Solar energy is one of the most promising renewable energy for future, particularly for the rural areas which are not connected to the national grid. In rural areas perhaps the most common practice for which they require electrical energy is the water pumping employed for the irrigation of fields. Solar energy can be directly converted into the electrical energy with the help of solar cell, which is basically a P-N junction that absorbs light, releases electrons and create holes to produce a voltage in the cell. However, the efficiency of solar cell is poor due to the involvement of number of stages for energy conversion before being available in the useful form [1].

For water pumping applications, usually low rating pumps in the range of 200-2000W are used in conjunction with the PV array. Centrifugal pumps and volumetric pumps are the two basic types of pumps used in the PV water pumping application. Generally, centrifugal pumps are preferred over other for the three important reasons: (i) in it PV energy utilization is higher, (ii) it can operate for long periods even for low insolation levels, and (iii) its load line is in close proximity to the maximum power point line [2].

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Although, several types of electric motors such as permanent magnet brushed DC motor, permanent magnet synchronous motor, switched reluctance motor, and induction motors have also already been tested and used for water pumping system with the PV array. But, due to the low maintenance requirement, low cost and readily availability induction motors are preferred. The induction motors are designed to give optimal performance on the rated conditions. So, variations in operating condition of motor can deteriorate the performance of the motor and hence the system [3]-[4].

The power and current characteristics of PV array are highly nonlinear and depends upon the various factors such as intensity of sunlight, temperature and cell area. Generally, these factors vary throughout day and hence the power of the PV array. So, for the full exploitation of PV array its maximum output power has to be tracked with the help of a controller under varying operating conditions [5]-[6].

Various MPP tracking schemes such perturbation and observation or hill climbing, incremental conductance and artificial intelligence based schemes had been addressed in the literature. Constant voltage controller proposed in [7] can be a good method for tracking of maximum power from PV array on different operating conditions. The method utilizes the fact that the maximum power line is almost linear in a narrow band of particular voltage. However, the work is limited to DC motor, which has higher cost and frequent maintenance problem. This work can be extended to assess the performance of system with induction motor.

In this paper the performance of the PV array fed pump coupled three phase induction motor with a constant voltage controller is investigated. The system under investigation is compared with the directly connected system for various operating conditions.

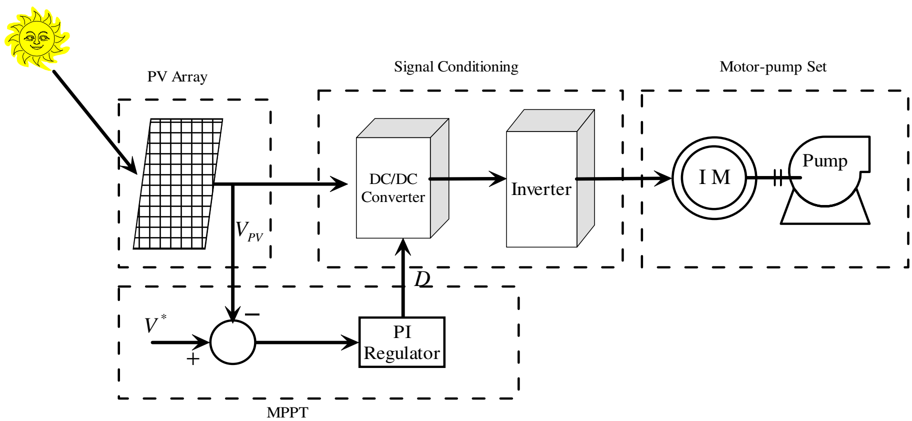

Fig. 1. Schematic diagram for constant voltage controlled system

2 System Description and Modeling

The system under investigation consists of a PV array, DC-DC converter, induction motor, and centrifugal pump. Simple but accurate model of PV array and centrifugal pump are derived in order to simulate the system. All components are modeled separately and then joined together. The Schematic diagram of the system under investigation is shown in Fig. 1.

2.1 PV Array Model

Interconnected number of solar cells in series/parallel combination is known as PV modules. A group of such modules connected in series/parallel combination to generate the required power is known as PV Array. For describing the electrical behavior of a solar cell, different mathematical models have been introduced. The most commonly used equivalent model is one diode or the two diode equivalent model [1, 3, 5]. As shown in Fig. 2 one diode equivalent model of solar cell is used because of its simple structure.

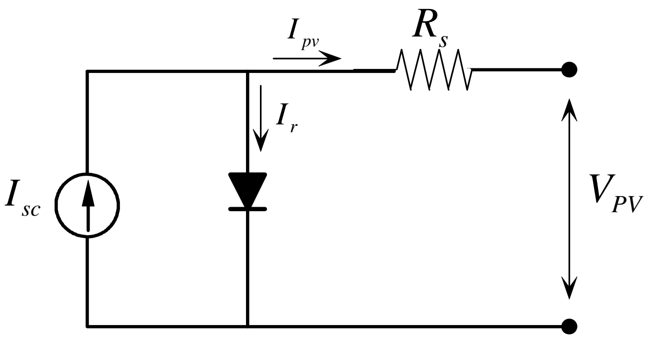

Fig. 2. Equivalent circuit of solar cell

The PV array has a non-linear output which varies with the variation in level of solar insolation and temperature. So, the effects of the changes in temperature and solar irradiation levels are also included in the final PV array model. The cell output voltage is given by eq. 1 [5].

$$V_{PV} = \frac{nkT_C}{q}\ln\left(\frac{I_{sc} + I_r - I_{pv}}{I_r}\right) - I_{pv}R_s \tag{1}$$

Where V_{PV} and I_{pv} are output voltage and currents of the cell respectively, R_s is cell resistance, I_{sc} is photocurrent or short circuit current, I_r is reverse saturation current of diode, q is electron charge, k is Boltzmann constant, T_r is reference operating temperature of cell and n is the ideality factor.

The solar cell operating temperature varies as a function of solar insolation level and ambient temperature. The effects of change in temperature on output voltage and current of solar cell are incorporated with the help of eq. (2)-(3).

$$T_V = 1 + \beta(T_c - T_a) \tag{2}$$

$$T_I = \frac{\gamma}{G_c}(T_a - T_C) \tag{3}$$

where, T_V & T_I are the temperature coefficients of solar cell output voltage and current resp., T_a & T_c are the ambient and operating temperatures resp., and β & γ are the constants.

The effect of change in temperature due to the change in solar insolation level is incorporated with the help of eq. (4)-(5)

$$C_V = 1 + \beta\alpha(G_X - G_C) \tag{4}$$

$$C_I = 1 + \frac{1}{G_C}(G_X - G_C) \tag{5}$$

Where, C_V & C_I are the correction factors for output voltage and current of solar cell respectively, G_X & G_C are the standard and operating insolation levels respectively, and α is a constant. The change in temperature ΔT_c due to change in insolation level is obtained by eq. (6)

$$\Delta T_C = \alpha(G_X - G_C) \tag{6}$$

2.2 Induction Motor Model

The dynamic equivalent circuit of a three phase induction motor expressed in *d-q* synchronously rotating reference frame is shown in Fig. 3 [8].

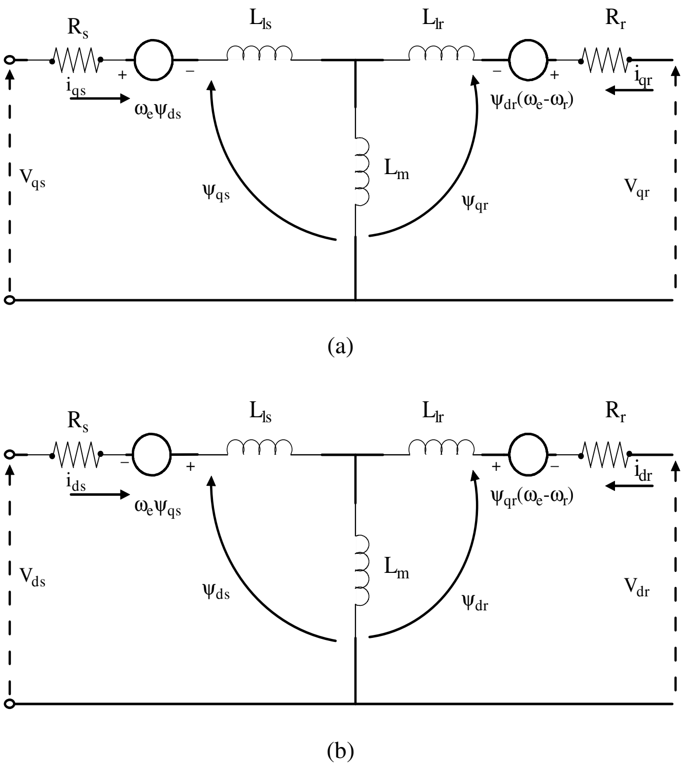

Fig. 3. Dynamic (a) *q- axis* (b) *d-axis* equivalent circuits of machine

where, R_s & R_r are the stator and rotor resistances resp., L_{ls} & L_{lr} are the stator and rotor leakage inductances resp., L_m is the mutual inductance, V_{ds} & V_{dr} are the *d*-axis stator and rotor voltages resp., V_{qs} & V_{qr} are *q*-axis stator and rotor voltages resp., ψ_{qs} & ψ_{qr} are the *q*-axis stator and rotor flux linkages resp., ψ_{ds} & ψ_{dr} are the *d*-axis stator and rotor flux linkages respectively.

The electromagnetic torque developed by an induction motor is given by:

$$T_e = \frac{3}{2}\frac{P}{2}L_m(I_{qs}I_{dr} - I_{ds}I_{qr}) \tag{7}$$

The mechanical part modeling of an electric motor is given by:

$$T_e = Jp\omega_m + B\omega_m + T_L \tag{8}$$

where J is the total inertia of motor shaft, B is the friction coefficient, and T_L is the load torque.

2.3 Centrifugal Pump Model

The centrifugal pump is identified by its head-flow rate (H-Q) performance curve at the nominal speed. Affinity laws are generally used to estimate the performance curve of the pump. Affinity Laws describes that the flow rate (Q), head (H) and power (P) is directly proportional to the speed, square of speed and cube of the speed respectively [9].

A centrifugal pump load is generally modeled in the form of a load torque applied to motor shaft. This load torque depends on the process requirements of head to be overcome, flow rate requirement, and the operating speed. The torque speed characteristic of the motor for a pump load is given by eq. (9) and shown in fig. 4[2].

$$T_L = T_P = K\omega_r^{\ 2} \tag{9}$$

where K is defined in terms of nominal power P_n and nominal speed ω_n of the centrifugal pump as:

$$K = \frac{P_n}{\omega_n^{\ 3}}$$

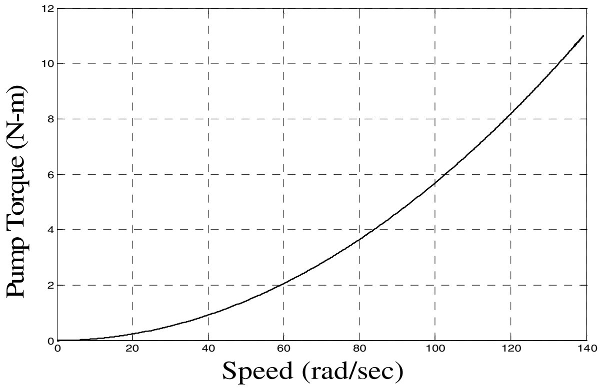

Fig. 4. Pump-torque characteristic of centrifugal pump

3 Constant Voltage Controller

In this work, a constant voltage controller (CVC) is designed to track the point of maximum power of PV array. The CVC in this work is basically a fixed gain Proportional–Integral (PI) controller used to control the DC bus voltage. The block diagram of the designed CVC scheme is shown in Figure 5.

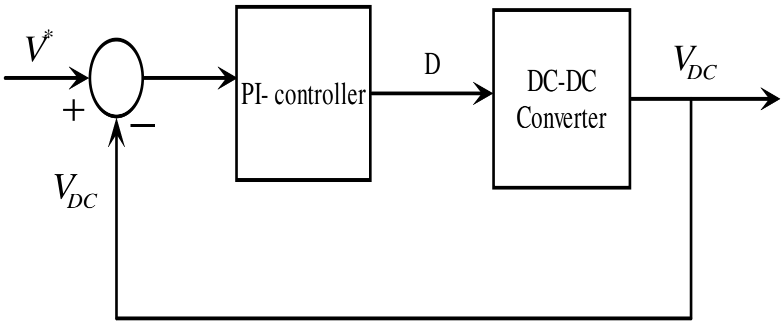

Fig. 5. Block diagram of constant voltage control

The voltage of a DC link is measured and feed backed to the comparator. In comparator, the measured value is compared with reference value of voltage and accordingly an error signal for the PI regulator is generated. PI regulator is used to generate the duty ratio of the controlled DC- DC converter circuit to maintain the constant voltage. The controller gains $K_p = 3$ and $K_i = 10$ are used after optimization by trial and error method.

4 Results and Discussion

The complete model of solar powered water pumping system in two modes i.e. directly connected and constant voltage controlled are simulated in the MATLAB with the sampling frequency of 50 KHz. As the output of the PV array is DC only so an inverter will always be an interfacing device for connecting the induction motor. A three phase, 2.2 KW, 220 V, 50 Hz induction motor is used in this work. The specifications of Induction motor are given in Table I of Appendix.

Fig. 6 shows the current-voltage (*I-V*) characteristics for the designed PV array. The *I-V* characteristics are obtained at different insolation levels of 1000 W/m^2, 800 W/m^2, 600W/m^2, 400 W/m^2, and 200 W/m^2. Fig. 7 shows the power-voltage (*P-V*) characteristics of the designed PV array at different insolation level. The PV array is designed to give short circuit current (I_{sc}) = 40 A and open circuit voltage (V_{oc}) = 230 V at an insolation of 1000 W/m^2 on an ambient temperature of 20ºC.

With an objective to investigate the performance of the system close to the real operating conditions the insolation level is randomly varied from 1000 W/m^2 to 600 W/m^2 as shown in Fig. 8. The response of PV Array voltage feeding directly a motor pump load is shown in Fig. 9. From the PV array voltage response it is evident that voltage varies about 10 % when the insolation level is varied from 1000 W/m^2 to 600 W/m^2. This variation in DC link/PV array voltage with the variation in insolation level varies the motor speed as can be depicted in Fig. 10.

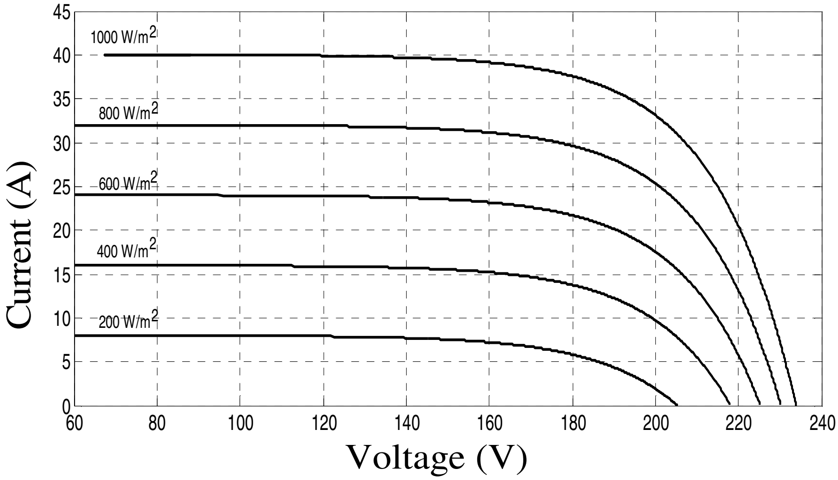

Fig. 6. Current-Voltage *(I-V)* characteristics at various insolation

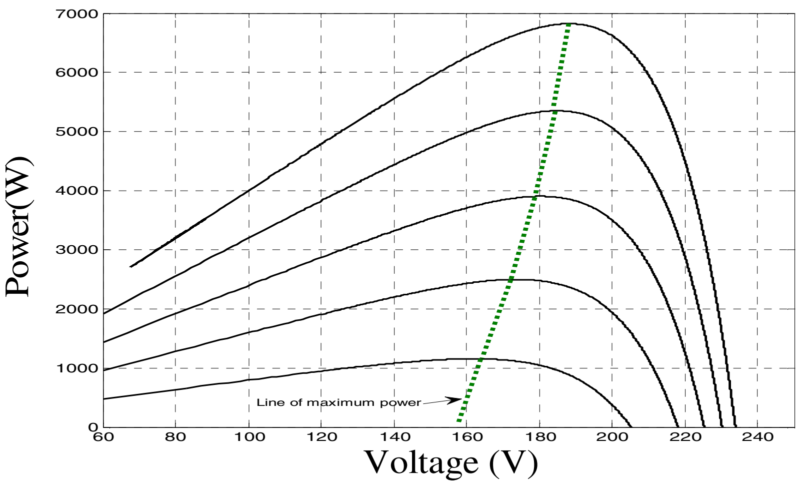

Fig. 7. Power-Voltage *(P-V)* characteristics at various insolation

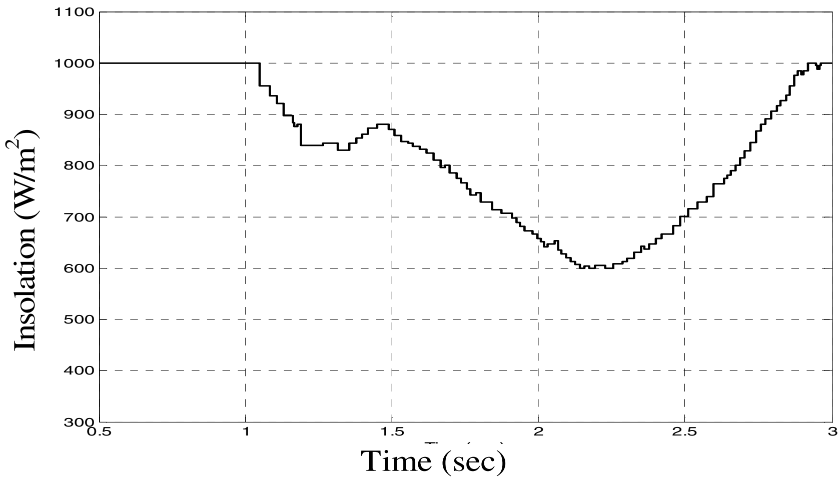

Fig. 8. Insolation level variation for directly connected system

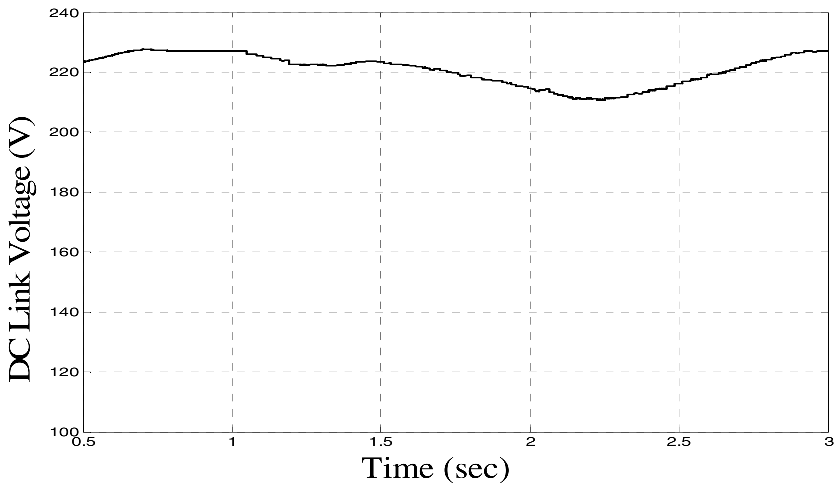

Fig. 9. Response of DC link voltage for directly connected system

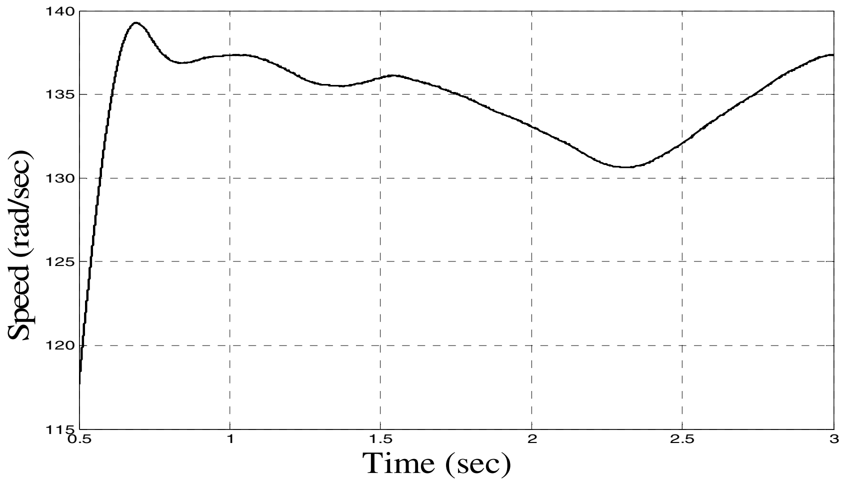

Fig. 10. Response of motor speed for directly connected system

Fig. 11 shows the variation in insolation level with maximum of 1000 W/m^2 and minimum of 600 W/m^2. Under these changing operating conditions the responses with the constant voltage controller are obtained. Fig. 12 shows the behavior of DC link/PV array voltage with the above operating conditions, from which almost constant voltage of 180 V is evident. Fig. 13 shows the speed response of the motor from which minor speed change is observed.

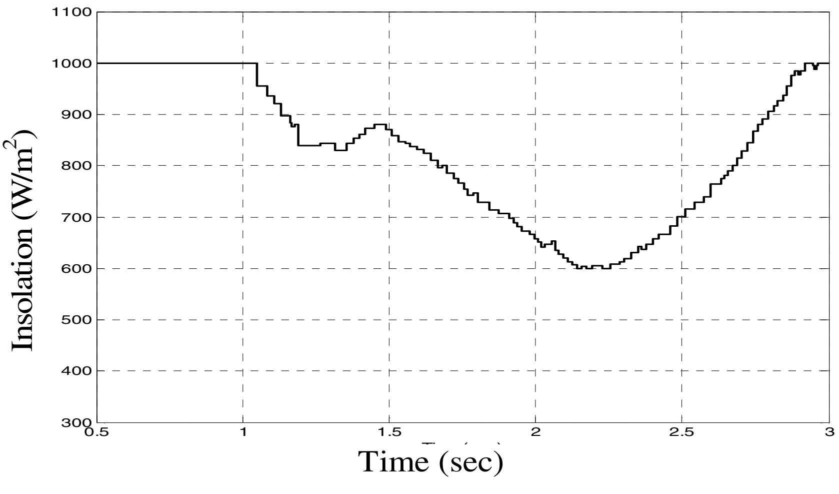

Fig. 11. Insolation level variation for constant voltage controlled system

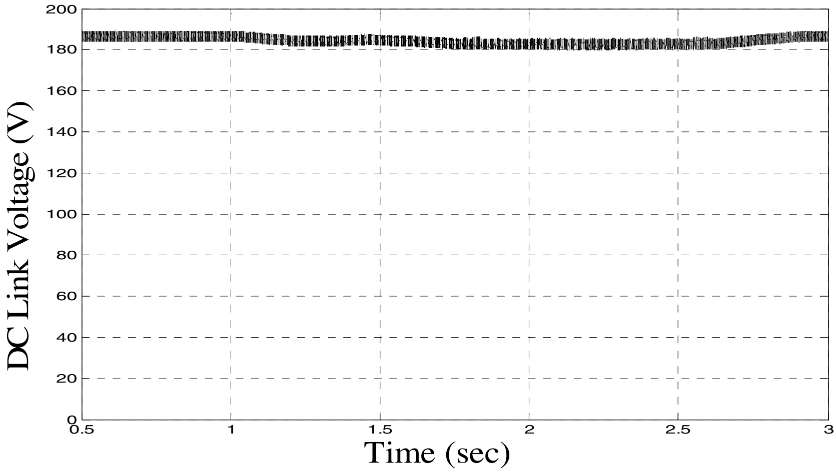

Fig. 12. Response of DC link voltage for constant voltage controlled system

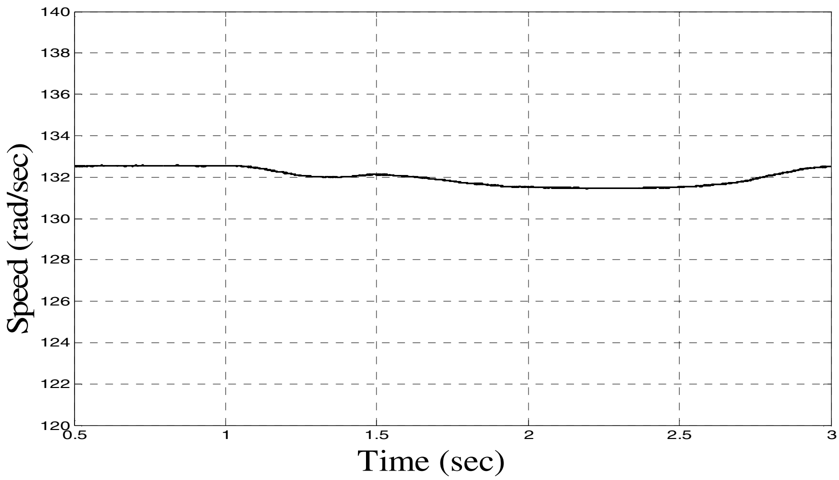

Fig. 13. Response of motor speed for constant voltage controlled system

5 Conclusion

In this paper, a one diode PV array model along with the other components of the induction motor driven water pump system are designed and simulated in the MATLAB/Simulink. The effects of solar insolation on the PV array assisted pump system have been investigated. A comparative study of performance of constant voltage controlled system with the directly connected PV system has been presented. The constant voltage controlled system offers good performance and therefore can be recommended for water pumping applications.

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Appendix

Table 1. Induction Motor Parameters

Parameters	Values
Stator Resistance (R_s)	0.435 Ω
Stator Inductance (L_{ls})	2.0 mH
Rotor Resistance (R_r)	0.816 Ω
Rotor Inductance (L_{lr})	2.0 mH
Mutual inductance (L_m)	69.3 mH
Inertia Constant (J)	0.02 Kg-m^2
Friction Factor (F)	0.002 N-m-sec