Single-Stage Solar Photovoltaic Array Fed Water Pumping System

Sonak Singh[1] Bhim Singh[2]

Abstract–The single stage solar photovoltaic (SPV) array fed water pumping system consists of a solar PV array, voltage source inverter (VSI) and an induction motor driven pump set. In this system, VSI performs maximum power tracking (MPP) from the solar PV array and also controls the speed of an induction motor using V/F control algorithm. The reference speed for V/F control is estimated by a new approach. The reference speed is estimated from two components, one from the dc-link voltage of VSI and other from the PV array power. The reference speed of the motor mainly depends on the PV array power and the tracking of maximum power, if variation occurs in the solar PV power then the reference speed of induction motor changes accordingly. The model of proposed system is developed in the MATLAB/Simulink and its simulated results have demonstrated the satisfactory performance in dynamic as well as in steady state operating conditions.

Keywords–solar PV panel, voltage source inverter, induction motor, pump set

I. INTRODUCTION

In Indian economy, GDP of agriculture is approximately 16%.According to the studies, India can contribute other countries not just itself in agricultural products but the output of agriculture products falls due to several factors. The main factor for agriculture products is the water [1]. Mainly rivers, canals, wells and monsoons water are used for the agriculture products. In India, 64% of cultivated land mainly depends on monsoons. Irrigation is important to reduce the dependence on monsoons in India. Diesel pump sets are used in India for irrigation but diesel pump-set has high maintenance cost and also creates pollution. The motor pump sets are also used for the irrigation where grid electricity is present but in India. Many rural areas are not so developed and the grid electricity is not present. So, the solar PV (Photo-Voltaic) array fed water pumping system can easily meet the irrigation problem easily [2]. Its maintenance cost is negligible and does not create pollution but its installation cost is high. Solar PV array fed water pumping system life span is observed approximately 25-30 years.

Solar PV water pumping systems are already in use in worldwide. Solar PV array fed dc motor driven pump sets are already in use. For extracting the maximum power, a dc-dc converter requires at output of solar PV array for this system. When the insolation varies a very small variation occurs in the output voltage of PV array but large variation occurs in the PV array current. The speed of the dc motor changed very less because the speed of the dc motor depends on the voltage but the large variation in load torque because it depends on the current [3,4]. Some authors have used lookup table in solar PV array fed dc motor pump set [5]-[7]. Carbon brushes are present in the dc motor which causes sparking inside the dc motor due to this loss in the dc motor are high and maintenance cost is high. So, the dc motor pump set cannot be used in mining and chemical industries.

Solar PV array fed induction motor driven pumps are also used but the efficiency of the low rating induction motor is less. So, high rating induction motor pump sets are mostly used for solar water pumping system. Such systems are of two types one is single-stage [8]-[12] and other is two-stage [13, 14]. In single stage, only VSI (Voltage Source Inverter) extracts the maximum power from SPV array and also controls the induction motor. In two stage system, a dc-dc converter is first stage and VSI is second stage. In two stage system, a dc-dc converter is used for MPPT of SPV array and VSI is used for the induction motor control. The two-stage system is used for higher power rating. Solar fed induction motor driven pumps are reliable and maintenance free and it can be used in any industry because of no sparking and less loss compared to the dc motor. Mainly two types of control of the induction motor are used for such systems as V/F control [8]-[10] and vector control [12]-[14]. Z-source inverters are also used for single stage solar water pumping system [11].

Solar PV array fed PM brushless DC motor is also used for this system [15]-[18]. DC source supplied to PM brushless DC motor via a VSI. The system requires dc-dc converter and VSI. This motor requires extra sensors for electronics control of the VSI. A PMBLDC motor is more efficient than an induction motor but it is more costly than an induction motor.

In this paper, a solar PV array fed induction motor driven pump is investigated in detail. This system is single-stage system, only an inverter performs both functions. One is MPPT of SPV array and controlling the speed of an induction motor. The reference speed of an induction motor for V/F control is estimated using a new approach. The reference speed in this control is estimated using two components one from the MPPT of SPV array and other from the SPV power. In this single-stage system, the dc-link voltage of VSI is floating. The system performance is demonstrating through simulated results.

II. PROPOSED SINGLE-STAGE SPV WATER PUMPING SYSTEM

Fig.1 shows the single-stage solar PV array fed water pumping system. The proposed system consists of three parts which are SPV array, VSI and an induction motor driven pump set. The proposed system requires only voltage and current sensors for MPPT of SPV array. In this

The paper first received 9June 2014 and in revised form 12 Aug 2015.
Digital Ref: APEJ-2014-06-0438
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system, the SPV array is directly connected to the dc-link of the VSI and the control of this VSI performs both task, one is maximum power point tracking and other is controlling the speed of an induction motor driven pump.

III. Design of single-stage SPV water pumping system

In the proposed system, a 5 hp (3.7 kW) pump driven by an induction motor is extracting the power from the solar PV array. For this pump, a 5.3 kW solar PV panel is selected because some losses are also present into the system.

A. Selection of DC Capacitor Voltage

In order to achieve proper dc-link voltage compensation, the minimum DC-link voltage of VSI must be greater than the phase voltage of the proposed system as [18],

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}} = \frac{2\sqrt{2}\times 415}{\sqrt{3}} = 677.7V \quad (1)$$

where V_{LL} is the line voltage of the induction motor. The estimated value of the V_{dc} from (1) is obtained as 677.7 V and it is selected as 700V.

B. Solar PV Panel Modeling

A solar PV panel consists of several solar cells in series or parallel to convert solar insolation into electricity. Here the PV panel system is designed to have peak power rating of 5.3 kW at 1000W/m^2.

The SPV array maximum rating used for proposed system is 5.3 kW. Each PV module has a rated power of 200 W, a rated current of 7.6 A, a rated voltage of 26.3 V, a short-circuit current of 8.21 A, and an open circuit voltage of 32.9V [19].

The active power generated by the SPV array is given as,

$$P_{maxM} = V_{mppM} * I_{mppM} \quad (2)$$

Maximum power of SPV array generally given as,
P_{maxM} = (80% of V_{oc} * 90% of I_{sc}) thus I_{mppM} is 7.61A and V_{mppM} is 26.3V of each module. In order to get a DC-link voltage of 700V, PV array voltage at MPP should around 700V under different insolation conditions. MPP voltage should vary around 700V for irradiance variation from 1000W/m^2 to 200W/m^2 for proper operation of the voltage source inverter.

$$P_{max} = V_{mpp} * I_{mpp} = 700\times 7.6 = 5.3 \text{ kW} \quad (3)$$

From (3), a 5.3 kW power capacity is achieved.

The numbers of PV modules connected in series are as,
N_s= 700/26.3=26.61 (27 selected)

The current rating required is as, I_{pv}=7.6A

Number of parallel strings is as, N_p=7.5/7.6 = 1

C. Design of DC-Link Capacitor

The energy conservation principle is used to estimate the value of DC capacitor [20],

$$\frac{1}{2}C_d\left[V_{dc}^2 - V_{dc1}^2\right] = 3aVIt \quad (4)$$

$$\Rightarrow \frac{1}{2}C_d\left[700^2 - 680^2\right] = 3\times 1.2\times 239.6\times 7.5\times 0.01 watts$$

It results in the dc link capacitance as, C_d = 4687.82µF.

where V_{dc} is the reference DC-link voltage and V_{dc1} is the minimum DC-link voltage, a is the overloading factor of VSI, V is the motor phase voltage, I is the motor phase current, and t is the time by which the DC-link capacitor

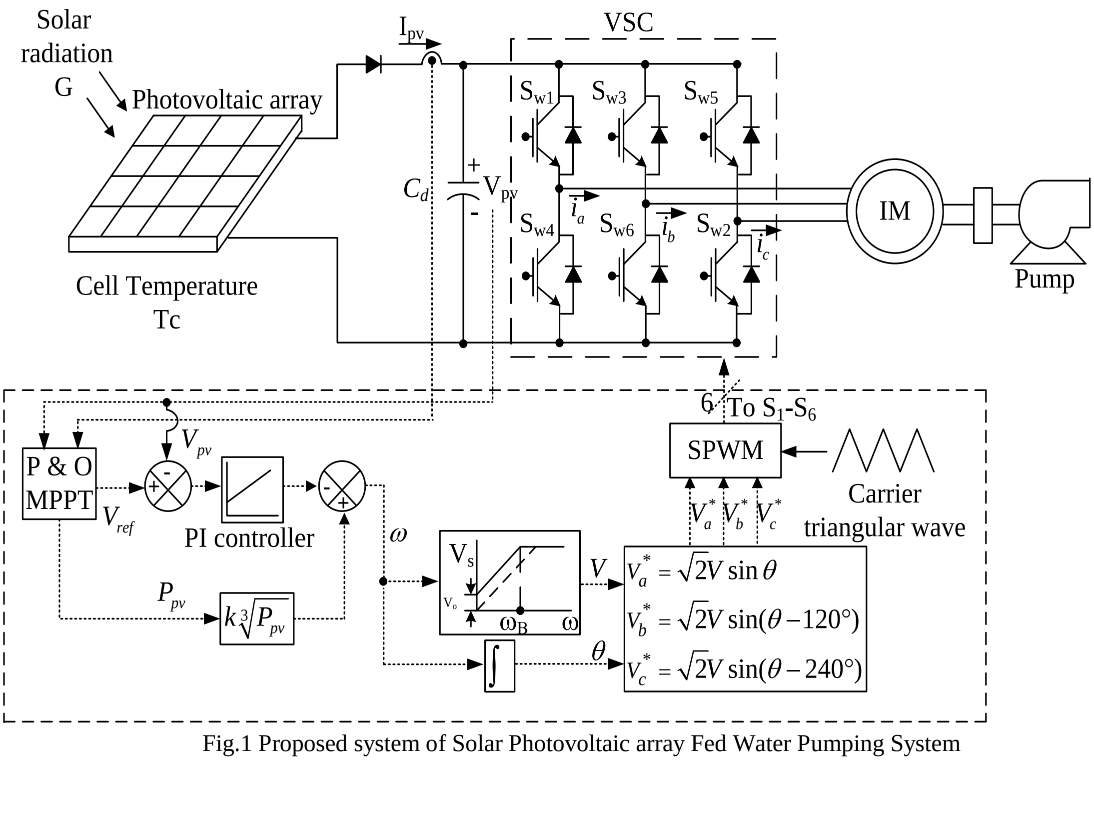


Fig.1 Proposed system of Solar Photovoltaic array Fed Water Pumping System

is to be charged. It results in the value of a dc capacitor C_d of the order of 4687.82 μF and it is selected as 5000 μF.

IV. CONTROL ALGORITHM FOR PROPOSED SPV WATER PUMPING SYSTEM

Fig.1 shows the proposed single-stage SPV water pumping system. The V/F control is used to control the speed of an induction motor. The proposed system control scheme is shown in Fig.1.

A. Maximum Power Point Tracking

Several MPPT algorithms are used to extract the maximum power from the solar PV array [21]. The P&O (Perturb & Observe) method is used in this system. This algorithm has been mainly used because its easy implementation and reduced complexity. Fig. 2 shows the P&O control algorithm.

In this method, voltage (dc-link voltage) and current of SPV array are sensed and are fed to the controller in which the change in sensed DC-link and PV power are estimated. The algorithm periodically tracks the MPP and operates by increasing or decreasing the reference dc-link voltage. From flow-chart shown in Fig.2, it can be observed that at first the present samples for $V_{pv}(k)$ and $I_{pv}(k)$ are sensed than $P_{pv}(k)$ is generated by multiplying the $V_{pv}(k)$ and $I_{pv}(k)$. The present and one past sample set $P_{pv}(k-1)$, $V_{pv}(k-1)$ are used for calculation of ΔP_{pv} and ΔV_{pv}. The governing equations used for the P&O MPPT at one insolation level are as,

$\Delta P_{pv} = 0$ and $\Delta V_{pv} = 0$, at MPP (5a)

$\Delta P_{pv} > 0$ and $\Delta V_{pv} > 0$, (5b)
Left of MPP on P_{pv} versus V_{pv} curve

$\Delta P_{pv} < 0$ and $\Delta V_{pv} < 0$, (5c)
Right of MPP on P_{pv} versus V_{pv} curve

The reference voltage is adjusted using eq. (6). The variation in reference voltage according to governing equations is as,

if $\Delta P_{pv} = 0$ and $\Delta V_{pv} = 0$

$$V_{refnew} = V_{refold}, \tag{6a}$$

if $\Delta P_{pv} > 0$ and $\Delta V_{pv} > 0$ or $\Delta P_{pv} < 0$ and $\Delta V_{pv} < 0$

$$V_{refnew} = V_{refold} + step, \tag{6b}$$

if $\Delta P_{pv} > 0$ and $\Delta V_{pv} < 0$ or $\Delta P_{pv} < 0$ and $\Delta V_{pv} > 0$

$$V_{refnew} = V_{refold} - step, \tag{6c}$$

Finally the values of $V_{pv}(k-1)$ and $I_{pv}(k-1)$ are updated for next iteration. V_{refnew} is assigned as output. The control of V_{ref} ensures that SPV array is operating at maximum power point.

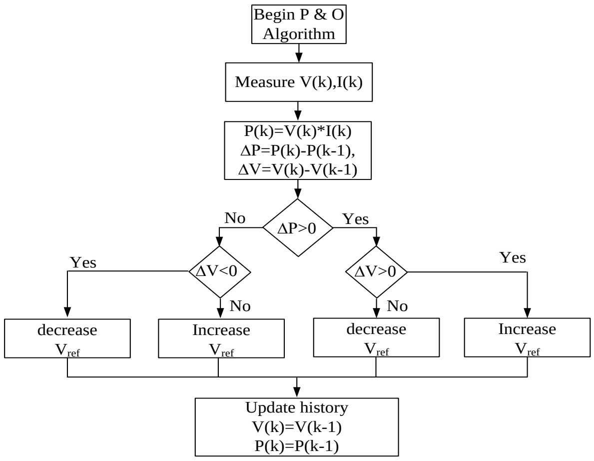


Fig.2 Flow chart of P & O algorithm

B. Control of an Induction Motor

In this system, the speed of an induction motor is controlled by the V/F control. The V/F control of an induction motor driven pump does not use any sensors for the motor control. It's an open loop control. In this system, the reference speed of the motor is calculated by the MPPT algorithm and solar PV array power. In this control, the speed control of the drive is directly controlled by a voltage source inverter.

1) Estimation of Reference Speed

The pump model correlation between the torque and speed is approximated as,

$$T = a_1 + a_2 \omega^2 \tag{7}$$

where, a_1, a_2 are the constants of the pump, T and ω are the torque and the speed of the pump respectively. Pump characteristics analogous to the flow rate and head of the pump. Manufacturer gives information about the hydraulic pumps. According to the affinity law states that power is proportional to the cube of the speed ω at which the centrifugal pump is running [12].

In this system, affinity law is used to estimate the one component of reference speed. So, the motor operates under the solar insolation variation and it determines the centrifugal pump flow rate. The one component of reference speed corresponding to the PV power is given as [12],

$$\omega_1 = K \sqrt[3]{P_{pv}} \tag{8}$$

where K is constant for converting the PV array power into speed and P_{pv} is the power of PV array.

The dc-link voltage controller is used to estimate the second component of the reference speed. In this system, the actual dc-link voltage (V_{dc}) compares with the reference dc-link voltage (V_{dc}^*) results in a voltage error is given as

$$V_{dcl(n)} = V^*_{dc(n)} - V_{dc(n)} \tag{9}$$

This error signal is passed through the voltage controller, and the output speed is given as,

$$\omega_{2(n)} = \omega_{2(n-1)} + K_{pdc}\left\{V_{dcl(n)} - V_{dcl(n-1)}\right\} + K_{idc}V_{dcl(n)} \quad (10)$$

where K_{pdc} and K_{idc} are the proportional and integral gains of the dc-link voltage PI controller. The losses of the system account the output of this PI controller.

The reference speed for an induction motor drive is given as,

$$\omega_r^* = \omega_1 - \omega_2 \quad (11)$$

where ω_r^* is the reference speed and ω_1 is used from (8) and ω_2 is used from (10).

2) V/F Control of an Induction Motor

In industry, the V/F control of an induction motor is commonly used for speed control. In this control, the air gap flux of the motor remains constant so that the ratio of voltage and frequency are changed proportionately. In this, no sensed signals are required for the control of the induction motor. Fig.1 shows the control scheme of V/f speed control.

The reference speed ω_r^* is the control parameter for V/F control. The phase voltage V of the induction motor changes, when the reference speed of an induction motor is controlled up-to base speed. The phase voltage of the induction motor remains at its rated value, if the reference speed is greater than the base speed. The power consumption in variable speed control drive is reduced when operated in fully open loop control. Angle θ is generating by integrating the ω signal, and the using of angle θ, reference voltage (v_a^*, v_b^* and v_c^*) signals are generated as shown in Fig.1. The reference voltages signals are comparing with the carrier wave and the switching PWM signals are generated for the VSI [8]-[10].

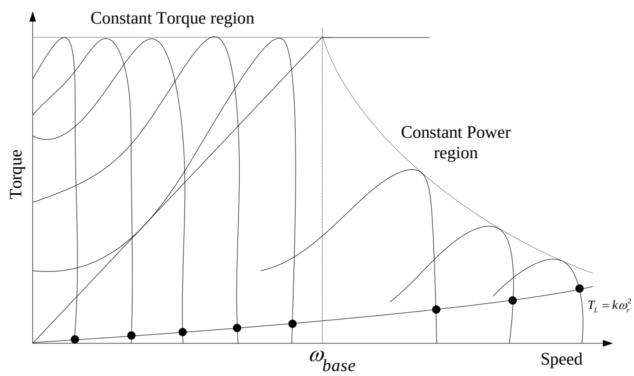


Fig.3 Torque -speed curve showing effect of frequency variation. Supply voltage and load torque changes

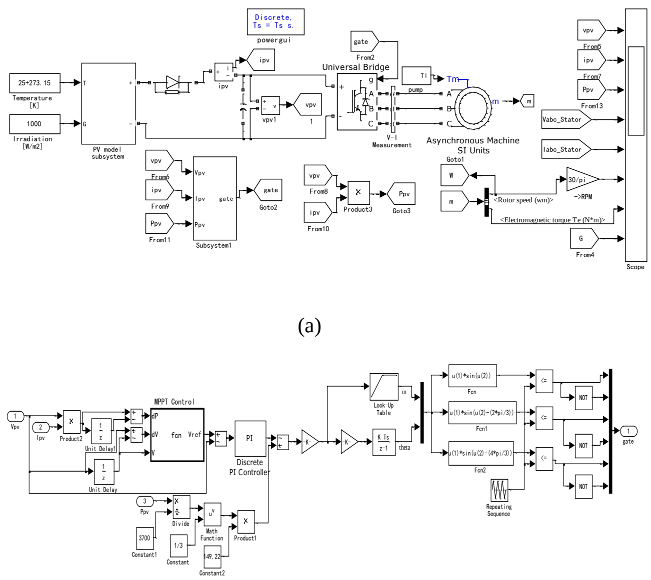
The steady-state performance of an induction motor drive on a torque-speed curve with a pump-type load ($T_L = K\omega_r^2$) is shown in Fig 3. The points are indicated that as the speed is gradually increased, the torque is proportional to the speed square. If the reference speed of induction motor changes than the operating point shifts to another torque-speed curve correspondingly the phase voltage of an induction motor increases up to base speed after that it remains constant.

V. Modeling and Simulation of Proposed SPV Water Pumping System

The performance of proposed single-stage solar photovoltaic array fed water pumping system is simulated using the developed model in MATLAB/Simulink platform as shown in Fig.4 (a).The developed Simulink model for generating reference speed using SPV power and MPPT voltage controller is shown in Fig.4 (b). The rating of the induction motor considered for this simulation is a 5 hp (3.7 kW), 415V and 50 Hz.

VI. Results and Discussion

A solar PV water pumping system is modeled using MATLAB\Simulink. The proposed SPV water pumping system not only extracting the maximum power from the PV array and also generates different reference speeds at different insolation level. To demonstrate this feature the results are shown in Figs.5-6 and following observations are made based on these results.



(a)

(b)

Fig.4 single stage solar water pumping system (a) MATLAB model, (b) control model

A.Performance for Maximum Power Tracking

Fig. 5 shows the dynamic response of MPPT of SPV array. In Fig.5, V_{pv} starts from 821 V because dc-link capacitor of VSI already charged with open circuit voltage of PV array, when the MPPT P&O algorithm is enabled then the voltage reduces and the current increases for tracking the maximum power point. Fig.5 shows the steady state response of MPPT of SPV array. Fig.6 shows the dynamic and steady state performances of maximum power point tracking at different solar insolation level.

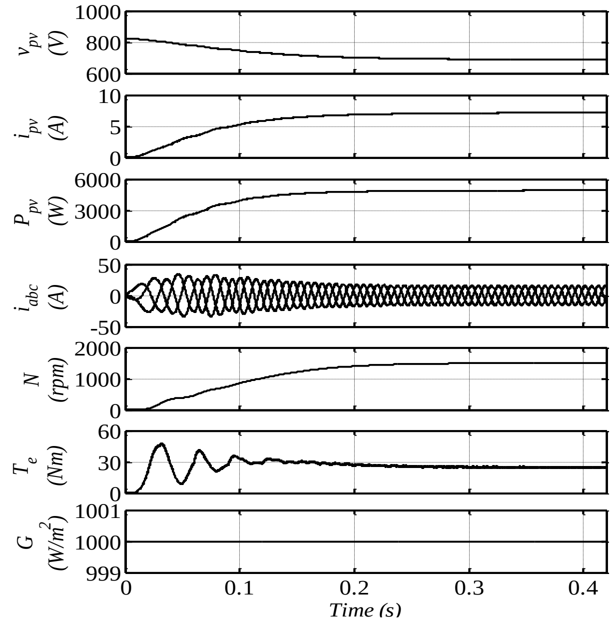


Fig.5 Dynamic and steady performances of PV array fed water pumping system at $1000W/m^2$

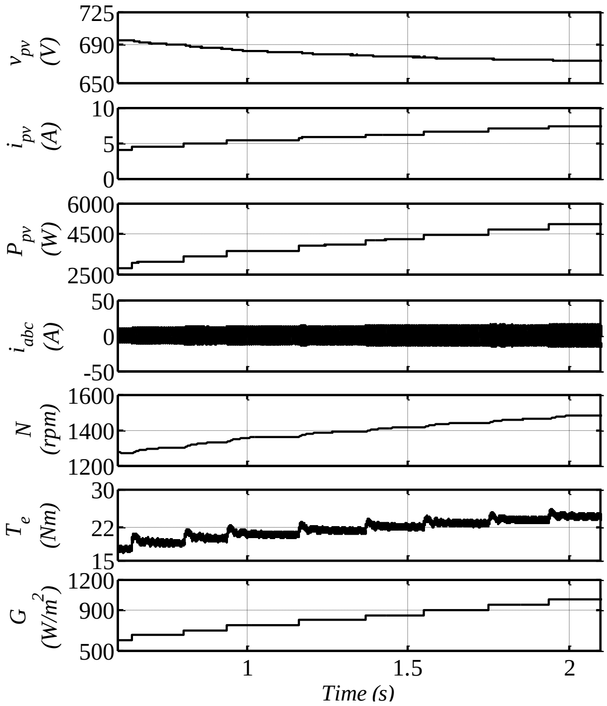


Fig.6 Effect of solar insolation level on the performance of SPV array fed pump

B. Performance of Solar PV Pumping System

The speed of an induction motor speed is controlled by the V/F control and the reference speed for this control is decided by the PV power (P_{MPPT}) or the radiation (G) and the MPPT algorithm. Fig.5 shows that the P&O algorithm is working well for MPPT of the SPV array. Fig.5 also shows the dynamics of SPV water pumping system at $1000W/m^2$. In this system, the solar radiation of $1000W/m^2$ is generated to study the performance of the proposed model, which sets the reference speed corresponding to the solar PV array power and dc-link voltage. Fig.5 also shows the steady state performance of SPV water pumping system at $1000W/m^2$. Fig.6 shows the results at different insolation levels. It shows that the speed changes, when the insolation changes. In this system, solar radiation varies between $200W/m^2$ to $1000W/m^2$ to study the performance of this control. According to the radiation, the reference speed changes and the load torque also changes because the load torque depends on the speed of the motor for pump load. Table-I shows the simulation results different reference speed, PV power and PV current at different insolation. From these results, it is observed that the proposed single stage SPV fed water pumping system works satisfactorily over the wide range of solar insolation level.

VII. CONCLUSION

The proposed single-stage solar PV water pumping system using V/F control has controlled the speed of an induction motor drive. A new approach has been used for generating reference speed for the V/F control of an induction motor which has been utilized by controlling the voltage at dc bus and the pump affinity law is used to achieve the different speeds. The reference speed has been generated by the difference of speed generated by solar PV power and MPPT algorithm. The reference speed of the induction motor has changed during varying atmospheric conditions for extracting the maximum power from solar PV array. The maximum power extracted by perturbs and observe algorithm optimizes the energy transfer towards the motor. The P&O technique reaches the maximum power without oscillations. In this system, dc-link voltage of VSI is floating because at the maximum power point voltage changes at different insolation level for MPPT. The simulation results of the controller shows satisfactory performance under steady state as well as dynamic conditions.

APPENDIX

A. Solar PV Array Data

V_{mppt} = 700V, I_{mppt} = 7.6A, V_{oc} = 821V,
I_{sc} = 8.21A.

B. Motor Characteristics

P = 3.7W, V = 415V, N = 1425rpm, f=50Hz,
R_s=1.7Ω, L_{ls}=0.00967H, R_r=1.85Ω,
L_{lr}=0.00967H, L_o=0.210527H, J=0.02428kg/m^2

C. Pump Characteristics

$T=a_1+a_2\omega^2$, a_1=-35.34, a_2= 2.7×10^{-03}

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