Standalone single stage PV fed reduced switch inverter based independent control of two PMSM drive

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***Abstract*— This paper proposes a standalone singe stage PV fed air cooler which consists of two motors (fan blower and water pump). The proposed system comprises of PV source, reduced switch inverter and two PMSM drive. The proposed system aims at reducing the switching losses and overall cost by using reduced switch inverter. The reduced switch inverter uses only eight switches whereas the conventional VSI utilizes twelve switches. In the proposed scheme, blower and pump are independently controlled using field oriented control scheme where speed reference is obtained using Perturb and Observe (P&O) technique. Simulation studies for the proposed PV fed two 400 W PMSM driven blower and pump is performed using MATLAB platform and respective results are presented to show the efficacy of the system.**

***Keywords*— Air cooler, PMSM, Field Oriented Control, reduced switch inverter, independent control.**

NOMENCLATURE

I_{pv}	Photovoltaic current of PV panel
I_o	Saturation current of PV panel
k	Boltzmann constant
q	Electron charge in Coulomb
a	Material constant
R_s	Series resistance
R_p	Shunt resistance
$I_{pv,n}$	current from the photovoltaic module at nominal condition (25°C and 1000W/m^2)
K_I	current coefficient
ΔT	$T - T_n$ T is actual temperature; T_n is nominal temperature
G_n	Solar irradiation at nominal condition
$I_{sc,n}$	Short circuit current of module at nominal condition
$V_{oc,n}$	Open circuit voltage of module at nominal condition
$V_{t,n}$	Thermal voltage of series connected cells in the module
v_{ds}, v_{qs}	*d-q* axes stator voltage
i_{ds}, i_{qs}	*d-q* axes stator current
R_s	Stator resistance
L_s	Stator inductance
ψ_m	PM flux linkage
P	Number of poles
T_L	Load torque
T_e	Electromagnetic torque
ω_r	Rotor speed

I. INTRODUCTION

In recent years, variable speed PMSM drives are slowly replacing the induction machines. PMSM have nearly 30%-60% higher torque capacity, high power density and power factor when compared to induction machines [1]. Due to the above mentioned advantages PMSM are being used in many applications like servo pump, traction, washing machines, dishwashers, air conditioning, etc.

Solar energy is one of the cleanliest sources of energy as it is environmental friendly i.e. free from pollution. India being tropical country has a vast scope to harness solar energy with advanced technologies [2]-[3]. Photovoltaic (PV) technology can function independently. PV based power generation, is important alternative for many applications [4]. So, in rural areas which are very far from the generating station these photovoltaic arrays can be used either for pumping water to the irrigation fields or for lighting purposes and air conditioning.

In [5], PV fed PMSM drive incorporate two stages: Firstly, dc-dc converter followed by voltage source inverter (VSI). To extract maximum power from PV module, maximum power point tracking (MPPT) technique [6]-[10] is employed to dc to dc converter. In [11]-[12], single stage PV fed induction motor and PMSM drive are proposed for water pumping application where PV module is directly connected to motor through inverter module. The PV module depends on temperature and solar irradiation. Any change in aforementioned parameters affects the speed of the motor. So, MPPT technique is used to generate the speed reference [11]-[12] to control speed of motor.

PV fed water pumping application consists of standard three phase inverter (three legs and each leg contains two switches) as reported in literature [11]-[12]. In these papers inverter can drive only one motor. In [13]-[16], the four-switch inverter is discussed to drive three phase motor. This configuration comprises, two capacitors in single leg and switches in rest two legs (each leg contains two switches, totally it has four switches). The advantage of this configuration is it reduces the number of switches, cost and volume of the system. Two inverters are used for independent control of two motors. The drawback of this configuration is, it requires twelve switches. In [17]-[18], the four leg inverter is reported to control two motors independently. Four leg inverter (FLI) comprises of two capacitors in single leg and eight switches in other four legs. In this configuration, the capacitor leg is shared between two motors. The advantage of FLI is as follows: (i). reduces the number of switches (it required only eight switches), (ii). Reduces the cost and volume of the system.

In existing air cooling system, the pump is operating at maximum (rated) speed and blower motor can be operated at desired speed. Thereby, power consumption is more as pump motor is operated at maximum speed irrespective of the blower speed. To overcome the above drawback, this paper proposes standalone single stage PV fed reduced switch inverter based independent control of two PMSM drive for air cooler application.

The paper is organized as follows. In section II, system architecture and modelling of the proposed system are described. In section III, simulation results are discussed.

II. System Architecture

The system architecture of the single stage PV fed air cooler consists of two motors (one for blower and other for water circulation) is shown in Fig.1. The proposed configuration employs only eight switches (four switches used to control PMSM1 and other four switches used to control PMSM2) whereas the conventional systems use twelve switches (six switches used to control motor1 and six more switches used to control motor2). Single diode model is employed to model the PV system. Perturb and Observe MPPT algorithm is used to obtain the speed reference. The proposed system uses two PMSM drive (each 400 W) which is powered by 900 W solar PV array.

A. PV System Modelling

The PV system is modelled by using following equations

$$I = I_{pv} - I_o\left[\exp\left(\frac{V+R_sI}{V_t a}\right)-1\right]-\frac{V+R_sI}{R_p} \qquad (1)$$

where $V_t = \dfrac{N_s kT}{q}$

The current from the module depends upon the temperature and irradiation. The increase in the temperature and irradiation results in increase of short circuit current, decrease of open circuit voltage and increase in the maximum power generated by PV module. The relationship between current, irradiation and temperature of the PV module is given below.

$$I_{pv} = \left(I_{pv,n}+K_I\Delta T\right)\frac{G}{G_n} \qquad (2)$$

The relationship between diode saturation current and temperature can be expressed as

$$I_o = I_{o,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n}-\frac{1}{T}\right)\right] \qquad (3)$$

The nominal diode saturation current can be expressed as

$$I_{o,n} = \frac{I_{sc,n}}{\exp\left(\dfrac{V_{oc,n}}{aV_{t,n}}\right)-1} \qquad (4)$$

B. PMSM Modelling

The stator voltage of surface mounted permanent magnet synchronous motor in the rotor reference frame can be expressed as

$$v_{qs} = R_s i_{qs} + \omega_r(L_s i_{ds}+\lambda_m) + \frac{d(L_s i_{qs})}{dt} \qquad (5)$$

$$v_{ds} = R_s i_{ds} - \omega_r L_s i_{qs} + \frac{d(L_s i_{ds}+\psi_m)}{dt} \qquad (6)$$

From (5) and (6), the stator *d-q* axes current can be described as

$$i_{qs} = \frac{1}{L_s}\int(v_{qs}-R_s i_{qs}-\omega_r L_s i_{ds}-\omega_r\lambda_m) \qquad (7)$$

$$i_{ds} = \frac{1}{L_s}\int(v_{ds}-R_s i_{ds}+\omega_r L_s i_{qs}) \qquad (8)$$

The electromagnetic torque is given by

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(i_{qs}\psi_m\right) \qquad (9)$$

The mechanical speed and position are given by

$$T_e - T_l = J\frac{d\omega_r}{dt}+B\omega_r \qquad (10)$$

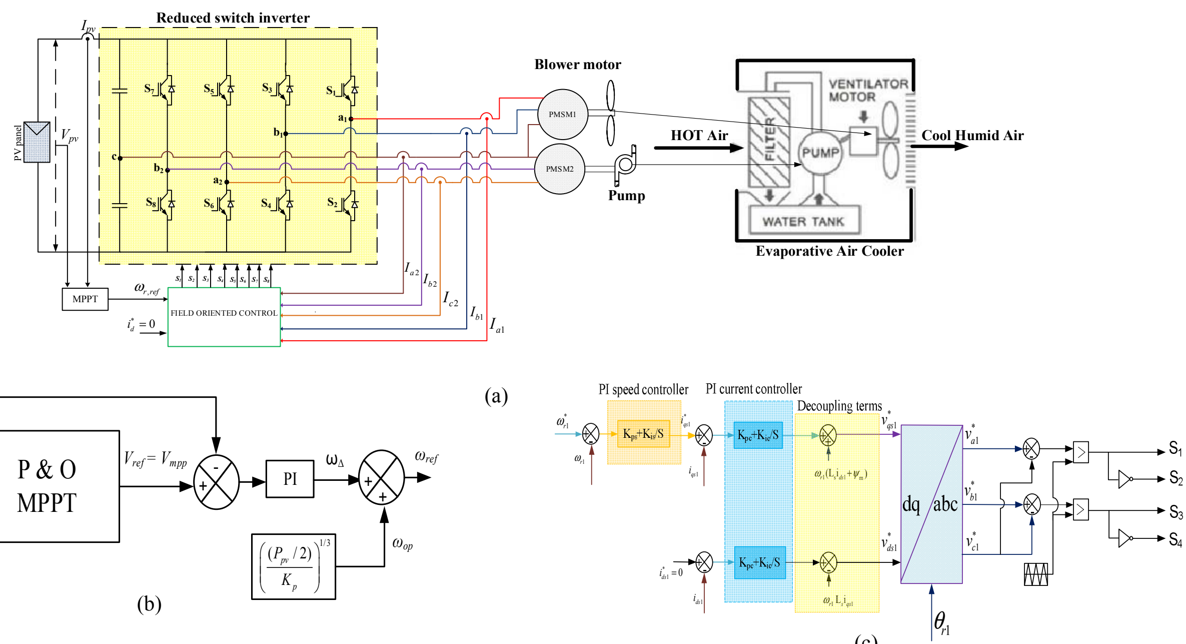

Fig.1.Architecture of the proposed system

a. Block diagram of proposed system. b. Reference speed generation c. FOC scheme for blower/pump

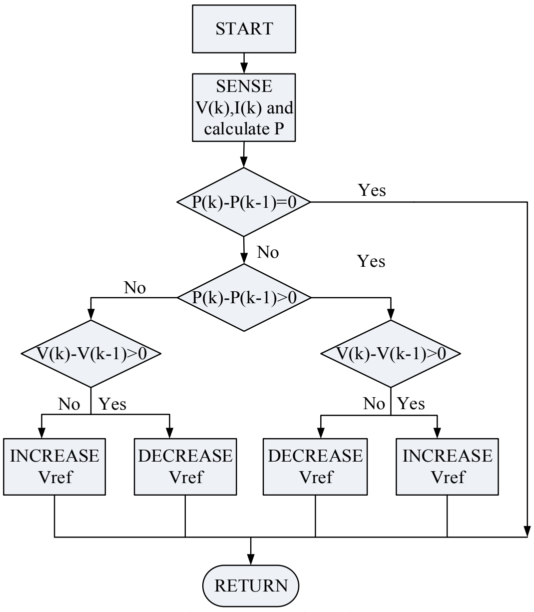

Fig. 2 P & O algorithm

C. Inverter Topology Used

The proposed system uses the reduced switch inverter and is shown in Fig 1a. It possesses the following advantages when compared to conventional voltage source inverter employing twelve switches (two inverter).

(i). It employs reduced number of switches (eight switches) when compared to conventional inverter (twelve switches) so it has less switching losses and it is compact in size. (ii). The number of drive circuits is also reduced (only eight switches) whereas the existing system has twelve switches.

D. Reference speed generation

Fig. 1b shows the structure of reference speed generation using P&O technique. Fig. 2 shows the P&O technique where the current and voltage of the PV module are continuously measured and the instantaneous PV power is computed. The change in irradiance or temperature reflects in the output voltage and power of PV module. The change in voltage (Δv) and power (Δp) of PV module is computed by comparing present voltage $v(k)$ & power $p(k)$ with previous voltage $v(k-1)$ & power $p(k-1)$ of PV module. The reference voltage should be changed based on the following condition viz. *case 1* ($\Delta p>0$): if $\Delta v>0$ results an increase in reference voltage to reach MPP, else reference voltage is decreased to reach MPP. *case 2* ($\Delta p<0$): if $\Delta v>0$ results a decrease in reference voltage to reach MPP, else reference voltage is increased to reach MPP until the change in power is near to zero. Further, maximum power point of PV voltage (V_{mpp}) is compared with instantaneous PV voltage (V_{pv}) and generates an error signal which passes through PI controller to compute change in speed (ω_{Δ}). ω_{op} represents operating speed which is computed by relating instantaneous PV power (P_{pv}) and blower/pump constant (K_p). The reference speed is calculated by adding rated speed with change in speed i.e. $\omega_{ref} = \omega_{\Delta} + \omega_{op}$.

E. Indepentent control of PMSM drive

In this proposed scheme, blower motor and pump motor are independently controlled using FOC scheme. The advantage of independent control scheme is reduction in power consumption without affecting the performance of the air cooler. This is achieved as pump speed can be varied according to the speed of the blower motor so that required cooling is maintained. Fig. 1c shows the general structure of FOC scheme, which is applicable for both blower and pump. FOC scheme involves two loops i.e. outer loop speed controller and inner loop current controller. To control blower, actual speed of blower and stator current of the PMSM1 (coupled to blower) is considered as feedback signal. The three phase voltage references are generated using FOC scheme. In the proposed configuration only four switches (two leg) are used to control PMSM1(couple to blower). Therefore, the three phase reference is modified into two phase references by subtracting one phase voltage from the other two phases (c is subtracted from b and a). Finally, modified references are compared with high frequency triangular wave to generate switching pulses (s_1-s_4) for the control of PMSM1 (coupled to blower).

To control pump, actual speed of pump and stator current of the PMSM2 (coupled to pump) is considered as feedback signal. Similarly, the corresponding switching pulses (s_5-s_8) are generated using FOC scheme to control PMSM2 (coupled to pump).

F. Design of blower/pump

The proposed system has two PMSM drive (fan blower and water pump). The equation governing the torque-speed characteristics of pump/blower is given by $T_L = K_p * \omega_r^2$. where T_L is rated load torque of PMSM, K_p is pump/blower constant and ω_r is rated rotor speed of PMSM. The pump/blower constant (K_p) is computed by relating rated load torque and speed of PMSM drive and is expressed as $K_p = T_L / \omega_r^2 = 1.27\ N.m / (314.15)^2 = 1.29 \times 10^{-5}$ Nm/(rad/sec)^2.

III. SIMULATION RESULTS

The start-up and dynamic performances of the standalone single stage PV fed reduced inverter based independent control of two PMSM drive is evaluated in MATLAB/SIMULINK environment. To evaluate the proposed configuration different case studies are considered viz. starting response and independent control of proposed system (at constant irradiation) and dynamic performance (during variation in the irradiation).

a. Starting response and independent control of proposed system during constant irradiation (600 W/m^2)

The average irradiance at NITK, India was found to be 600 W/m^2. The proposed system is analyzed at 600 W/m^2 as shown in Fig. 3 for two modes, which are mode I: Starting response of proposed system (operates at MPPT) and mode II: independent control of two PMSM (not operating at MPP).

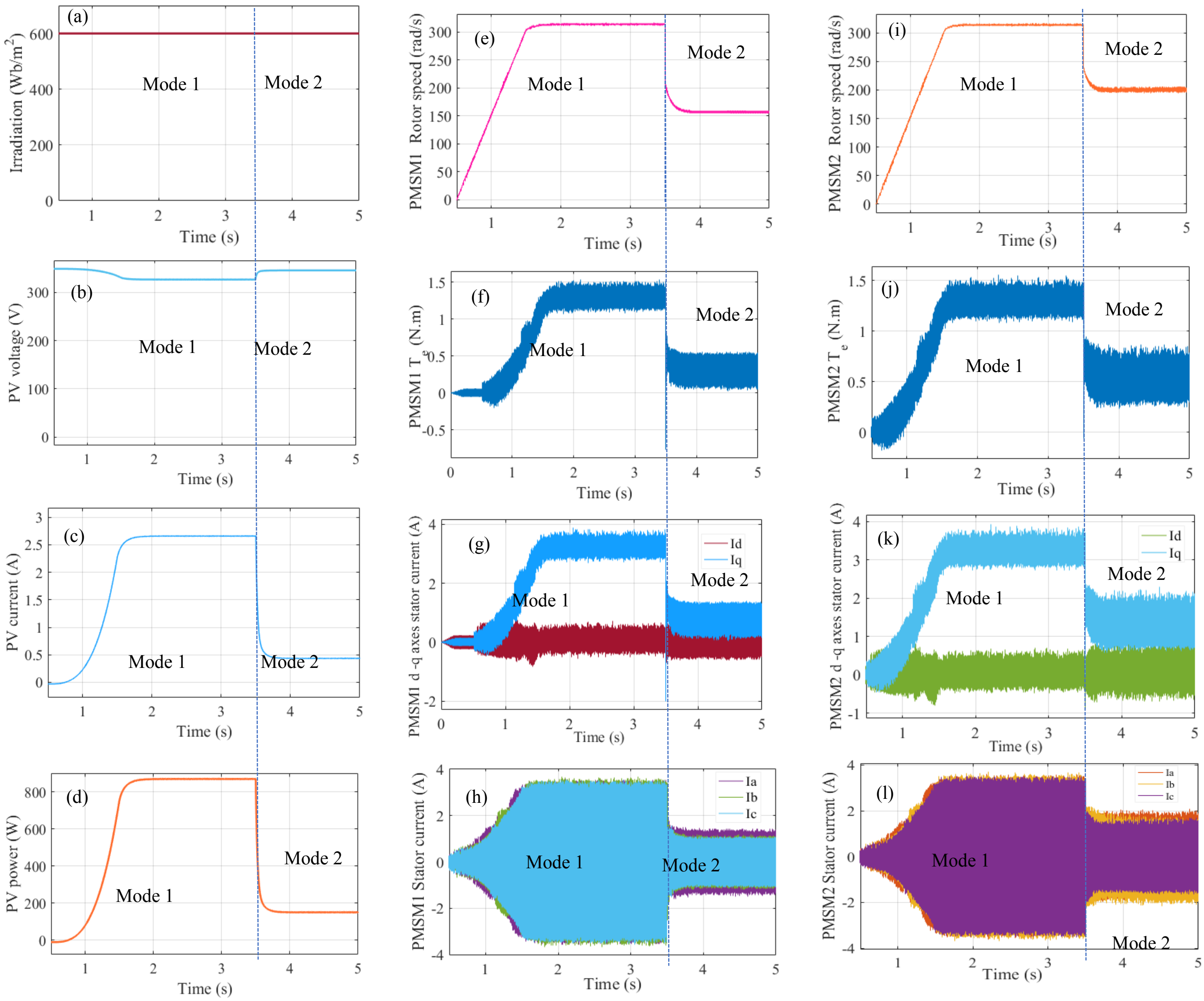

Fig. 3. Starting response and independent control of proposed system during constant irradiation (600 W/m^2). (a) Irradiation. (b) PV panel voltage. (c) PV panel current. (d) PV power. (e) Rotor speed of PMSM1. (f) Electromagnetic torque of PMSM1. (g). *d-q* axes stator currents of PMSM1. (h) three phase stator current response of PMSM1. (i) Rotor speed of PMSM2. (j) Electromagnetic torque of PMSM1. (k). *d-q* axes stator currents of PMSM2. (l) three phase stator current response of PMSM2

Mode 1: A constant irradiance of 600 W/m^2 is considered as shown in Fig. 3a. Fig. 3b, c and d show that P&O algorithm tracks the MPP under constant temperature and irradiation (36°, 600 W/m^2). It is observed that during forward acceleration of the motors MPPT is extracting the maximum power from the PV panel i.e. the current is gradually increasing from zero to its maximum operating point (I_{mpp}) and voltage is decreased from open circuit value to its maximum operating point (V_{oc} to V_{mpp}). The speed reference is generated for both blower and pump using P&O technique. Further the smooth start up is achieved for PMSM drive (for both motors) by using FOC scheme. It can be inferred from Fig. 3e and i that the actual speed of both PMSM's (fan blower and water pump) are ramped up from 0 to 314 rad/s (rated speed) without transients. Fig. 3 f and i shows the electromagnetic torque response of both motor's. Fig. 3g, k and Fig. 3h, l shows the *d-q* axes stator current and respective three phase currents for both PMSM drive. It is observed that, both motors has smooth stator current response.

Mode 2: To validate independent control of two PMSM, two different types of speed reference are considered. The speed reference for PMSM1 is varied from 314 to 157 rad/s at 3.5 s. Similarly, the speed reference for PMSM2 is varied from 314 to 200 rad/s at 3.5 s. The following observations are made from Fig. 3a-h. (i) The actual speed of blower and water pumping system follows respective speed reference (ii). It is clearly seen from Fig. 3d, the power obtained from PV module is reduced because of reduction in the speed reference value. Further its noted that, in this mode the system is not operated at maximum power point. (iii) Fig. 3h and k shows the *d-q* axes stator current of PMSM (1&2), for both the motors the *d* axis stator current is maintained near to zero where the *q* axis stator current has 1.5 A, 2 A for PMSM1, PMSM2 respectively due to the different speed references.

B. Dynamic performance of PMSM drive during irradiance decrement from 600 W/m^2 to 400 W/m^2

The dynamic behavior of the proposed system is analyzed for the change in the solar irradiation i.e. (600 W/m^2 to

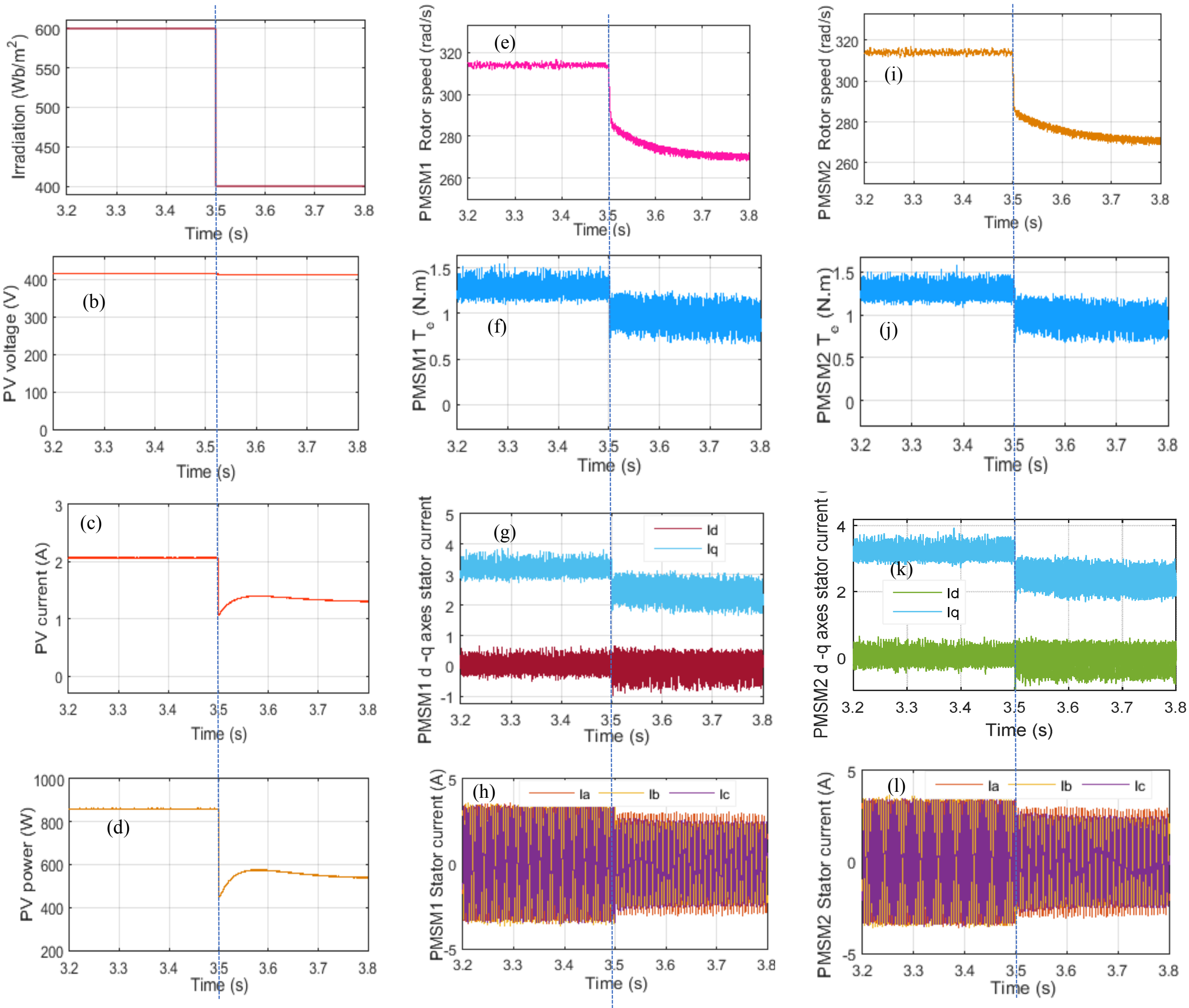

Fig. 4. Dynamic performance of PMSM drive during change in irradiation from 600 W/m2 to 400 W/ m2. (a) Irradiation. (b) PV panel voltage. (c) PV panel current. (d) PV power. (e) Rotor speed of PMSM1. (f) Electromagnetic torque of PMSM1. (g). *d-q* axes stator currents of PMSM1. (h) three phase stator current response of PMSM1. (i) Rotor speed of PMSM2. (j) Electromagnetic torque of PMSM1. (k). *d-q* axes stator currents of PMSM2. (l) three phase stator current response of PMSM2.

400 W/m^2) as shown in Fig. 4. This irradiation variation is shown in Fig. 4a. It is observed from Fig. 4b, c and d that the maximum operating point of PV voltage (V_{mpp}), current (I_{mpp}) and power are attained during the irradiation change. If there is a change in irradiation the power output from the PV panel changes and the corresponding speed reference is generated using P&O MPPT algorithm. The speed is reduced from 314 rad/sec to 270 rad/sec during the changes in irradiation (600 W/m^2 to 400 W/m^2). The following observations are made from Fig. 4e-l. (i). It is clearly seen from Fig. 4e and h, the actual speed of both PMSM's (fan blower and water pump) follows the reference speed. (ii). Fig. 4f and i shows the electromagnetic torque response of two motor's. (iii). The *d-q* axes stator current and respective three phase currents of the proposed reduced switch inverter fed field oriented controlled PMSM drive are shown in Fig. 4g and k. (iv). the three-phase current response of the proposed system are shown in Fig. 4h and l. it is noted that sinusoidal current output can be achieved by employing a reduced switch inverter thus eliminating the need of conventional VSI (six switches).

IV. CONCLUSION

This paper proposes standalone single stage PV fed independent control of two PMSM drive (fan blower and water pump). The proposed system is grid independent and also employs reduced switch inverter which possess the advantages viz. reduce switches, switching loss and cost of the overall system. P&O technique is used to generate speed reference for PMSM drive. The independent control scheme is employed in the proposed configuration to control speed of the blower and pump simultaneously and independently. The simulation results show the effectiveness of independent control of two PMSM drive during startup and variation in the speed for constant and change in the irradiation.

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