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Performance Analysis of Boost and Cuk Converters under Variable Irradiation for Synchronous Drive Based Water Pumping Applications

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Abstract:

This project presents a standalone solar PV supplied PMSM drive for water pumping system. Pumping water is a universal need for agriculture and the use of PV panels is a natural choice for such applications. The high speed Photo voltaic (PV) powered permanent magnet synchronous motor (PMSM) drive is investigated. The PV electrical vehicle application is prospected, in order to highlight the irradiation effect on the PV panel feeding the PMSM. This yields to the direct effect on the inverter DC Bus behavior the speed of a PMSM drive is a function of solar irradiation. Three phase VSI (Voltage Source Inverter) is controlled to supply PMSM under change in irradiation in vector oriented mode. The solar PV system has found many potential applications such as residential, vehicular, space air craft and water pumping system. PV water-pumping is highly competitive compared to traditional energy technologies and best suited for remote site applications that have small to moderate power requirements. The proposed system consists of solar PV panel, a boost converter, a three phase VSI (Voltage Source Inverter) and a PMSM coupled with a centrifugal water pump. By using MATLAB/SIMULINK software.

Keywords:
DC to DC boost converter, cuk converter; PMSM drive; photovoltaic; vector control; water pumping system.

I.INTRODUCTION:

Solar energy is free, inexhaustible, and clean; it has a great potential to be a very attractive supply option for industrial and domestic applications, especially in remote areas, such as water pumping, heating, and cooling.

Solar photovoltaic (PV) systems use the PV modules in order to convert the sunlight into electrical energy. PV generation is gaining increased importance as a renewable source due to its advantages, which include few maintenance requirements, the absence of fuel cost, and lack of noise due to the absence of moving parts [1].PV pumping systems are receiving more attention in recent years especially in remote areas where connection to the grid is technically not possible or costly. In addition, PV pumps have recently received considerable attention due to major developments in the field of solar cell material and technology. They are widely used in domestic and livestock water supplies and small-scale irrigation systems [2, 3]. For such solar PV systems, maximum power point tracking control is preferred for efficient operation. Matsui et. Al have presented a MPPT control system for solar PV system by utilizing steady state power balancing condition at DC link. It has further improved by Mikihiko for sensorless application.

The solar PV system has found many potential applications such as residential, vehicular, space air craft and water pumping system. PV water-pumping is highly competitive compared to traditional energy technologies and best suited for remote site applications that have small to moderate power requirements. Most of the existing photovoltaic irrigation systems offer a mechanical output power from 0.85 kW up to 2.2 kW. The efficiency of Induction motors are less compared to permanent magnet motors, whereas DC machines are not suitable for submersible installations [12]. DC motor driven PV pumps are used overall the world because they can be directly connected to the PV generator and an adjustable DC drive is easy to achieve. However, this system suffers from increased motor cost and maintenance problems due to the presence of a commutator and brushes [3–5].

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Hence, a pumping system based on brushless motors represents an attractive alternative due to its merits over DC motors. Brushless permanent magnet DC motors have been proposed [4]; however, this solution is limited to only low-power PV systems. Several studies have investigated AC systems using either current source or voltage source inverters [1]. The PV pumping system based on an induction motor (IM) offers an alternative motor for more reliable and maintenance-free systems. The main advantages of IMs are reduced unit cost, ruggedness, brushless rotor construction, and ease of maintenance [1, 3, 6]. The permanent magnet synchronous motor (PMSM), also called the brushless DC motor, coupled to a centrifugal pump is found to be suitable for PV water pumping systems [7, 8].In recent years, the use of PMSM (Permanent Magnet Synchronous Motors) are increased for drives applications due to its high efficiency, large torque to weight ratio, longer life and recent development in permanent magnet technologies [9]-[10]. It need power processor for effective control. PMSM become a serious challenger of induction motors in hybrid electric vehicle applications. This paper presents a stand alone solar PV supplied PMSM drive for water pumping system. Pumping water is a universal need for agriculture and the use of PV panels is a natural choice for such applications. In the proposed system, duty cycle of boost converter is controlled to maintain the DC link voltage at required level. The speed of a PMSM drive is a function of solar irradiation. Three phase VSI (Voltage Source Inverter) is controlled to supply PMSM under change in irradiation in vector oriented mode.

II. PHOTO VOLTAIC SYSTEM:

The PV system considered in this paper contains single PV array as shown in Fig. 2(a).In this paper a PV model is considered. The modeling is attempted by (1), where, IPV, VPV are the PV array current and voltage respectively. Rsh and Rs are the intrinsic shunt and series resistances of the array, Isc is being the short circuit current of the array, G is the solar irradiance (W/m2), q = 1.602 ×10−19 C being the electron charge, Boltzman's constant (K) =1.3806 ×10−23 J/K, p-n junction's ideality factor (A) = 2 , T is array temperature (in 0K), I0 is diode reverse saturation current, Tr is cell reference temperature and Irr is reverse saturation current at Tr.

$$I_{PV}=I_{ph}-I_0\left[\exp\left(\frac{q(I_{PV}\times R_s+V_{PV})}{AKT}\right)-1\right]-\frac{V_{PV}+I_{PV}\times R_s}{R_{sh}} \quad (1)$$

where $I_{ph}=[I_{sc}+k(T-T_r)]\frac{G}{1000}$ and

$$I_0=I_{rr}\left[\frac{T}{T_r}\right]^3\exp\left(\frac{qV_{oc}}{AK}\left[\frac{1}{T_r}-\frac{1}{T}\right]\right)$$

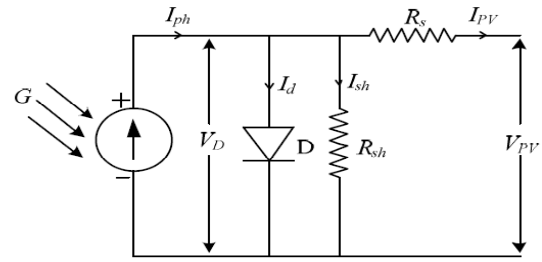

Fig. 2(a): PV system

III.SYSTEM CONFIGURATION AND PRINCIPLE OF OPERATION:

Fig.1 shows schematic diagram for the stand-alone solar PV based PMSM drive for water pumping system. The proposed system consists of solar PV panel, a boost converter, a three phase VSI (Voltage Source Inverter) and a PMSM coupled with a centrifugal water pump. A PV or solar cell is the basic building block of a PV system. An individual PV cell is usually quite small, typically producing about 1 or 2W of power. To increase the power output of PV cells, these cells are connected in series and parallel to assemble larger unit called PV module. The PV array is connected to the DC to DC boost converter to increase the output voltage level. An IGBT (Insulated Gate Bipolar Transistor) based VSI is used for DC to AC conversion and connected to the PMSM drive. The constant DC voltage is converted to the AC output using a VSI. Reference speed of PMSM is a function of solar irradiation.

a.Design of PV based PMSM Drive:

The design of a PV based PMSM drive consists of PV array, a DC to DC converter, a DC link capacitor and a VSI. Ratings of selected parameters are given in Appendix. The designs of various components of drive system are as follows,

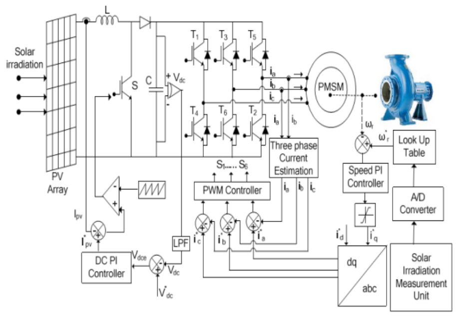

Fig. 1 Schematic diagram of standalone solar PV based PMSM drive for water pumping system

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b.Design of Boost Converter:

The boost converter is used to feed the active power from PV array to the DC link capacitor connected VSI fed PMSM. The design parameters of the boost converter are given as, The value of a boost inductor L is given as,

$$L = \frac{V_{PV}\, D}{2 * \Delta i * f_{sw}} = 2.67\ \text{mH}$$

Where D is duty cycle, Vpv is output voltage of PV array, few is switching frequency, Δi is ripple in output current of PV array. Considering Vpv=198.99V, Δi=10% of PV current and fsw= 15 kHz, the value of L is obtained as 2.67 mH. The maximum current through boost converter IGBTs is obtained as 1.25 (ipp+ Ipv) where ipp is peak to peak ripple current considering 10% ripple 25 A, 600 V IGBT is used for boost converter.

c.Voltage Source Inverter

The apparent power rating of a VSI is given as,

$$S_{VSI} = \sqrt{P^2 + Q^2}$$

It is obtained as 1500 VA. The rms current through a VSI is given as,

$$I_{VSI} = \frac{kW * 10^3}{\sqrt{3} V_m} = 2.165\text{A}$$

Where Vmis stator voltage of PMSM. The maximum current through IGBTs is obtained as 1.25 (ipp+ IVSI). Considering 7.5% peak-peak ripple current, 25 A, 600 V IGBTs are used in a VSI.

d.Control Scheme:

Fig.1 shows the comprehensive control scheme for a standalone solar PV based PMSM drive. The control scheme is discussed in two parts, i.e. control of boost converter to maintain constant DC link voltage and control of VSI in vector oriented mode to achieve fast dynamic response under change in solar irradiances and load conditions. Basic Eq. Used in control algorithms are as follows,

e.Control of Boost Converter:

The DC bus voltage and the output of the DC PI controller is used to estimate the DC voltage error at the kth sampling instant is as,

$$V_{dce}(k) = V^*_{dc}(k) - V_{dc}(k)$$

Where Vdc and V*dcare sensed and reference DC bus voltages respectively. The output of the DC PI controller at the kth sampling instant is expressed as

$$I^*_{pv}(k) = I^*_{pv}(k-1) + k_{pa}[V_{dce}(k) - V_{dce}(k-1)] + k_{ia} V_{dce}(k)$$

where kpa and kia are the proportional and integral gain constants of the PI controller. Vdce (k) and Vdce (k-1) are the DC bus voltage errors in the kth and (k-1)th sampling instant and I*pv (k) and I*pv (k-1) are output of DC PI controller in the kth and (k-1)th instant needed for voltage control. The reference and actual PV bus current are used to estimate the PV bus current error at the kth sampling instant as,

$$I_{pve}(k) = I^*_{pv}(k) - I_{pv}(k)$$

The PV bus current error (Ipve) is amplified using gain K and compared with fixed frequency carrier signal to generate switching signals for IGBT used in boost converter.

f.Control of VSI :

For the VSI, a VOC (Vector Oriented Control) scheme is used. Two Hall effect current sensors are used to sense two phase motor currents ia , ib and third phase source current ic is estimated considering that instantaneous sum of three-phase Currents is zero. Reference motor speed (ω*r) is the function of solar irradiation and used to track the maximum power. Irradiation sensor transducer gives the output in the form of voltage signal which is fed to the look up table. Reference speed is compared with the measured rotor speed (ωr) and it provided speed error ωe. The speed error at the kth sampling instant is given as,

$$\omega_{re}(k) = \omega^*_r(k) - \omega_r(k)$$

Speed error is processed using the speed PI controller, which provide the reference electromagnetic torque (T*ref). The reference torque (T*ref) is used to generate reference axis current (i*q) as follows,

$$i^*_q(k) = i^*_q(k-1) + k_{pa}[\omega_e(k) - \omega_e(k-1)] + k_{ia}\omega_e(k)$$

Here kpa and kia are the proportional and integral gain constants of the PI controller. ωe (k) and ωe (k-1) are the speed errors in the kth and (k-1)th sampling instant and i*q (k) and i*q (k-1) is the output of speed PI controller in the kth and (k-1)th instant needed for speed control. Similarly, from the sensed rotor speed of the PMSM, magnitude of d-axis PMSM current (i*d) is obtained which is consider zero below rated speed.

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$$i_d^* = 0$$

For the estimation of three phase PMSM currents the transformation angle (θre) is obtained as,

$$\theta_{re} = \frac{P}{2}\theta_r$$

where P is the number of poles of the PMSM. Three-phase reference PMSM currents (i*a, i*b, i*c) are obtained using i*d and i*q and the rotor angular position in electrical rad/sec by inverse park transformation. Three-phase reference PMSM currents are as [13]

$$i_a^* = i_d^* \cos\theta_{re} - i_q^* \sin\theta_{re}$$

$$i_b^* = i_d^* \cos(\theta_{re} - 2\pi/3) - i_q^* \sin(\theta_{re} - 2\pi/3)$$

$$i_c^* = i_d^* \cos(\theta_{re} + 2\pi/3) - i_q^* \sin(\theta_{re} + 2\pi/3)$$

Three phase reference currents (i*a, i*b, i*c) are compared with sensed PMSM currents (ia, ib, ic) and resulting current errors are fed to the PWM current controller for generating the switching signals.

IV.CUK CONVERTER:

The circuit setup is like a combination of the buck and boost converters. Like the buck-boost circuit it delivers an inverted output. Virtually all of the output current passes through C1, and as ripple current. So C1 is usually a large electrolytic with a high ripple current rating and low ESR (equivalent series resistance), to minimize losses. The main difference between the cuk and the other converters is that the cuk used a capacitor as the energy storing element.

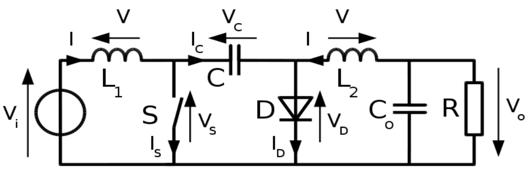

Fig.3. A non-isolated Cuk converter

When S is turned on, current flows from the input source through L1 and S, storing energy in L1's magnetic field. Then when S is turned off, the voltage across L1 reverses to maintain current flow. As in the boost converter current then flows from the input source, through L1 and D1, charging up C1 to a voltage somewhat higher than Vin and transferring to it some of the energy that was stored in L1. When S is turned on again, C1 discharges through via L2 into the load, with L2 and C2 acting as a smoothing filter. Meanwhile energy is being stored again in L1, ready for the next cycle. As with other converters (buck converter, boost converter, buck-boost converter) the Cuk converter can operate in two modes 1) continuous 2) discontinuous current mode. However, unlike these converters, it can also operate in discontinuous voltage mode (i.e., the voltage across the capacitor drops to zero during the commutation cycle).

2.2.2. Continuous mode:

The current through the inductors has to be the same at the beginning and the end of the commutation cycle. As the evolution of the current through an inductor is related to the voltage across it:

$$V_L = L\frac{dI}{dt}$$

it can be seen that the average value of the inductor voltages over a commutation period have to be zero to satisfy the steady-state requirements. If we consider that the capacitors C and Co are large enough for the voltage ripple across them to be negligible, the inductor voltages become: in the off-state, inductor L1 is connected in series with Vi and C. Therefore VL1 = Vi − VC.

As the diode D is forward biased (we consider zero voltage drop), L2 is directlyconnected to the output capacitor. Therefore VL2 = Vo in the on-state, inductor L1 is directly connected to the input source. Therefore VL1 = Vi. Inductor L2 is connected in series with C and the output capacitor, so VL2 = Vo + VC.The converter operates in on-state from t=0 to t=D•T (D is the duty cycle), and in off state from D•T to T (that is, during a period equal to (1-D)•T). The average values of VL1 and VL2 are therefore:

$$\bar{V}_{L1} = D\cdot V_i + (1-D)\cdot(V_i - V_C) = (V_i - (1-D)\cdot V_C)$$

$$\bar{V}_{L2} = D(V_o + V_C) + (1-D)\cdot -V_o = (V_o + D\cdot V_C)$$

As both average voltage have to be zero to satisfy the steady-state conditions we can write, using the last equation:

$$V_C = \frac{V_o}{D}$$

So the average voltage across L1 becomes:

$$\bar{V}_{L1} = \left(V_i + (1-D)\cdot\frac{V_o}{D}\right) = 0$$

This can be written as:

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$V_o = -V_i.D/(1-D)$

As with the buck-boost converter, the ratio between the output voltage and the input voltage is Vout/Vin = -D/(1-D) = -Ton/Toff. The output voltage is in negative polarity. The output voltage can either be stepped up or down, depending on the switching duty cycle. The main difference between buck-boost and cuk converter is that because of the series inductors at both input and output, the Cuk converter has much lower current ripple in both circuits. By careful adjustment of the inductor values, the ripple in either input or output can be nulled completely.

2.2.3 Discontinuous mode:

Like all DC-DC converters Cuk converters rely on the ability of the inductors in the circuit to provide continuous current, in much the same way a capacitor in a rectifier filter provides continuous voltage. If this inductor is too small or below the "critical inductance", then the current will be discontinuous. The minimum inductance is given by:

$$L_1 min = \frac{(1-D)^2 R}{2 D f_s}$$

Where fs is the switching frequency

Filters are used on the input and the output side of the converters to maintain constant output and input voltage and current. The filters also eliminate the switching harmonics (EMI). A capacitor is used in a filter to reduce ripple in voltage. Since switched power regulators are usually used in high current, high-performance power supplies, the capacitor should be chosen for minimum loss.

V. MATLAB/SIMULINK RESULTS:

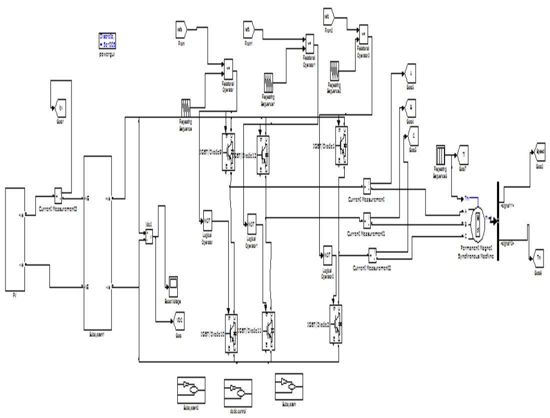

Fig.4. Simulink circuit for pmsm drive with pv cell

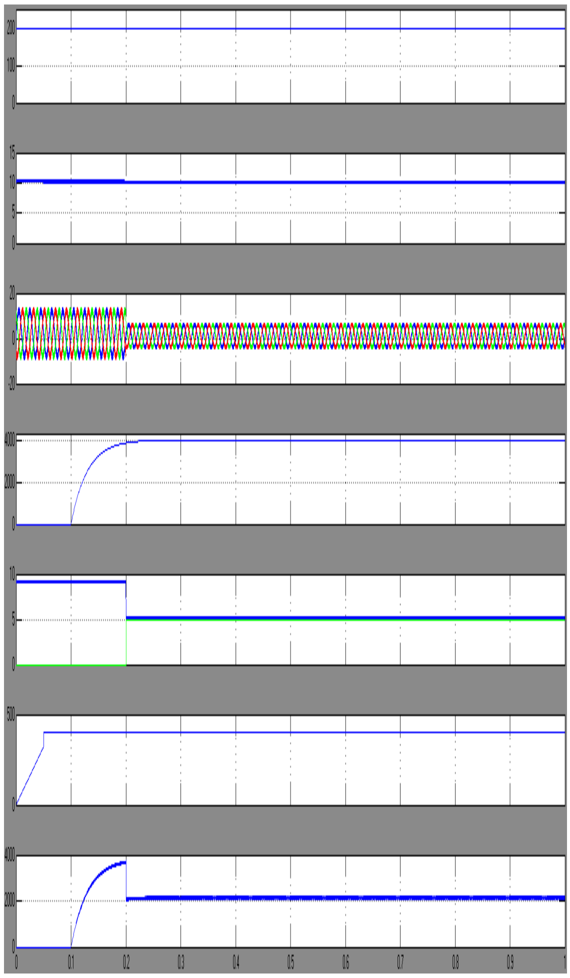

Fig.5. simulation results during constant solar radiation for (a) pv cell voltage, (b) pv cell current, (c) stator currents of motor (d) speed of motor (e) torque (f) dc link voltage (g) power

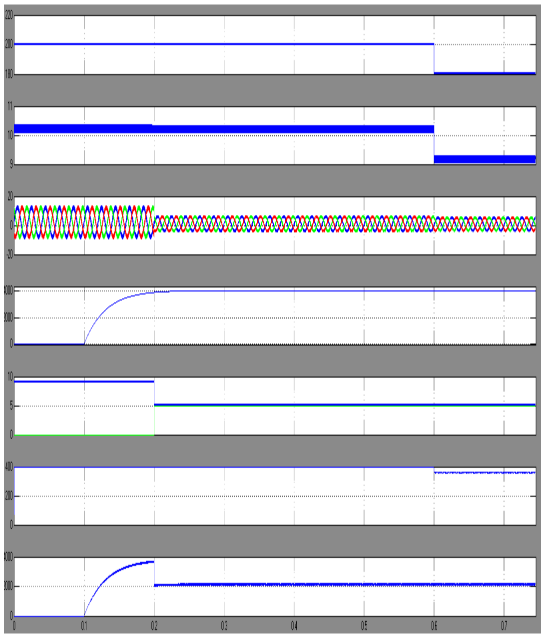

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Fig.6. simulation results during change in solar radaition for (a) pv cell voltage, (b) pv cell current, (c) stator currents of motor (d) speed of motor (e) torque (f) dc link voltage (g) power

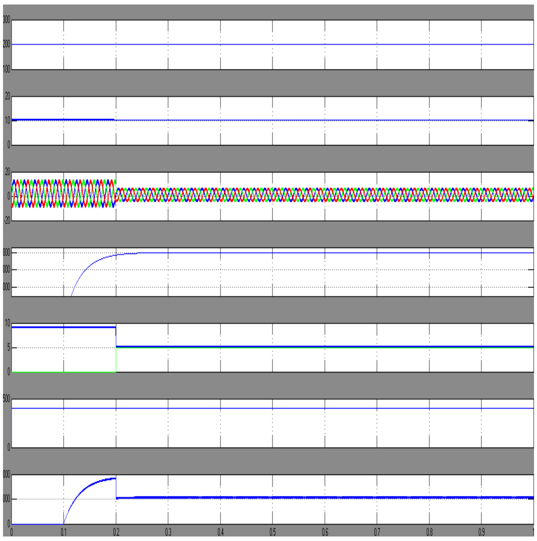

Fig.7. simulation results during motor starting condition for (a) pv cell voltage, (b) pv cell current, (c) stator currents of motor (d) speed of motor (e) torque (f) dc link voltage (g) power.

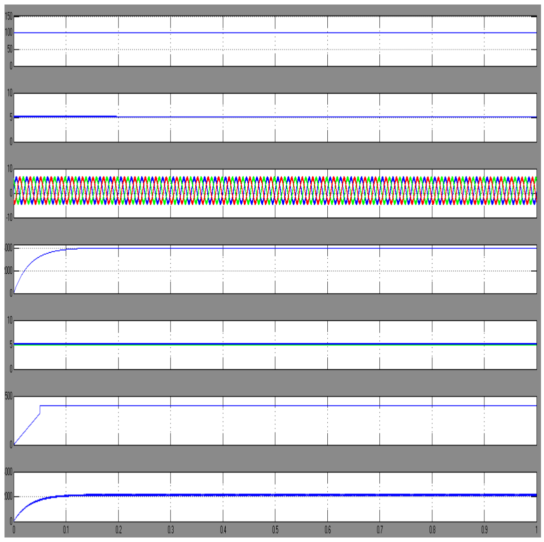

Fig.8. Simulink circuit for pmsm drive with pv cell and cuk converter.

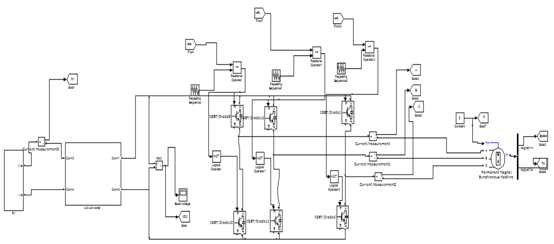

Fig.9. Simulink circuit for cuk converter.

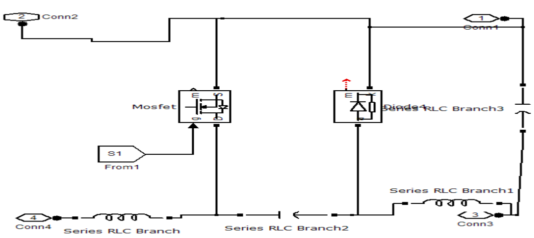

Fig.5. simulation results for (a) pv cell voltage, (b) pv cell current, (c) stator currents of motor (d) speed of motor (e) torque (f) dc link voltage (g) power.

VI. CONCLUSION:

The photovoltaic powered water pump is presented in the paper. The power required by the pump can be delivered by PMSM depending on the head and flow rate. In this paper a PMSM is used to drive the pump for mentioned head and flow rate. The PMSM drive is powered by a PV array. A constant dc voltage can be obtained using DC-DC boost converter or cuk converter. The inverter comprising of SPWM, and filter blocks delivers a sinusoidal ac waveform to the PMSM drive. The scheme can be developed for any power requirement and connecting more PV panels in series.

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