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Modeling and Simulation of Cascaded Multilevel Inverter fed PMSM Drive with PV Stand-Alone Water Pumping System

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ABSTRACT

In this paper is to present PV system directly coupled to water pumping system for such areas where no facility for electricity. Solar PV system have, PV Module, non-isolated Boost converter, Sinusoidal Pulse width modulation inverter and pumping system through PMSM drive. The system is controlled by PI controller. DC-DC converter is controlled in order to extract the maximum power from Solar PV system. The implementation of multilevel inverters improved the torque and speed response under various operating conditions. PI controller is employed as speed controller and PWM technique is used to trigger switches of multilevel inverter. 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, multi level inverter; PMSM drive; photovoltaic; vector control; water pumping system.*

I. Introduction

Energy is necessary for economic and social development of any country. Renewable or non-conventional energy resources are the used day by day due to increasing energy demand. Solar PV system considered as most sustainable resources among renewable sources [1]. PV used for water pumping is playing an important role in agriculture where short of electricity, this system as a boon for farmer. The advantage of solar energy, it is free of cost for whole life, but its initial cost is high. Solar powered pump water volume depends upon the amount of solar energy in that time. The main advantage of solar powered water pumping system are low maintenance, installation easy, reliability and the matching power generated and water usage needs[2]. PV module as a PV energy generation, which output characteristics depends upon the solar radiation and PV temperature. PV System has the nonlinear characteristics, so MPPT required for require for PV system application. The output of the Solar PV system is DC voltage but it is not suitable for load so there is need of a converter, which converts the DC voltage at desire DC value. So DC- DC Boost converter is required. Converter fed to SPIM drive to operate the Water pump. However, this system suffers from increased motor cost and maintenance problems due to the presence of a commutator and brushes [3–5]. 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 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. 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. Photovoltaic System

The PV system considered in this paper contains single PV array as shown in Fig. 1.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.*

$$I_{PV} = I_{ph} - I_0\left[\exp\left(\frac{q(I_{PV}\times R_s + V_{PV})}{AKT}\right) - 1\right] - \frac{V_{PV} + I_{PV}\times R_s}{R_{sh}} \quad (1) \text{ where } I_{ph} = [I_{sc} + k(T - T_r)]\frac{G}{1000} \text{ and}$$

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

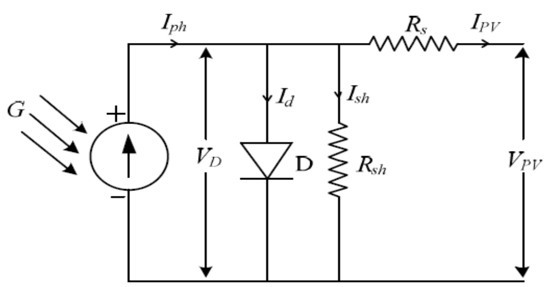


Fig.1.PV system

III. System Configuration and Principle of Operation

Fig.2. 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,

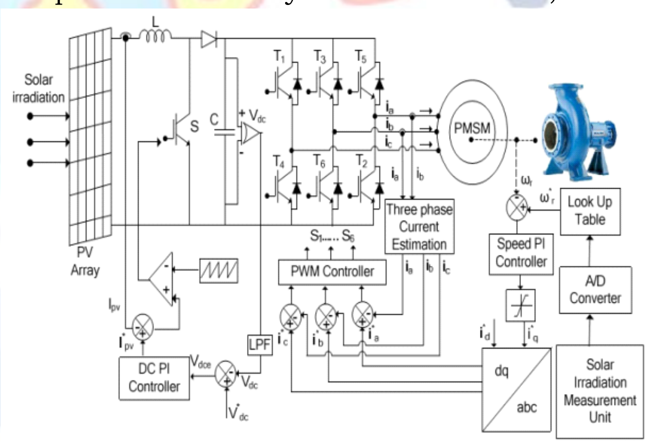


Fig.2. Schematic diagram of standalone solar PV based PMSM drive for water pumping system

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,

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

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.2 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.

$$i_d^* = 0$$

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

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

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

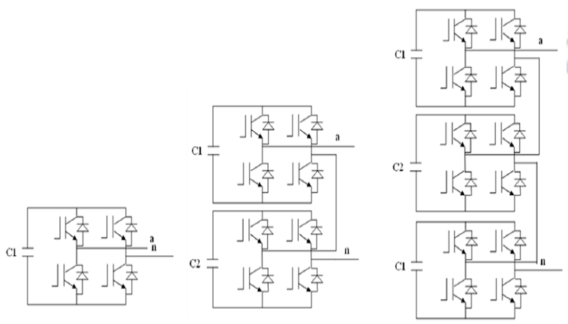
$$i_c^* = i_d^* \cos(\theta_{re} + 2\pi/3) - i_q^* \sin(\theta_{re} + 2\pi/3)$$

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. Multilevel Inverter

The cascaded H-bridge multilevel Inverter uses separate dc sources (SDCSs). The multilevel inverter using cascaded-inverter with SDCSs synthesizes a desired voltage from several independent sources of dc voltages, which may be obtained from batteries, fuel cells, or solar cells. This configuration recently becomes very popular in ac power supply and adjustable speed drive applications. This new inverter can avoid extra clamping diodes or voltage balancing capacitors. Again, the cascaded multilevel inverters are classified depending the type of DC sources used throughout the input.

A single-phase structure of an m-level cascaded inverter is each separate dc source (SDCS) is connected to a single-phase full-bridge, or H-bridge, inverter. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0, and $-V_{dc}$ by connecting the dc source to the ac output by different combinations of the four switches, S_1, S_2, S_3, and S_4. To obtain $+V_{dc}$, switches S_1 and S_4 are turned on, whereas $-V_{dc}$ can be obtained by turning on switches S_2 and S_3. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs.



(a) (b) (c)

Fig.3.Single phase structures of Cascaded inverter (a) 3-level, (b) 5-level.

One more alternative for a multilevel inverter is the cascaded multilevel inverter or series H-bridge inverter. The series H-bridge inverter appeared in 1975. Cascaded multilevel inverter was not fully realized until two researchers, Lai and Peng. They patented it and presented its various advantages in 1997. Since then, the CMI has been utilized in a wide range of applications. With its modularity and flexibility, the CMI shows superiority in high-power applications, especially shunt and series connected FACTS controllers.

The CMI synthesizes its output nearly sinusoidal voltage waveforms by combining many isolated voltage levels. By adding more H-bridge converters, the amount of Var can simply increased without redesign the power stage, and build-in redundancy against individual H-bridge converter failure can be realized. A series of single-phase full bridges makes up a phase for the inverter.

A three-phase CMI topology is essentially composed of three identical phase legs of the series-chain of H-bridge converters, which can possibly generate different output voltage waveforms and offers the potential for AC system phase-balancing. This feature is impossible in other VSC topologies utilizing a common DC link. Since this topology consists of series power conversion cells, the voltage and power level may be easily scaled. The dc link supply for each full bridge converter is provided separately, and this is typically achieved using diode rectifiers fed from isolated secondary windings of a three-phase transformer. Phase-shifted transformers can supply the cells in medium-voltage systems in order to provide high power quality at the utility connection.

V. MATLAB/Simulink Results

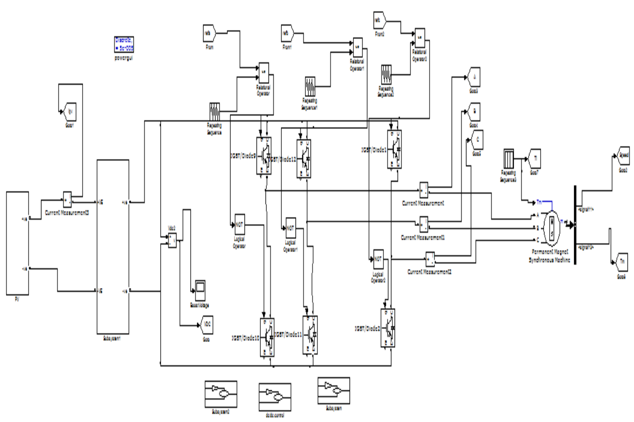


Fig.4.Simulink Circuit for PMSM Drive with PV Cell

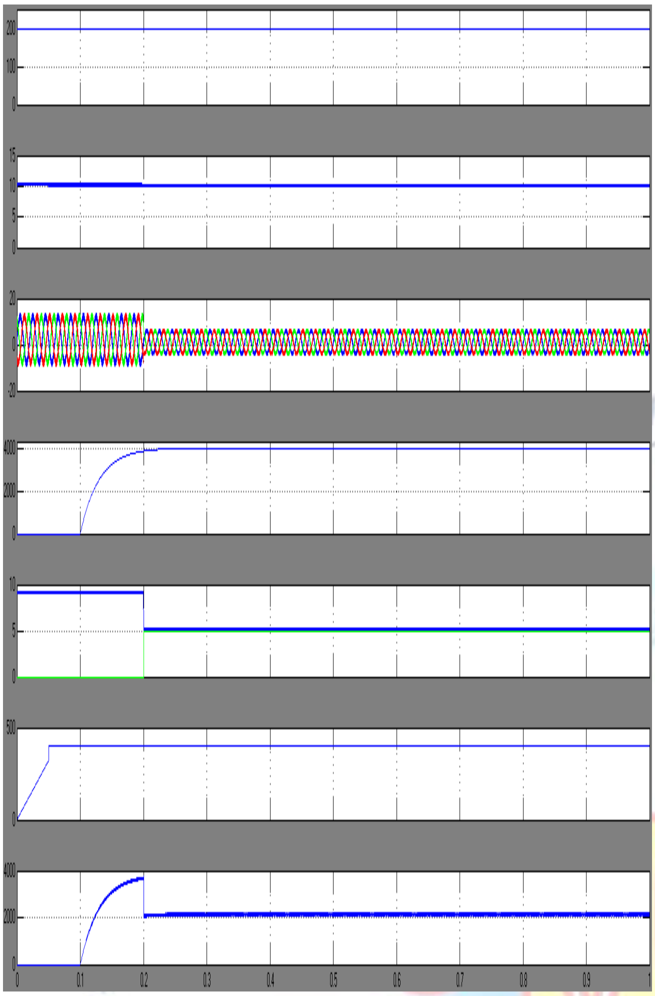


Fig.5. Simulation Results During Constant Solar Radiation For (A) PV Cell Voltage, (B) PV Cell Current, (C) Stator Currents Of Motor (D) Speed Of Motor (E) Torque (F) Dc Link Voltage (G) Power.

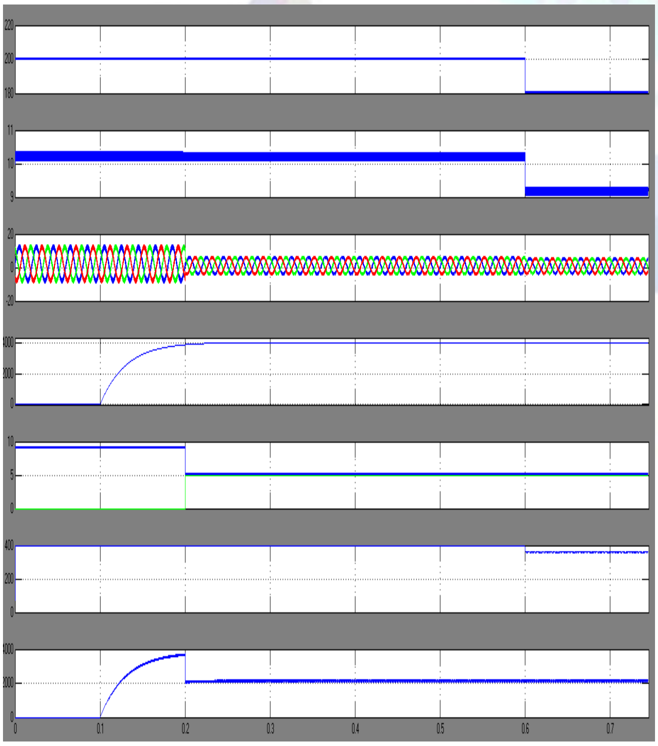


Fig.6. Simulation Results During Change In Solar Radaition For (A) PV Cell Voltage, (B) PV Cell Current, (C) Stator Currents Of Motor (D) Speed Of Motor (E) Torque (F) Dc Link Voltage (G) Power

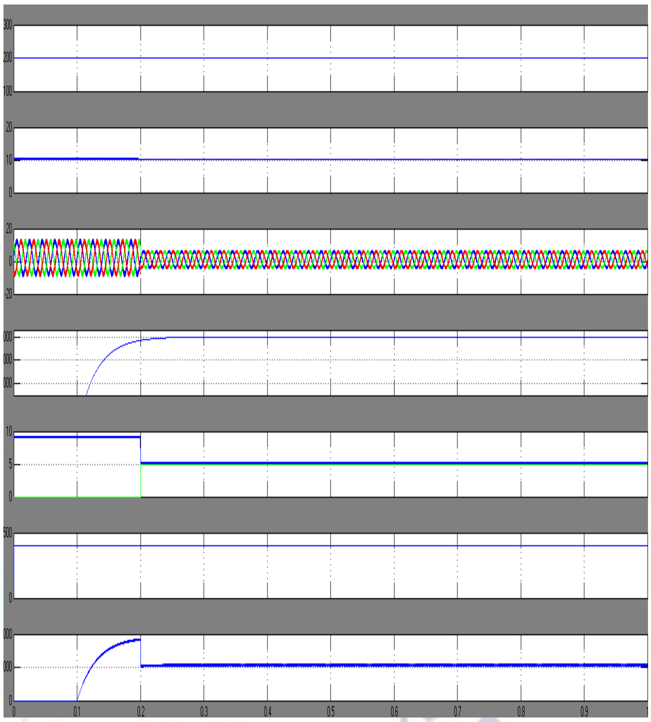


Fig.7. Simulation Results During Motor Starting Condition For (A) PV Cell Voltage, (B) PV Cell Current, (C) Stator Currents Of Motor (D) Speed Of Motor (E) Torque (F) DC Link Voltage (G) Power

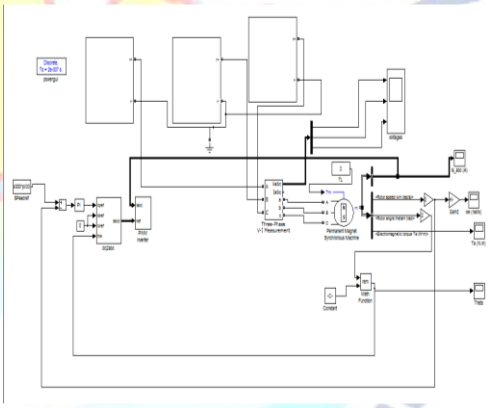


Fig.8. Simulink Circuit for PMSM Drive with Multilevel inverter

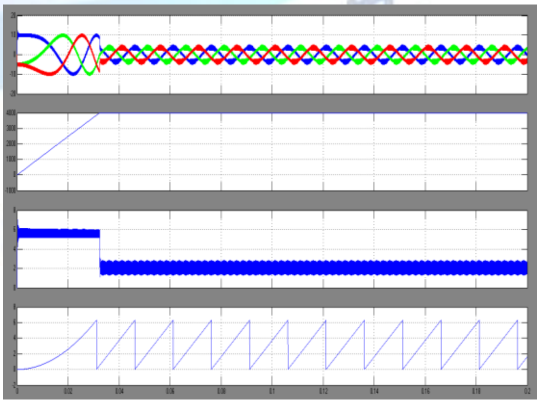


Fig.9.Simulation Results for (A) Stator Currents of Motor (B) Speed of Motor (C) Torque (D) theta

VI. Conclusion

In this paper vector control has been described in adequate detail and has been implemented on

PMSM in combination with multilevel inverter with three and five levels. This method enables the operation of the drive at zero direct axis stator current. The inverter comprising of SPWM, and filter blocks delivers a sinusoidal ac waveform to the PMSM drive. The motor needs much smaller voltage compared to the conventional synchronous motor. The performance of vector control is quite satisfactory for achieving fast reversal of PMSM even at very high speed ranges. The scheme can be developed for any power requirement and connecting more PV panels in series.

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