Analysis and development of a low-cost permanent magnet brushless DC motor drive for PV-array fed water pumping system

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Abstract

This paper deals with the analysis and development of a permanent magnet brushless DC (PMBLDC) motor drive coupled to a pump load powered by solar photovoltaic (PV) array for water pumping system. A simple low-cost prototype controller has been designed and developed without current and position sensors which reduces drastically the overall cost of the drive system. This controller is used to test the dynamic behavior of the PMBLDC motor drive system. The mathematical model of the system is developed with a view to carry out a comparison between experimental and simulated response of the drive system. A simple filter circuit incorporated in between PV-array and an inverter to reduce ripples and to improve the performance of the PV-array. The necessary computer algorithm is developed to analyze the performance under different conditions of varying solar insolation for a pump load.

Keywords: Permanent magnet brushless DC motor; Photovoltaic array; Solar insolation; Water pumping system

1. Introduction

New types of electric motors like permanent magnet (PM) motors, switched reluctance motors (SRM) and stepper motors (SM) have emerged due to the development in engineering material technology and improvement in solid-state devices and circuits [1, 2]. Owing to the technical improvements in motors, controllers and
feedback techniques, electronically commutated motors (ECM) (also known as brushless motors) are replacing brushed motors in many applications. The main advantages of the ECM over the brushed motors are less maintenance requirements, reduced environmental effects and less electromagnetic radiation [2]. Within the last three decades, several improved magnetic materials are developed for high-performance PM motors. Rare-earth magnets which are usually samarium cobalt alloys, are still among the best performing magnetic materials. The most recent developments are the neodymium–iron–boron alloys. The magnetic performance of these alloys is about 30% better compared to samarium cobalt magnets [1]. PMBLDC motor drives have received a considerable attention recently as their performance is superior to those of the brushed DC motors and AC motors for servo and adjustable speed applications. Specially designed low-inertia motors fed by the MOSFET-based current-controlled voltage-source inverter (CC-VSI), provide desirable features such as high power-to-weight ratio, high torque-to-current ratio, fast response and above all high operating efficiency. The features of high operating efficiency, brushless construction, maintenance-free operation and increasing awareness about energy conservation have given a scope to the demand of the PMBLDC motor in water pumping application operated by PV-array, particularly, in remote villages where electric supply is not available.

Needless to say, the global energy crisis experienced today is the result of disproportionate and wasteful use of some of the fossil fuels, such as petroleum, coal and natural gas, which took several million years in their synthesis. The humankind today is beset with global environmental problems of the green-house effect and acid rain [3–7]. The key to resolving these problems lies in the development of cleaner forms of energy. Solar cells, which convert directly the solar energy into electricity through the PV effects of semiconductors are very useful in conquering the global environmental problems. One of the important characteristics of solar energy systems is their “invariant” nature. They do not extract any material from earth and they do not return any pollutant to the environment [4–6]. New process used for manufacturing of PV cells and thereby enhancing efficiency of cells, are currently being explored, aiming at reducing the cost per peak watt. Solar energy is an ideal form of energy with the features of being environment friendly and substitute of dwindling energy resources. It is clean, non-exhaustible and available all over the world with varying intensity [7]. Furthermore, silicon – the main material used in manufacturing of solar cells – is the second-most plentiful element available on the earth. Thus, there is no problem of resource availability [8, 9].

In view of the above, countries like India have made it a national mission to install large number of PV-operated pump sets to irrigate remote and rural areas. While adequate financial input from global agencies is available, appropriate technological input is found lacking. The PV-panels energized DC motors drive the pumps. Since the system has to be installed in technically unattended zones, it must be robust, economical and maintenance-free. The PM-brushed motors using mechanized commutators and brushes need regular maintenance and are also prone to failure. Electronically commutated PMBLDC motors may be a natural alternative. Such motors used for other applications such as aerospace are found to be prohibitively
expensive, necessitating the development of a system which is reliable and within reach of the customer.

Several authors have studied different aspects of steady-state performance of various types of electric motors operated from a PV-array [3–12]. Appelbum et al. [7] have examined the starting characteristics of PM-brushed DC and series motors powered by a solar cell. Rehman [3] have discussed the diversity in the application of the photovoltaic systems. Alhuwainem [5] has analyzed steady-state performance of DC motors supplied from PV generators with step-up conversion. Bhat et al. [6] have discussed the performance optimization of an induction-motor pump system using a PV energy source. There is not enough literature about the dynamic behavior of PMBLDC motor which drives the water pump when power is fed from a PV-source. The authors have already reported [8] the dynamic behavior of the current-controlled PMBLDC motor with closed-loop control. This work is extension of the earlier work and also verifies the simulated results experimentally.

The PMBLDC motor is considered to be one of the best motor which exhibits the highest efficiency among all conventional motors [1]. Due to its performance superiority, this motor is more suitable for solar energy powered water pumping application. A water pumping system does not require accurate speed control for its satisfactory performance, but cost reduction is the prime consideration in such systems. The elimination of position sensor and current sensors, greatly reduces the overall cost of the drive system and also simplifies the controller circuit. Hence, in this paper a new low-cost scheme has been proposed for PV-array powered PMBLDC motor coupled to a water pump. A prototype laboratory model is developed with a view to extend experimental verification for the simulated results.

2. Control strategy

Fig. 1 shows a schematic diagram of the PMBLDC motor drive coupled to water pump powered by PV-array through the filter and an inverter. The PV-array directly converts solar insolation into DC electrical power. The magnitude of PV-array current depends upon the intensity of sunlight. This current is fed to the MOSFET-based VSI which supplies the necessary power to the PMBLDC motor to drive the water pump. The switching pattern can be obtained by estimating the position by sensing the back-emf. In this system the current is restricted without current controller, because the PV-array itself controls the current up to its maximum value. In this drive, therefore, the use of current sensors and position sensor is not required, thus resulting in low cost and robust drive.

3. Analysis of the drive system

All the accessories of the drive system are modeled independently and integrated together for the purpose of performance simulation.
3.1. PV-array

The solar cells are connected in series and parallel combinations in order to get the desired level of voltage and current. The equivalent circuit of PV array is shown in Fig. 2.

The \( I-V \) equations of a solar cell is given by

\[
V = -IR_s + \frac{1}{D} \ln(1 + (I_{ph} - I)/I_0)),
\]

where \( I_{ph} \) is the photon current proportional to the insolation, \( R_s \) the series resistance of the cell, \( I_0 \) the cell reverse saturation current, \( D \) the \( q/AKT \), \( q \) the electric charge of an electron, \( K \) the Boltzmann constant, \( T \) the absolute temperature, and \( A \) the compilation factor.
3.2. Inverter and motor

The detailed modeling is already reported in Ref. [8]. The volt-ampere equations in state-space current derivative form can be expressed as

\[ P_i = 1/(L + M) [v_n - i_n R - e_n], \]
\[ P_b = 1/(L + M) [v_b - i_b R - e_b], \]
\[ P_c = 1/(L + M) [v_c - i_c R - e_c]. \]

where \( i_n, i_b \) and \( i_c \) are winding currents of the phases, \( L \) the self-inductance and \( M \) the mutual inductance. \( v_n, v_b \) and \( v_c \) are phase voltages, \( e_n, e_b \) and \( e_c \) are phase to neutral back-emfs and \( R \) is the resistance per phase of stator winding.

The torque expression becomes

\[ T_c = K_b[f_a(\theta_r)i_a + f_b(\theta_r)i_b + f_c(\theta_r)i_c], \]

where \( f_a(\theta_r), f_b(\theta_r) \) and \( f_c(\theta_r) \) are functions of rotor position. The mechanical equation of the motion in speed derivative form can be expressed as

\[ Pw_r = (P/2)(T_c - T_1 - Bw_r)/J. \]

where \( T_1 \) is the load torque, \( B \) the frictional coefficient, \( P \) the number of poles and \( J \) the moment of inertia.

3.3. Modeling of filter circuit

A simple L-C filter circuit is introduced in between the PV-array and MOSFET-based inverter which helps in reducing ripples at the input of the inverter. The filter also increases the life of the PV-array and improves the response of the drive system. The DC link voltage \( v_d \) and current \( i_d \) in the state-space form can be obtained as

\[ p_d = (v_a - v_d)/L, \]
\[ pv = (i_d - i_{d1})C. \]

where \( v_a, v_d, i_d \) and \( i_{d1} \) are the array voltage, DC link voltage, array current and DC link current, respectively, \( L \) the filter inductance and \( C \) the capacitance.

3.4. Position detection by using back EMF

The induced emf in the phase windings are \( E_a, E_b \) and \( E_c \) and are generally in trapezoidal shape as shown in Fig. 3. The line-induced voltages across the line, \( E_{ab}, E_{bc}, \) and \( E_{ca} \) are derived from the phase-induced voltages as \( E_{ab} = E_a - E_b \), \( E_{bc} = E_b - E_c \) and \( E_{ca} = E_c - E_a \). From these three line voltages \( E_{ab}, E_{bc} \) and \( E_{ca} \), the six pulse signals of \( 180^\circ \) duration are obtained with the help of zero-crossing detectors. These signals can be represented as \( S_a, S_b, S_c, S_d, S_e \) and \( S_f \) as shown in Fig. 3.
Fig. 3. Detection of position signals using back emfs.

The necessary six pulse signals, namely, F1–F6 for conduction period and six pulse signals, namely, F11–F16 for commutation period are obtained by logically adding the 180° pulse signals. The signals so-obtained have 120° conduction period and 60° commutation period and these are shown in Fig. 3.

At the time of starting of the motor, the induced emfs are zero and, hence, information about the rotor position cannot be extracted. As a solution to this
problem, the low-frequency currents are injected through the motor phase. This results in the production of an average positive torque which provides rotation of the motor shaft. When rotor shaft picks up speed at which the induced emfs are detectable, these are used to obtain the switching signals for controlling the VSI.

4. Hardware description

Figs. 4 and 5 show the block diagram of starting scheme and normal running scheme. In order to obtain square-wave pulses of low frequencies, an astable multivibrator using the 555 IC is used. The output of the stable multivibrator is not a symmetrical square wave. Therefore, a divide by two circuit is used to generate a symmetrical square wave and which reduces the frequency of the signal obtained from 555 to the half. Two three-stage ring counters are used for generating signals for six inverter devices. The IC 74121 is used to provide the necessary delay signal. The two output stages of ring counters are used to determine, whether the gating signals to the MOSFET are obtained from the starting circuit or from motor terminals. The output of the ring counter and the Q of the 74121 are connected to input of the AND and OR gate. These two operations (AND and OR) ensure that the gate driver, signals obtained from starting circuit when output Q of 74121 is high.

4.1. Scheme for normal running

The PMBLDC motor has star-connected windings without neutral, it is not possible to directly sense the back-emfs across the phases. Therefore, the line voltages are sensed and their zero-crossing signals are obtained. These zero-crossing signals (a, b and c) and their inverted signals (a, b and c) are used to derive the gating signals as follows:

![Diagram](image-url)

Fig. 4. Starting scheme of sensorless operation.
Fig. 5. Normal running scheme of sensorless operation.

\[ G_1 = a, \quad G_2 = b, \quad G_3 = c, \quad G_4 = c, \quad G_5 = b, \quad G_6 = a, b, \]

where \( G_1 - G_6 \) are the gating signals of the MOSFET 1–6, respectively. While \( a, b \) and \( c \) are the positive zero-crossing signals of line voltages \( E_{ab}, E_{bc} \) and \( E_{ca} \), respectively.

These signals \( G_1 - G_6 \) are fed to one of the inputs of the two-input AND gate, the other input being the signal \( Q \) of one shot. The output of these AND gates are connected to one input terminal of the OR gates, while the other input for the OR gate is fed from the starting circuit.

5. Realization of PV-array

The PV-array power considered in this investigation is to supply the DC power required to drive the PMBLDC motor which is coupled to the water pumping system. The array power is an equivalent to a DC source with series resistance. Due to nonavailability of the required rating of PV-array, in the laboratory, an attempt has been made to simulate the effect of PV-array by considering the ripple-free DC source along with series resistance. By suitably controlling the series resistance, it is possible to simulate different DC power levels which are equivalent to the actual PV-system with different solar insolation.

6. Results and discussion

A classical numerical technique called the fourth-order Runge-Kutta method is used to solve the first-order nonlinear differential Eqs. (1)–(8), in order to obtain the dynamic performance of the PMBLDC motor fed from PV-array.
Fig. 6. Response of the PMBLDC motor drive fed by PV-array without filter circuit.

The dynamic response of 3-phase, 4-pole, 1500 RPM, star-connected PMBLDC motor coupled to a water pumping system is shown in Fig. 6. To reveal the effectiveness of the drive system, the following observations are made from the results obtained. First, the simulation results are demonstrated without the filter circuit, which shows the ripples in both array voltage and array current. These ripples are drastically reduced when the L–C-filter is introduced in between the PV-array and the inverter.

Fig. 6a–Fig. 6f show the variations of array voltage, array current, motor winding current, rotor speed, load torque and electromagnetic torque with respect to time at a given solar insolation. From part (a) of this figure it may be seen that the array voltage starts form its initial low value and increases slowly till the motor reaches the steady-state condition. Under the steady-state condition the array voltage is maintained at a constant value with small ripples. The voltage suffers from small
fluctuations at every 60° due to commutation. The array current rises very rapidly to the level of photon current (2.0 A) at standstill condition, and current reduces to a nominal value as the motor accelerates, thereby attaining a constant value with small fluctuation. The winding current also fluctuates due to the regular commutation of inverter devices. The speed steadily increases till the load torque equals to the developed electromagnetic torque and remains at constant value under steady-state running condition.

Fig. 7a–Fig. 7d show the variations of array voltage, array current, rotor speed and winding current with respect to time when the filter circuit is introduced in between the PV-array and inverter. It can be clearly observed from the response obtained that the ripples found in the earlier responses (without filter) are drastically reduced with the inclusion of filter.

To validate the mathematical model developed, some of the simulated responses are verified with the experimental results obtained with equivalent PV-source. There is close agreement between the simulated results and experimental results. These are shown in Fig. 8.

The measured and simulated responses are shown in Fig. 8. Part (a) of this figure shows the variation of the speed with respect to time. The winding current (a-phase) is shown in part (b). Part (c) shows the winding current and DC link voltage during transient condition. In the experimental results also, small oscillations are found due to the commutation at every 60°.
(a) Rotor Speed

(b) Winding Current

(c) DC link Current and DC link Voltage

Fig. 8. Response of the PMBLDC Motor Drive with Filter by using equivalent source of PV-array.
7. Conclusions

The proposed model of the low-cost PMBLDC motor has been found effective in analyzing the dynamic performance of the drive system. The developed prototype operates satisfactorily with different DC bus voltages. The elimination of rotor position sensor and current sensors have made the system simpler and resulted in the reduction of overall cost of the drive system. The drive system is found suitable to pump the water even during the condition of low-power caused by low solar insolation. An $L$–$C$ filter introduced between the PV-array and the inverter, has been found instrumental in reducing a current and voltage fluctuations, thereby smoothing the input supply (PV-array) to the inverter. The position detection through the sensing of back-emf has been found easier to implement. It has worked satisfactorily with different power levels. It is hoped that owing to its improved performance, high efficiency and low cost, PMBLDC motor drive has become an ideal drive for water pumping, application, especially in isolated places.

Appendix A.

Data of Motor and PV-Source

$R_s = 0.03$ Ohms, $R = 5$ Ohms $L_s = 0.006$H/phase, $K_b = 0.13$ V/rpm, $P = 4$, $J = 0.0132$ kg/m$^2$, $I_o = 0.000025$ A, $A = 1.66$, $C = 0.001$ F $L = 0.0025$ H, $I_{ph} = 2.0$ A, Rated Speed 1500 rpm.

Equivalent PV-source

DC link voltage = 160.0 V, series resistance = 100.0 Ohms

References


