Simulation and experimental validation of AC motor and PMDC motor pumping system fed by photovoltaic cell

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Solar water pumping is a promising renewable alternative to conventional water pumping for large, medium and small power applications. This system is also useful in remote areas where electricity is not available and it is very expensive to lay long transmission lines. This paper deals with basics of solar powered water pumping system and the comparison of performance between AC motor and PMDC motor pumping systems. In this work, the MATLAB based modelling of a PV array, single-phase induction motor and permanent magnet DC motor are studied and developed. The photovoltaic is used to feed power to the water pumping systems. The performance characteristics of single-phase induction motor and permanent magnet direct current motor are obtained by using MATLAB simulation and are validated with experimental results. From the experimental results, it is found that the permanent magnet direct current motor is best suitable for photovoltaic water pumping than the single-phase induction motor in low power applications.

Keywords: Photovoltaic cell, AC motor, PMDC motor, simulation, Water pumping

Water and access to a clean supply of water are essential for everyday life, irrigation, health of livestock and many other uses. An estimated 1.2 billion people in the world today do not have access to clean water. The variety of water pumping applications is considerable and they can vary widely, both in their requirements and the conditions under which water is pumped. Solar water pumping is done all over the world and it greatly enhances the quality of life of people living in rural and remote places. Solar PV water pumping systems are reliable and are very cost-effective and they can replace manual pumps, if used in the right location. A solar water pumping system does not require batteries to provide power if the water stored in a tank for the use at night. In the simplest solar water pumping systems, the solar panels are connected directly to a small DC motor that drives the water pump. These simplified systems use centrifugal pumps, because of their ability to be matched with the output of the solar panels.

Displacement pumps, otherwise known as volumetric pumps, have very different speed-torque characteristics and are not very well suited in getting connected directly to solar panels. When such pumps are used, power conditioning or maximum power point tracking is commonly included between the solar panel and the pump, so that the electrical energy can be converted into a more usable form. Just like varieties of water pumps, there is a huge variety of motor types used in water pumping systems with each motor having its own advantages and disadvantages, and they result in the type of application they can be used for. If AC motors are used, an inverter should be placed between the solar panels and the motor which will add value to the cost of the system while comparing with DC motor based water pumps. In this paper, PV fed single-phase induction motor and permanent magnet DC motors are simulated by using MATLAB and compared with the experimental results. It is found from the work that PMDC motor water pumping system is better than the AC motor water pumping system. The general block diagram of AC motor and PMDC motor water pumping systems are shown in Fig.1 (a) and (b) respectively.

Materials and Methods

PV Model

The solar cell represents the fundamental power conversion unit of a PV system. For practical use, they are usually assembled into modules. About 36 cells are typically interconnected in series in order
to give a charging voltage for a 12 V battery. For a high power requirement, the modules are interconnected in series/parallel to form a DC power-producing unit known as an array. The equivalent circuit of PV cell is shown in Fig. 2. The strategy of modeling a PV module is no different from modeling a PV cell. It uses the same PV cell model. The parameters are all the same, but only a voltage parameter (such as the open-circuit voltage) is different and must be divided by the number of cells. The model consists of a current source ($I_{ph}$), a diode ($D$), and a series resistance ($R_{se}$). The effect of parallel resistance ($R_{pa}$) is very small in a single module and therefore the model does not include it. By using Faraday’s law for the boost inductor

$$V_s DT = (V_0 - V_s)(1 - D)T$$

from which the DC voltage transfer function turns out to be

$$M_v = \frac{V_0}{V_s} = \frac{1}{1 - D}$$

The boost converter steps up the output voltage of PV array to the required value before feeding to the pumping system.

**PMDC Motor model**

Among different types of DC motors, a permanent magnet DC (PMDC) motor is preferred in PV systems because it can provide higher starting torque. The circuit diagram of a permanent magnet DC motor is shown in Fig. 4. The motor voltage equation is given by

$$V = E + IR + V_b$$

where, $V$ is the applied voltage, $E$ is the motor back e.m.f., $I$ is the armature current, $R$ is the armature resistance and $V_b$ is the brushes voltage drop.
The back e.m.f. of a permanent magnet DC motor can be expressed as
\[ E = k_E \omega \] \hspace{1cm} ... (6)
where, \( k_E \) is the voltage constant and \( \omega \) is angular speed. The motor shaft torque can be written as
\[ T = T_{em} - T_O \] \hspace{1cm} ... (7)
where, \( T \) is the motor shaft torque, \( T_{em} \) is the electromagnetic torque and \( T_O \) is the torque representing the mechanical (friction and windage) and iron losses.

The expression for the electromagnetic torque is given by
\[ T_{em} = k_T I \] \hspace{1cm} ... (8)
where, \( k_T \) is the torque constant.

The motor losses at load current \( I \) can be expressed as

\[ \text{Motor losses} = \text{Armature copper loss} + \text{Brush loss} + \text{Iron loss} + \text{Mech. loss} \]

The no load motor losses can be expressed as
\[ \text{No load Motor losses} = \text{No load Copper loss} + \text{No load Brush loss} + \text{Iron loss} + \text{Mech. Loss} \]

At no-load, the armature losses are very small and they may be neglected. Based on the first order approximation, brush losses may also be neglected so that the motor shaft output power is expressed as \( P = T_{O} \omega \), and it can also be written as
\[ P = k_T (I - I_o) \omega \] \hspace{1cm} ... (9)

Using the fact that \( k_E = k_T \), the constants for the above model are obtained from the manufacturers rated data and \( I_O \) from no load test.

**Inverter model**

Voltage source inverters are widely used in power supplies, power quality controllers, and renewable energy, marine and military applications. If the input DC is a voltage source, then the inverter is called a voltage source inverter (VSI). The simplest DC voltage source for a VSI may be a battery bank or a solar photovoltaic cells stack. They are at the heart of applications requiring an AC supply from a DC source. Therefore, it is important that they are designed to be robust and efficient, especially in remote areas and renewable energy applications. Figure 5 shows the circuit topology for a full bridge inverter.

It is an electronic power converter that is necessary as an interface between the power input and the load. The full bridge single-phase inverter consists of the DC voltage source, four switching elements \( T_1 \), \( T_2 \), \( T_3 \) and \( T_4 \) and load. The full bridge single-phase inverter has two legs, left or right or ‘A’ phase leg and ‘B’ phase leg. Each leg consists of two power devices connected in series. The load is connected between the midpoints of the two-phase legs. Each power control device has a diode connected anti-parallely to it. The diodes provide an alternative path for the load current if the power switches are turned OFF. The control pulse to the switches may be generated either by microcontroller or by DSP. A variable voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. The output voltage waveform of single-phase inverter is shown in Fig. 6.

The RMS output voltage can be found from
\[ V_O = \left( \frac{2}{T_O} \int_0^{T_o/2} V_S^2 \, dt \right)^{1/2} = V_S \] \hspace{1cm} ... (10)
AC Motor model

The equivalent circuit of the induction motor based on double revolving field theory is shown in Fig. 7 where ‘a’ is the turns ratio of the auxiliary to main winding; \( R_{lm}, X_{lm} \) are the resistance and reactance of the main winding; \( R_{la}, X_{la} \) are the resistance and reactance of the auxiliary winding; \( R_c, X_c \) are the equivalent series resistance and reactance of the capacitor; \( R_b, X_b \) are the backward equivalent series resistance and leakage reactance of the rotor referred to the main winding; \( R_{fa}, X_{fa} \) are the mutually induced voltages in auxiliary winding by its forward and backward fluxes of the main winding respectively; \( E_{fa}, E_{ba} \) are the self induced voltages in auxiliary winding by its forward and backward fluxes of the main winding respectively. From Fig.7, the following equations are written:

\[
V = Z_{lm} I_m + E_{fm} + E_{bm} - jE_{fa} / a + jE_{ba} / a \quad \ldots (11)
\]

\[
V = (Z_{la} + Z_c) I_a + E_{fb} + E_{ba} + jaE_{fm} - jaE_{bm} \quad \ldots (12)
\]

where,

\[
E_m = Z_f I_m = I_m (R_f + jX_f) \quad \ldots (13)
\]

\[
E_{bm} = Z_b I_m = I_m (R_b + jX_b) \quad \ldots (14)
\]

\[
E_{fa} = a^2 Z_f I_a = a^2 I_a (R_f + jX_f) \quad \ldots (15)
\]

\[
E_{ba} = a^2 Z_b I_a = a^2 (I_a (R_b + jX_b)) \quad \ldots (16)
\]

The net amount of power transferred across the air gap is obtained as

\[
P_g = (1 - S) P_m \quad \ldots (19)
\]

where, \( P_m \) is the mechanical power developed.

The output power is

\[
P_o = P_m - P_{rot} \quad \ldots (20)
\]

where, \( P_{rot} \) is the rotational losses.

Centrifugal pump model

In general, two types of pumps are commonly used for water-pumping applications. One is positive displacement pump and the other is centrifugal pump.

In displacement pumps, the water output is directly
proportionate to the speed of the pump, but almost independent of head. Centrifugal pumps are used for low-head applications, especially if they are directly interfaced with the solar panels.\(^2\)

Centrifugal pumps are designed for fixed-head applications, and the pressure difference generated increases in relation to the speed of the pump. Centrifugal pumps also have relatively high efficiency and are capable of pumping a high volume of water.\(^9\) Due to the above mentioned advantages the centrifugal pump is chosen for this work. The PMDC motor with centrifugal pump is not available in the market. Any pump is characterized by its absorptive power which is obviously the mechanical power on the shaft coupled to the pump, which is given by

\[ P = \frac{\rho gHQ}{\eta} \quad \ldots \text{(23)} \]

Useful power: power consumed of the absorptive power is given by

\[ P_u = \rho gHQ \quad \ldots \text{(24)} \]

where \(\eta\) is efficiency; \(\rho\) is density (kg/m\(^3\)); \(g\) is acceleration of gravity (m/s\(^2\)); \(H\) is height of rise (m); \(Q\) is flow (m\(^3\)/s).

**Simulation of PV fed PMDC Motor Pump**

The overall simulation model of permanent magnet direct current (PMDC) motor powered by solar array is shown in Fig. 8. The DC voltage from the solar system is less in value and it is increased to the required level by means of boost converter. The MPPT block changes the duty ratio of the boost converter so that the maximum power from the solar array can be extracted.\(^1,5\) The type of solver used is ode23tb (stiff/TR-BDF2). The minimum step size is 1e-6 and the maximum step size is 1e-5.

The ratings of PMDC motor used in this system is given in Table 1. The output voltage and current of boost converter in PMDC motor system for the input of 70 V is shown in Figs 9 and 10 respectively. The output voltage of the boost converter is 116.7 where the duty ratio is 0.4. Table 2 gives the numerical data measured from simulation of PV fed permanent magnet DC motor at the irradiance of \(G=1000 \text{ W/m}^2\).

The simulation can also be done for different insolation levels. Table 2 gives the efficiency of boost converter and permanent magnet DC motor at a specific irradiance condition (\(G=1000 \text{ W/m}^2\)). It is

**Table 1—Ratings of PMDC Motor**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power</td>
<td>0.5hp</td>
</tr>
<tr>
<td>2</td>
<td>Voltage</td>
<td>120v</td>
</tr>
<tr>
<td>3</td>
<td>Current</td>
<td>3A</td>
</tr>
<tr>
<td>4</td>
<td>Speed</td>
<td>3000rpm</td>
</tr>
<tr>
<td>5</td>
<td>Insulation</td>
<td>Class F</td>
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</tbody>
</table>

**Table 2—Ratings of single phase AC motor**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type</td>
<td>Single-phase</td>
</tr>
<tr>
<td>2</td>
<td>Power</td>
<td>0.5 HP</td>
</tr>
<tr>
<td>3</td>
<td>Voltage</td>
<td>220 V</td>
</tr>
<tr>
<td>4</td>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>5</td>
<td>Current</td>
<td>2.5 A</td>
</tr>
<tr>
<td>6</td>
<td>Speed</td>
<td>3000 rpm</td>
</tr>
<tr>
<td>7</td>
<td>Capacitance</td>
<td>10 (\mu)F</td>
</tr>
</tbody>
</table>

Fig. 8—Simulink diagram of PV based PMDC motor system
clear that the efficiency of boost converter is more than 90%. The speed range of PMDC motor is between 2650 rpm and 1550 rpm. The performance characteristics of PMDC motor like speed and torque curves can also be obtained from the simulation which is found in most of the literatures.

Simulation of PV fed Single-Phase AC Motor
The simulink circuit model of single-phase induction motor fed by solar array is shown in Fig. 11. The MATLAB model consists of simulink blocks for PV array, MPPT controller, boost converter, single-phase inverter and single-phase induction motor. The subsystems created for all the components are interconnected to form the whole system. The specifications of PV module BP SX150S are used for the simulation. The type of solver used is ode23tb (stiff/TR-BDF2). The minimum step size is 1e-6 and the maximum step size is 1e-5.

The rating of single-phase AC motor used is given in Table 3. The output voltage of PV array varies from 170 V to 200 V depending on the insolation level. The output voltage from the solar array is increased to the required level by means of boost converter. The output voltage from boost converter is 330 V. The MPPT block is connected between PV array and boost converter. Maximum power point tracking, frequently referred to as MPPT, is an electronic system that operates the photovoltaic (PV) modules in a manner that allows the modules to produce all the power they are capable of.

Whenever the value of solar insolation varies, the MPPT changes the duty ratio of the boost converter to extract maximum power from it. The simulation is

<table>
<thead>
<tr>
<th>S.No.</th>
<th>$P_{IN}$ (W)</th>
<th>$P_{OUT}=P_{IN}$ (W)</th>
<th>$C_{EFF}$ (%)</th>
<th>$N$ (RPM)</th>
<th>$P_{OUT}$ (W)</th>
<th>$\eta_{DCM}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>118.69</td>
<td>115.74</td>
<td>97.51</td>
<td>2650</td>
<td>67.36</td>
<td>58.2</td>
</tr>
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<td>2</td>
<td>146.85</td>
<td>143.13</td>
<td>97.46</td>
<td>2400</td>
<td>89.45</td>
<td>62.5</td>
</tr>
<tr>
<td>3</td>
<td>188.69</td>
<td>179.78</td>
<td>95.27</td>
<td>2150</td>
<td>128.18</td>
<td>71.3</td>
</tr>
<tr>
<td>4</td>
<td>235.35</td>
<td>222.04</td>
<td>94.34</td>
<td>1900</td>
<td>174.30</td>
<td>78.5</td>
</tr>
<tr>
<td>5</td>
<td>294.69</td>
<td>272.65</td>
<td>92.52</td>
<td>1700</td>
<td>225.48</td>
<td>82.7</td>
</tr>
<tr>
<td>6</td>
<td>352.02</td>
<td>323.85</td>
<td>91.99</td>
<td>1550</td>
<td>280.45</td>
<td>86.6</td>
</tr>
</tbody>
</table>

Fig. 11—Simulink diagram of PV based AC motor system
carried out for various voltages at different irradiance conditions for the analysis purpose. The output voltage and the current of boost converter for input of 200 V are shown in Figs 12 and 13 respectively.

The boost converter is stepping up the input voltage from 200 V to 333 V. The value of duty ratio is 0.4. The output voltage of the boost converter is applied to the single-phase bridge type inverter. The switches in the inverter are triggered by SPWM pulse generator. The output voltage of inverter is 220 V. The output voltage and current of inverter are shown in Figs 14 and 15, respectively. Table 4 gives the numerical data measured from the MATLAB simulation of PV fed AC single-phase induction motor at the irradiance of $G = 1000 \text{ W/m}^2$. Similarly, the data can be measured for various insolation levels. The efficiency of boost converter and single-phase induction motor are tabulated.

The simulation data of PV fed PMDC motor system and PV fed AC motor system are compared. It is clear from the simulation data Tables 3 and 4 that the dynamic performance and the efficiency of PMDC motor are better than AC induction motor.

**Comparison of performance characteristics of PV fed PMDC and Single phase AC motor**

The PMDC motor is small in size and is rugged when compared to AC motor. The PMDC motor will not require a separate dc source for excitation of field coils. The speed range of the PMDC motor is more. But, in AC motor system there is a problem of harmonics. The power factor also should be taken into care.

The cost of AC motor is more than the PMDC motor. The comparison of speed and torque of single-phase AC motor and PMDC motor is shown in Figs 16 and 17, respectively.

It is seen from the comparison of speed and torque curves that the dynamic performance of PMDC motor is better than the AC single-phase induction motor. It is evident from the numerical data of the simulation results that the PMDC motor has more efficiency than AC motor.
Experimental set-up and Results

The experimental set-up of PV fed water pumping system is shown in Fig. 18. A DC to DC boost converter and single-phase inverter are used to interface the PV array output to AC motor driven centrifugal pump. BP Solar BP SX 150S PV module is chosen for this work. Table 5 gives the electrical specifications of BP SX 150S. The module is made of 72 multi-crystalline silicon solar cells in series and it provides 150 W of nominal maximum power.

The control unit consists of a microchip dsPIC33FJ16GS504 microcontroller and interface circuits which are required to lead the PV array’s voltage and current signals to the microcontroller. The controller on chip pulse width modulation (PWM) generator output drives the DC to DC boost converter according to MPPT’s algorithms.

The boost converter comprises of MOSFET switch IRF730, diode BYT 71 and coil (L = 9 mH), and a capacitor (1000 µF). The switching frequency (20 kHz) is designed to obtain low output ripple. The single-phase inverter also has an inductor (1.91 mH) and capacitor (0.530 µF) on its output side. According to the voltage and the current of the PV array or flow rate, the microcontroller computes the output and generates a command representing the duty cycle given by the microcontroller PWM pin which is applied to the MOSFET driver, amplified and injected between gate terminal and source terminal of the MOSFET. The converter duty cycle is adjusted in such a manner that maximum PV array output power is extracted under all operating conditions and it is transferred to AC motor-pump which in turn draws water. The PMDC motor water pump has the same experimental set-up without inverter. The experiment is conducted and the results are obtained for various duty cycles of the boost converter at different insolation conditions for the analysis purpose. All the experimental waveforms are observed by using digital storage oscilloscope (DSO).

In AC motor pumping system, the output voltage of PV array is 200 V DC which is increased to 333.33 V DC by boost converter with the duty ratio of 0.4 at 1000 W/m². The output voltage of boost converter is applied to AC motor pumping system. This system needs 6 modules to get the required voltage.

In PMDC motor pumping system, the output voltage of PV array is 70 V DC which is increased to 116.6 V DC by boost converter with the duty ratio of 0.4 at 1000 W/m². The output voltage of boost converter is applied to PMDC motor pumping system. PMDC motor pumping system needs only 3 modules to get required voltage.
Similarly the output voltage and current of single-phase inverter are shown in Figs 21 and 22 respectively.

The experiment is conducted at solar irradiation of 1000 W/m$^2$. The experiment results are taken for the head of 20 m. Table 6 shows the experimental data of AC motor pumping system for various insolation levels. Irradiance is measured at W/m$^2$ with the help of Pyrometer. The maximum power point tracker fixes the duty ratio of boost converter as 0.4 to extract maximum power from the PV module.

The power factor of single-phase inverter varies from 0.47 to 0.7. The data are collected by controlling the speed of the pump. The collected data provide various values of discharge capacity for different speed. The speed of the AC pumping system ranges from 2650 rpm to 1455 rpm. It is seen from the data of the above table that the output voltage from the solar array increases with the increase in irradiance. The discharge of water from the water pump is directly proportionate to the speed. The efficiency of boost converter has values more than 90% but the efficiency of single-phase inverter varies from 40% to 48%. From the experimental data and calculations, it can be seen that the motor-pump efficiency of AC motor pumping system ranges from 44% to 8%.

In case of PMDC motor pumping system, the output of boost converter is directly applied to PMDC motor pumping system. The number of power switches as well as power conversion stages are lesser in PMDC pumping system. The input voltage and current of boost converter, speed of pump, and...
Table 7—Experimental data of PMDC pumping system at $G = 1000 \text{ W/m}^2$

<table>
<thead>
<tr>
<th>S.No.</th>
<th>$N$ (RPM)</th>
<th>$C_{\text{eff}}$ (%)</th>
<th>$Q_{\text{L/h}}$</th>
<th>$q$ (m/s$^2$)</th>
<th>$g$ (m)</th>
<th>$h$ (m)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$P_{\text{h}}$ (kW)</th>
<th>$P_{\text{m}}$ (W)</th>
<th>$\eta_{\text{MP}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2655</td>
<td>96.65</td>
<td>1050</td>
<td>1.05</td>
<td>9.8</td>
<td>20</td>
<td>1000</td>
<td>0.057</td>
<td>112.76</td>
<td>50.69</td>
</tr>
<tr>
<td>2</td>
<td>2410</td>
<td>96.07</td>
<td>950</td>
<td>0.95</td>
<td>9.8</td>
<td>20</td>
<td>1000</td>
<td>0.051</td>
<td>140.10</td>
<td>36.91</td>
</tr>
<tr>
<td>3</td>
<td>2155</td>
<td>95.24</td>
<td>875</td>
<td>0.88</td>
<td>9.8</td>
<td>20</td>
<td>1000</td>
<td>0.047</td>
<td>177.79</td>
<td>26.79</td>
</tr>
<tr>
<td>4</td>
<td>1910</td>
<td>94.30</td>
<td>780</td>
<td>0.78</td>
<td>9.8</td>
<td>20</td>
<td>1000</td>
<td>0.042</td>
<td>220.04</td>
<td>19.29</td>
</tr>
<tr>
<td>5</td>
<td>1705</td>
<td>93.12</td>
<td>690</td>
<td>0.69</td>
<td>9.8</td>
<td>20</td>
<td>1000</td>
<td>0.037</td>
<td>271.62</td>
<td>13.83</td>
</tr>
<tr>
<td>6</td>
<td>1560</td>
<td>91.95</td>
<td>625</td>
<td>1.130</td>
<td>9.8</td>
<td>20</td>
<td>1000</td>
<td>0.034</td>
<td>321.82</td>
<td>10.57</td>
</tr>
</tbody>
</table>

Fig. 23—Pump output power (kW) Vs Discharge (L/h)

Fig. 24—Speed (RPM) Vs Discharge (L/h)

Fig. 25—Motor-Pump efficiency (%) Vs Discharge (L/h)

The measured and the calculated experimental data of PMDC pumping system are given in Table 7. Figures 23-25 show the plot between hydraulic power output power versus discharge, speed versus discharge and motor-pump efficiency versus discharge for AC and PMDC pumping systems at irradiance of $G = 1000 \text{ W/m}^2$. It is clear from the plots that the discharge of PMDC pump is more than the AC pump.

**Conclusions**

This work gives knowledge of modeling and simulation of the photovoltaic systems by using MATLAB. The numerical data measured in simulation show that the efficiency of PMDC motor is better than the AC motor. The results obtained from both simulation and experiment are satisfactory. The simulation results are validated with the experimental results. PMDC motor pumping system is simpler, durable and PMDC motor itself does not require power to excite its field. The number of components required and the power stages are lesser in PMDC motor water pumping system. The number of power switches required in PMDC pumping system is only
whereas 6 switches are needed in AC pumping system. Speed range of AC pumping system varies from 1455 rpm to 2650 rpm and PMDC pumping system varies between 1560 rpm and 2655 rpm. PMDC motor water pumping system is found to be economical. The quantity of water pumped by PMDC motor water pumping system is around 75 L/h and it is more than AC motor pumping system. The motor and converter efficiencies are separated. PMDC motor water pumping system requires lesser complex control systems. It is evident from this work that permanent magnet direct motor is more suitable for photovoltaic powered water pumping applications. This kind of water pumping is useful in places where the power supply from grid is not possible.

References