One stage solar photovoltaic fed brushless DC motor operated water pump

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ABSTRACT

In order to optimize the solar Photovoltaic (PV) generated power using a Maximum Power Point Tracking (MPPT) technique, a DC-DC conversion stage is usually required in solar PV fed water pumping which is driven by a Brushless DC (BLDC) motor. This power conversion stage leads to an increased cost, size, complexity and reduced efficiency. As a unique solution, this work addresses a single stage solar PV energy conversion system feeding a BLDC motor-pump, which eliminates the DC-DC conversion stage. A simple control technique capable of operating the solar PV array at its peak power using a common Voltage Source Inverter (VSI), is proposed for BLDC motor control. The proposed control eliminates the BLDC motor phase current sensors. No supplementary control is associated with the speed control of motor-pump and its soft start. The speed is controlled through the optimum power of the solar PV array. The suitability of the proposed system is manifested through its performance evaluation using MATLAB/Simulink based simulated results and experimental validation on a developed prototype, under the practical operating conditions.

Keywords— Solar PV array, MPPT, BLDC motor, VSI, Water pump, Soft-starting, Speed control

1. INTRODUCTION

The anticipated global energy critical moment in near future due to the rapid depletion of conventional fossil fuel resources [1]and a consistently diminishing costs of solar photovoltaic (PV) modules, power electronic devices and microprocessors [2-3], induce the researchers and industrialists towards effective utilization of solar PV technology. Among the various applications of solar PV energy, an independently operated PV powered water pumping system seems to be the most encouraging and attractive in various areas such as rustic farm irrigation, Town Street watering and fish farms [4]. Modernizations of human community and developing utilization of electric motors have exponentially enlarged they require for electrical energy. The motors embrace more than 40% of overall electric power expenditure [5]. Therefore, a motor plays a prominent role to realize a solar PV based energy efficient and cost-effective water pumping. An efficient motor drastically minimizes the number of solar modules for a given power requirement and hence its initial cost.

The DC motors are used in a low power solar PV water pumping [6]. The DC motors with brushes own a low efficiency, and it needs regular maintenance due to the sliding brush contacts and the commutator. An induction motor based PV pumping system is reliable, rugged and maintenance-free with superior efficiency and offers more flexibility for control in comparison to DC motors [5-7]. The brushless DC (BLDC) motor is identified as a better substitute of the DC motor and an induction motor for PV fed water pumping. This motor is compact, rugged and efficient in comparison to an AC motor [8]. Moreover, a BLDC motor possesses several merits such as reliability, least maintenance requirement; a wide range of speed, easy-to-drive and simple controls [9-12]. Therefore, this motor has received improved attention for water pumping in the last decade outstanding to its various merits which represent the attractive features mostly for this application.

Figure 1 and figure 2 present the schematics of the conventional brushless DC motor drives for PV-water pumping [8, 13-14]. As shown in fig 1, the maximum power point tracking (MPPT) [15-21] is performed by a DC-DC converter. Two-phase currents are required to be sensed for motor control [8]. Another conventional topology which claims to eliminate the phase current sensors is presented in Fig. 2 [13]. A DC-DC converter, as usual, is establishing to optimize the operating power of a PV array, speed control of a BLDC motor-pump, and soft starting. The speed control is performed through a variable voltage at the DC bus of voltage source inverter (VSI). However, a bulky capacitor is essential at the DC link due to adopting a fundamental frequency function of VSI. A Z-source inverter (ZSI) replaces the DC-DC converter in [14], other components of Fig. 1 remaining unchanged, asserting a single stage solution. However, the sensing of motor phase currents and DC bus voltage is still obligatory. On the way of sensor reduction, recently, the position sensor-free BLDC motor drive has been reported in [22-23] for the same application. However, those usefulness models are based on two-stage power conversion.

The previously mentioned conventional topologies adopt a two-stage solar energy conversion system, which basically requires an intermediate DC-DC converter to optimize the working power point of a PV array. This power conversion causes an enlarged cost, size, complexity and abridged efficiency. As a sole solution of the abovementioned problems, the present work...
proposes a one stage solar energy conversion system which completely removes the DC-DC conversion stage. It is talented in operating the solar PV array at its peak power using the same VSI used for motor control. In accumulation, it constitutes the merits of conventional topology shown in figure 2, such as the elimination of BLDC motor phase current sensing and soft starting. The speed of the BLDC motor is restricted through the optimum power of the solar PV array. The large capacitor at the DC link is re-placed with a low rating capacitor using a pulse width modulation (PWM) switching of VSI. As now, a one stage PV system has been proposed for an induction motor is driven water pump [5, 24-26]. No deliberation has been paid towards BLDC motor drive for such a system. An exchange of an induction motor with BLDC motor in solar PV water pumping offers following merits in terms of simplicity, cost-effectiveness and neatness.

The proposed speed control method for BLDC motor is much simpler than that of an induction motor. No supplementary VSI and phase current sensing is involved in the proposed control, not like the speed control of an induction motor [5, 24-26]. The method suggested in [5, 25] uses two voltage source inverters. Thus, the aforementioned famed features of proposed control make the solar PV based water pumping system further simple, low cost and condensed. The system under study is first planned by selecting a BLDC motor-pump set and a PV array such that it successfully works under all the probable variations in climate conditions, and then demonstrated through its steady state, starting and dynamic works, using MATLAB based simulation and an experimental system. It works suitably under the desired circumstances without offering its performances, especially the MPP operation of PV array.

2. PRINCIPLE OF OPERATION

Fig.3 explains the proposed brushless DC motor-water pumping based on a one stage solar PV energy conversion system. The solar PV array is straightforwardly connected to a VSI which feeds the BLDC motor-pump. A diode in series with the PV array obstructs the flow of reverse current. A small DC link capacitor is connected to permit a power transfer from the PV array to the BLDC motor-pump. An incremental conductance (INC) MPPT method is adopted for the optimum utilization of solar PV array. This method uses PV voltage and current as the feedback signals to produce an optimum duty ratio, corresponding to the maximum power of the solar PV array. The motor has three intrinsic Hall sensors to achieve electronic commutation.

3. SYSTEM SCHEME AND SPECIFICATIONS

Suitable design and specifications of BLDC motor-pump and solar PV array play an important role in the desired operation of a water pump. A 6-pole, 3000 rpm, 3.5 kW BLDC motor is selected to drive the water pump. The detailed specifications of the BLDC motor are mentioned below.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (Pm)</td>
<td>3.5kW</td>
</tr>
<tr>
<td>Speed (N)</td>
<td>3000rpm</td>
</tr>
<tr>
<td>No of poles (P)</td>
<td>6</td>
</tr>
<tr>
<td>Resistance (R)</td>
<td>0.9ohm</td>
</tr>
<tr>
<td>Inductance (L)</td>
<td>2.8mH</td>
</tr>
<tr>
<td>Motor Torque Constant (Kt)</td>
<td>0.74Nm/A</td>
</tr>
<tr>
<td>Motor Voltage Constant (Ke)</td>
<td>78V/rpm</td>
</tr>
<tr>
<td>Moment of Inertia (J)</td>
<td>20.79kg.cm²</td>
</tr>
</tbody>
</table>

The PV array, DC link capacitor and BLDC motor are preferred such that execution of the system is not degraded even by sudden instability in the atmospheric conditions.

3.1 Estimation of Parameters of Solar PV

A PV array with a maximum power capacity of 4 kW at usual atmospheric condition (1000 W/m²; 25°C) is designed as per...
the ratings of a selected BLDC motor-pump. The working power capacity of the selected PV array is sufficient to run the motor-pump system at its rated provision, in accumulation to compensate the power losses associated with the VSI and motor-pump. A PV module with 36 cells connected in series is measured to make a PV array of the applicable size. From a solar cell has an open circuit voltage in the collection of 0.5 V-0.6 V range at standard atmospheric condition [27], it is assumed that a module generates 36X0.54 = 19.4V as its open circuit voltage. The voltage of a module at MPP is around 72%-77% of the open circuit voltage [28]. Consequently, it is projected as, 19.8X0.78 = 15.44 V. The PV array voltage necessary at the DC link of VSI to run the chosen BLDC motor-pump at its rated torque and speed is 310 V. It is observable that the voltage of PV array at MPP should be 310V. Thus, the numbers of series connected modules are estimated as, 310/15.44 ≈ 20. From the mandatory maximum power capacity of the PV array is 4000 W, the PV current at MPP is estimated as, 4000/310 = 12.9 A. As per the plan, this current is produced by the three modules connected in parallel, each module has an MPP current of 12.9/3 = 4.3 A. It is usually found to be between 78% and 92% of short circuit current [28]. The short circuit current of each module is therefore expected as 4.3x0.9 = 4.8A. Finally, 60 modules each with PV voltage and current of 15.44 V and 4.3 A at MPP, are connected (20 in series and 3 in parallel) to plan the PV array of 310 V, 12.9 A and 4 kW at MPP.

3.2 Rating of DC Link Capacitor
A low range capacitor connected across the PV array gives as the DC link capacitor of VSI. This capacitor transmits the ripple current. The switching frequency is selected in the vision of the component size, system response, and noise disruption and transfer efficiency. These factors are directly exaggerated by the switching frequency. A high switching frequency results in a decrease in the size of the DC link capacitor. It also progresses the transient response and avoids the frequency bands in which noise would be disorderly. On the other side, a high-frequency switching of the VSI reasons low transferred efficiency. The switching loss boosted with increasing switching frequency due to the high number or constant energy switching actions in a period. Considering the aforesaid professional and convict of higher switching frequency, it is visional selected as 10 kHz. At last, a capacitor of 100 µF, 400 V is connected, as the DC link capacitor of VSI. This value is quite low in comparison with the existing topologies [13].

4. SIMULATED PERFORMANCE
The proposed water pumping system is a pattern and its presentation is simulated in MATLAB/Simulink under a variety of steady states, starting and other dynamic conditions. Simulated results demonstrate the value of the proposed system as shown in Figure 4-8.

4.1 Stable State and Starting performance at 1000w/m²
The stable state and starting response of the BLDC motor pump and PV array are shown in figure 4 and illustrate in the following sub-sections.

4.1.1. Solar PV Array working: Figure 4(a) displays the voltage, Vpv, current,Ipv and power, Ppv of solar PV array at sun rays, S of 1kW/m². These indices exhibit a good tracking of the MPP. The initial duty cycle and its step size are selected properly (0.5 and 0.001 respectively) to find a safe starting of the motor. At a stable state, D is one and no modulation in the pulse width of the six basic frequency pulses take place.

![](image)

**Fig. 4:** Stable state and starting performance of (a) PV array and (b) motor-pump, of proposed system at 1 kW/m²

4.1.2. Brushless Dc Motor pump working: The a variety of indices of BLDC motor viz. back emf(e_b); winding current(i_w); speed(N); torque(Te) and load torque(Tl) are described in figure 4(b). The motor expanded a rated torque, and the pump is driven at its full speed. In addition, the response of i_w reveals that starting current is controlled and the motor is operated smoothly. A little ripple in the torque presents because of phase current commutation and phase current sensor-less operation of the motor. This causes noise and vibration in the motor, in general, at low speed. At higher speed range, there is no importance of this physical strange appearance, as then the motor grows adequate kinetic energy because of its inertia and speed. The proposed system is also designed to run the motor-pump at high range speed (above 1100 rpm, even up to the solar rays of 200w/m²) in order to achieve a successful water pumping. Thus, the aforementioned physical strange appearance has not much power in the proposed application. In addition, the motor-pump is habitually installed in an isolated area e.g. agricultural land or it is submerged, and hence there is no trouble in the surroundings due to the noise. Consequently, this level of commutation ripple is relatively acceptable for water pumping application.

The different techniques for the decrease of commutation torque ripple have been reported in the literature [29]-[32]. A reduction in the torque ripple certainly may lead to an enhancement in the efficiency of the motor. However, the various solutions reported to date, add more hardware into the system such as motor phase
The best ripple elimination method [30] made brushless DC motor, which participates in the control of motor pump speed. Tests are carried out on a 1.16 kW, 3000 rpm BLDC motor, delivered by a solar array simulator which is set at 1355 Wp. A current sensor (LA-55P) and a voltage sensor (LV-25P) are used for maximum power point control. The sensed signals are transformed into the digital form through the analog to digital converters (ADCs) and pass on to the DSP-dSPACE 1104 for the implementation process. The Hall signals are directly conveyed via the digital Input/Output pins to carry out an electronic commutation and motor control. At last, the gate pulses have established a gain through the Input/output pins. To isolate the gate drivers from the real-time controller, the optocoupler ICs (6N136) is used in an opto-isolation circuit. Figure 9 presents a photograph of the urbanized experimental system. The experimental presentation of the proposed topology is analyzed in the following sections.
Hall signals and a switching pulse of the VSI. No sensor is run at its rated speed of 3000 rpm as shown in the performances of PV array and motor. The irradiance is altered from 1000 W/m² to 200 W/m² to test the behavior of the system. The and uniqueness are recorded and shown in figures 09 (a) (at 1000W/m²) and (b) (200 W/m²). The recorded curves demonstrate the successful MPPT by presenting the tracking efficiency above 98%.

5.2 Performance under stable State at 1000 W/m²
The wave forms shown in figure 10 authorize, at 1000 W/m², the performances of PV array and motor-pump under stable state condition. As shown in figure 10(a), the PV array is activated at its peak power and the corresponding value of a duty ratio is one. The motor takes its rated current of 4.2 and the pump is run at its rated speed of 3000 rpm as shown in figure 10(b). Additionally, figure 10(c) shows the corresponding Hall sensor guide with the motor speed and Fig. 10(d) shows the Hall signals and a switching pulse of the VSI. No inflection in the six basic frequency pulses takes place. It is experiential that the frequencies of Hall signals are 100 Hz, related to 3000 rpm.

5.3 Steady State Performance of BLDC Motor at 200 W/m²
Figure 11 illustrates the test results of the BLDC motor at 200 W/m² under stable state condition. The motor-pump reaches rpm, as described in figure 11 (a), which is an adequate speed for water pumping. Additionally, figure 11 (b) shows the Hall signals and a switching pulse of the VSI. The pulse width of the six basic frequency pulses is modulated according to a duty ratio produced by the MPPT technique. It is practical that the frequencies of Hall signals are corresponding to 1100 rpm and the switching frequency components are reproduced in the waveforms of stator currents.

5.4 Performance under Dynamic Condition
The Test results of the proposed water pumping system under the dynamically varying irradiance are offered in figure 12 the and N are noted under this condition. As the sun rays increases from 400 W/m² to 1000 W/m², PV array and BLDC motor-pump reach the rated values of their various indices \( (v_{pv} = \ 275V, \ i_{pv} = 4.8A, \ i_{sa} = 4.3A \ \text{and} \ N = 3000rpm) \), corresponding to MPP, as exposed in figure 12 (a). Likewise, figure 13(b) shows the behavior of PV array and BLDC motor indices, as the sun rays drop from 1 kW/m² to 400 W/m². All these indices reach their stable state values corresponding to 400 W/m² \( (v_{pv} = \ 265V, \ i_{pv} = 2A, \ i_{sa} = 2.75A \ \text{and} \ N = 1745rpm) \). The motor-pump speed is efficiently controlled by the duty ratio at each irradiance level. Therefore, doing well operation is validated under dynamic condition.

5.5 Starting Performance
Figure 13 exposed the test results of the proposed system under starting condition at a standard solar irradiance of 1000 W/m². The main purpose is to demonstrate that the motor is safely
started. The initial duty ratio is set to 0.5 to rotate the motor at
starting. Figure 13, demonstrating the various PV array and
BLDC motor indices, confirms the soft starting by controlling
the starting current.

Fig. 13: Test results of the proposed system under starting
condition at 1 kW/m²

6. COMPARISON OF CONVENTIONAL AND
PROPOSED SYSTEM

There are several benefits of the proposed system over
conventional schemes. The proposed one appears advanced in
every feature. Furthermore, the efficiency of the conventional
and proposed schemes at various sun rays levels, under the like
operating conditions, is projected based on the experimental
measurements. Although the power losses in the water pump
are not integrated into the efficiency calculation. The efficiencies
of these schemes are compared and graphically symbolize in figure 14 the proposed system seems more
efficient than its conventional co-equal parts.

Fig. 14: Efficiency comparisons for the proposed and
conventional scheme

7. CONCLUSION

The proposed BLDC motor-driven water pumping based on a
one stage solar PV production has been validated through a
demonstration of its various stable state, starting and dynamic
performances. The system has been simulated using the
MATLAB toolboxes and executed on an experimental prototype. The topology of the proposed system has provided a
DC-DC converter fewer solutions for PV fed brushless DC
motor driven by water pumping. Furthermore, the motor phase
current sensing elements have been removed, resulting in a
simple and gainful drive. The other desired functions are the
speed control without any extra circuit and a soft start of the
motor-pump. A detailed proportional analysis of the proposed
and the existing topologies has eventually manifested the
advantage of the proposed work.

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