Standalone Photovoltaic Water Pumping System Using Induction Motor Drive With Reduced Sensors.
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ABSTRACT
A simple and efficient solar photovoltaic (PV) water pumping system utilizing an induction motor drive (IMD) is presented in this paper. This solar PV water pumping system comprises two stages of power conversion. The first stage extracts the maximum power from a solar PV array by controlling the duty ratio of a dc–dc boost converter. The dc bus voltage is maintained by controlling the motor speed. This regulation helps in the reduction of motor losses by reducing motor currents at higher voltage for the same power injection. To control the duty ratio, an incremental conductance based maximum power point tracking (MPPT) control technique is utilized. A scalar-controlled voltage source inverter serves the purpose of operating an IMD. The stator frequency reference of IMD is generated by the proposed control scheme. The proposed system is modeled, and its performance is simulated in detail. The scalar control eliminates the requirement of a speed sensor/encoder. Consequently, the need of motor current sensor is also eliminated. Moreover, the dynamics are improved by an additional speed feedforward term in the control scheme. The proposed control scheme makes the system inherently immune to the variation in the pump constant. The prototype of PV-powered IMD emulating the pump characteristics is developed in the laboratory to examine the performance under different operating conditions.

Keywords

1. INTRODUCTION
To control the IMD-tied VSI, a simple V/f(voltage/frequency) control approach is utilized in [14] and [15]. The pumping system with a dc–dc converter and VSI is used for water pumping application in [16]–[18]. However, the presented approach suffers from dc link voltage instability. The V/f approach is simple, easy to implement, and cost effective. Dual inverters are used to supply power to a centrifugal pump with the sample-averaged zero-sequence elimination pulse-width modulation technique [19]. Apart from V/f control, direct torque control (DTC) and vector control techniques are complicated and they require extra current sensors for implementation [20]. In V/f control, only PV array current, voltage, and dc bus volt- age are sensed. The proposed system tracks the MPP point by altering the modulation frequency so that the IMD is able to extract the maximum power from the solar PV array at sustained torque for different solar insulation levels. The proposed system is able to supply more water compared to a solar PV fed dc motor based water pump. By utilizing V/f control, the starting performance of the IMD is improved even if IMD is started with lower solar insolation. Therefore, water is permanently pumped from morning till evening. The starting current of the induction motor connected to the fixed voltage ac mains is around 5–6 times of full load current. Therefore, to start the motor without any control, a higher number of solar modules are required, whereas smooth start of the induction motor is possible by using V/f control without drawing high starting curr-rent. This also improves the life of the motor. Moreover, the areas that are favored by the electrical connectivity may utilize the grid-interfaced PVPs [21]. In Indian context, still many in-door villages and agricultural lands do not possess a privilege of having electrical network.

1.2. Objectives
The main objective of this project is to Simulate a model of a simple and efficient solar photovoltaic (PV) water pumping system utilizing an induction motor drive (IMD) is studying. This helps in the reduction of motor losses by reducing motor currents at higher voltage for the same power injection. To control the duty ratio, an incremental conductance based maximum power point tracking (MPPT) control technique is utilized. A Scalar-controlled voltage source inverter serves the purpose of operating Induction motor Drives (IMD). The stator frequency reference of IMD is generated by the proposed control scheme. The scalar control eliminates the requirement of a speed sensor/encoder. Consequently, the need of motor current sensor is also eliminated. Moreover, the dynamics are improved by an additional speed feed forward term in the control scheme. The proposed control scheme makes the system inherently immune to the variation in the pump constant. The prototype of PV-powered IMD emulating the pump characteristics is developed in the laboratory to examine the performance under different operating conditions.

3. SYSTEM DESIGN
3.1 Design of Proposed System
The system Configuration of the PV water pumping system is depicted in Fig. 1.1 it consists of a PV array followed by a boost converter. A VSI is used to provide pulse width modulated voltage input to the motor and pump assembly. The power from the PV array is regulated using the INC method to attain its maximum value with available radiation. The V/f control is used to give reference speed to IMD.

3.1.1 Design of the Solar PV Array
An induction motor of 2.2 kW is selected for the proposed system. If losses of the motor and pump are neglected, the capacity of the PV array should be equivalent to the motor capacity. In this case, a 2.4-kW PV array is selected Where Pmp is the maximum power that can be drawn from panels at a given radiation, Vmp is the PV panel voltage at MPP, and Imp is the current at MPP. Ns and Np are the number of modules connected in series and parallel, respectively.
Considering an open-circuit voltage of the panel to be near to a dc link voltage and the power drawn from the panel to be 2.4 kW, the number of modules in series and parallel are selected to be 11 and 1, respectively. The individual module and array specifications are provided in Table I.

**Table No 1 Specifications of the Solar Module and Array**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Module Peak power of the single Module</th>
<th>225 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module Open Circuit Voltage (Voc)</td>
<td></td>
<td>41.79 V</td>
</tr>
<tr>
<td>Module Short Circuit Current (Isc)</td>
<td></td>
<td>7.13 A</td>
</tr>
<tr>
<td>Module Voltage at MPP (Vmp)</td>
<td></td>
<td>33.9 V</td>
</tr>
<tr>
<td>Module Current at MPP (Imp)</td>
<td></td>
<td>6.63 A</td>
</tr>
<tr>
<td>Array Peak Power (Pavg)</td>
<td></td>
<td>2.4 Kw</td>
</tr>
<tr>
<td>Array Open Circuit Voltage (Voc)</td>
<td></td>
<td>459.69</td>
</tr>
<tr>
<td>Array Short Circuit Voltage (Vsc)</td>
<td></td>
<td>7.13 A</td>
</tr>
<tr>
<td>Array short Circuit Current (Isc)</td>
<td></td>
<td>372.9 A</td>
</tr>
<tr>
<td>Array Current at MPP (Imp)</td>
<td></td>
<td>6.63 A</td>
</tr>
</tbody>
</table>

### 3.1.2 Selection of DC Link Voltage

The dc bus voltage of VSI is estimated from the following relation: where m is the modulation index and VL-L is the line voltage across the motor terminals. Hence, \( V_{dc} = 2\sqrt{2} \sqrt{3} \times 230 = 375 \) V, which is the voltage required when modulation index is 1. The dc link voltage is chosen to be 400 V.

### 3.1.3 Design of DC Link Capacitor

The dc link capacitor is supposed to provide sufficient energy at the time of transients such as fall in radiation and an increase in the load. Its value is calculated as [22]

\[
1/2 C_{dc} [V*dc^2 - V_{dc1}^2] = 3\alpha V t
\]

\[
1/2 C_{dc} [400^2 - 375^2] = 3 \times 1.2 \times 133 \times 8.2 \times 0.005
\]

\[C_{dc}=2026\mu F.\]

In above expression, \( V*dc \) refers to the set dc bus voltage, while \( V_{dc1} \) is the acceptable to the lower most voltage during transients. Moreover, \( \alpha \) is an overloading factor and \( t \) is the duration of transient.

### 3.14 Scalar (V/f) Control of Induction Motor

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Fig. No 1 System architecture for the standalone solar water pumping system.

Fig. No 2 Flowchart for the INC algorithm for MPPT.
The scalar control of an induction motor is the most common and simplest control so far. Usually, induction motors are designed for 50-Hz input voltage. For operation at a lower speed, the voltage has to be reduced. The frequency control along with voltage magnitude control is also desired for constant flux operation. The voltage should be proportional to the frequency such that flux magnitude is maintained constant as \( v_s = V/\omega \). An IM is usually fed from a three-phase PWM VSI. Only an input parameter is the reference speed. Neglecting the small slip speed, the speed of the motor is approximately equal to the reference speed. The speed reference is integrated to generate \( \theta \), which is used to obtain three sinusoidal voltage references, which are compared with high-frequency triangular wave to generate the switching pulses for VSI. The speed reference is estimated from the control scheme as mentioned in the previous subsection.

4. SIMULATION & RESULT ANALYSIS

4.1 Results and Discussion
Performance of a two-stage PV-fed water pumping system is evaluated using the simulation package. The proposed system is designed, modeled, and simulated in the MATLAB/Simulink environment. The step change in the solar radiation is also simulated in order to determine the satisfactory performance of the system under dynamic conditions.

A. Starting Performance of the Proposed System
Fig. 3 shows various parameters of the proposed water pumping system at 500 W/m² radiations. The dc link of VSI is energized initially. Since the switching device of the boost converter is OFF, the voltage across the dc link of VSI is the open circuit voltage of the PV array. It starts falling once the motor speed increases. The PV array current starts from zero and rises up to Imp. The PV voltage reaches Vmp once a motor speed increases. The PV array current starts from zero approximately equal to the reference speed. The speed reference is integrated to generate \( \theta \), which is used to obtain three sinusoidal voltage references, which are compared with high-frequency triangular wave to generate the switching pulses for VSI. The speed reference is estimated from the control scheme as mentioned in the previous subsection.

4.2 Steady-State and Dynamic Performances of the Proposed System
The behavior of the proposed standalone PV water pumping system is shown in simulation results. This figure comprises simulation of varied solar insolation changes. From \( t = 1 \) to \( 2 \), the solar insolation is constant at 800 W/m². The PV indices are at the corresponding MPP. At \( t = 2 \), a slope decrement in the solar insolation is simulated to test the MPPT algorithm effectiveness. The PV voltage observes negligible change, while the PV current varies proportional to the available insolation. Moreover, the dc bus voltage is also maintained at reference voltage of 400 V without any failure. The speed and torque of the motor are reduced with the reduction in PV power. This continues to happen till \( t = 4 \), from where the system experiences a slope increase in the solar insolation. Similar to the previous behavior, the PV current starts increasing proportional to the solar radiation, while there is no much change in the PV voltage. Consequently, the available power from a PV source ramps up along with the motor speed and motor torque. At \( t = 6 \), the system operates in a steady state at a solar radiation of 1000 W/m². The system faces a step decrement in the solar insolation from 1000 to 500 W/m² at \( t = 7 \), owing to which the PV current reduces instantly. However, still the PV voltage does not face many transients. The dc bus voltage experiences a slight transient change; however, it restores to a reference voltage quickly. It is noteworthy that the dc bus voltage is maintained even at 50% reduction in rated power. Similarly, a step increase in a solar insolation is observed at \( t = 9 \). As anticipated from the previous behavior of the system, the dc bus voltage is maintained to a reference value, while there is no significant change in the PV voltage. The motor speed and torque increase proportionally to balance a power from a source.

4.3 Proposed Control Scheme
The proposed control system has a salient feature of being immune to the variation in the estimation of the pump constant. Moreover, the frictional loss across the pump column is well taken care off by the proposed control. A base speed/frequency reference is estimated from the MPPT algorithm, which depends on the pump constant K_pump. However, an additional term is subtracted from this base speed/frequency, which is obtained from the PI controller. The error in dc bus voltage corresponds to the imbalance in the active power in the system and the losses of the converter. In the absence of the feed forward term, the estimated reference speed is generated by the PI controller. Hence, the performance is sluggish and dynamic behavior of the system is also not satisfactory. Moreover, even if a wrong value of the pump constant is chosen, the proposed control system estimates the reference speed accurately. The performance of the proposed system with two pump constants. One of these constants deviates from the actual value. In the figure, the blue line corresponds to the control with the actual value of the pump constant, i.e., 6.554×10⁻⁴ Nm/(rad/s)², while the red curve depicts the performance when the pump constant is 8.025 × 10⁻⁴ Nm/(rad/s)². It is interesting to note that the output of the PI controller is about 4 rpm in the blue curve, while that in the red curve is ~88 rpm. The feed forward term or the base speed is 1372 rpm in the blue curve, while it reduces to 1286 rpm in the red curve. This is because of an increase in the fed value of the pump constant. However, in
both the cases, the subtraction of these quantities gives the accurate reference speed for the extraction of the maximum power from the PV array. The value of reference frequency is 45.8 Hz in both the cases. Moreover, the dc bus voltage is settled to a reference value of 400 V. The proposed control algorithm is inherently immune to the pump constant.

4.4 Simulink Model of Proposed System

![Fig No 4. Simulink model of Proposed System](image)

![Fig No 5 Simulink model of Proposed Controller](image)

![Fig No 6 Simulink Results : Irradiation :1000](image)

![Fig No 7 Simulink Results of Proposed System When Irradiation 1000](image)

Speed = 1405
DC bus vdg: 408
T= 14.6 Nm
Dc current: 6.26
CONCLUSION

A standalone PV water pumping system with a reduced sensor has been proposed. It utilizes only three sensors eliminating position and line current sensors. The reference speed generation for the V/f control scheme has been proposed based on the available power by regulating the active power at dc bus. The PWM frequency and pump affinity law have been used to control the speed of an induction motor drive. Its feasibility of operation has been verified through simulation and experimental validation. Various performance conditions such as starting, variation in radiation, and steady state have been experimentally verified and found to be satisfactory. The main contribution of the proposed control scheme is that it is inherently immune to the error in estimation of the pump constant. The system tracks the MPP with acceptable tolerance even at varying radiations.

REFERENCES


