PV-Grid Tie System Energizing Water Pump

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Received June 27th, 2013; revised July 27th, 2013; accepted August 4th, 2013

ABSTRACT

This paper presents the behaviors of three-phase induction motor driving centrifugal pump under various solar irradiation levels, where the motor speed and torque depend on the source voltage and frequency, while the water-flow rate depends on the motor speed, density, and static head according to affinity flow. Matlab/Simulink model is proposed for studying the behaviors of these machines with respect to water flow capacity, motor current, electromagnetic torque, and motor efficiency. The proposed photovoltaic with maximum power point tracking model based on observation and perturbation (O&P) maximum power tracking model is applied. The output voltage is regulated throughout Buck-Boost converter with purpose maintaining the output voltage at predetermined values. Since Induction motors are widely used in pump systems, the electromagnetic torque, water-flow rate are studied for various source frequencies. Comparison analysis is conducted for both motors with respect to water flow-rate, heads elevation, and motor current. In addition to that, the proposed system presents Photovoltaic-Grid (PV-Grid) Integrated model, where the power shortage required for normally operation of the pump is drawn from the electrical grid.

Keywords: Photovoltaic; Induction Motor; Centrifugal Pumps; Electrical Grids; Matlab/Simulink

1. Introduction

Photovoltaic energy resources presents alternative and friendly to the environment sources. It presents unique solution for providing remote area with clean and sustainable energy during the daytime in heating, lighting, refrigeration and water pumps systems [1-3] without the need of battery system, while during the night time the accumulated energy can be fully or partially used to cover the energy domain. The output circuit connected to the photovoltaic system is usually dc-dc converters mainly boost choppers in order to boost the voltage to the predetermined levels.

The DC/DC converters are widely used in regulated switch mode power supplies, where the input voltage to these converters varies in wide range especially in the case of Photovoltaic (PV) supply source due to unpredictable and sudden change in the solar irradiation level as well as the cell operating temperature. Several connection topologies concerning the switching systems have been proposed [4-8] aiming at realizing the required voltage level during different periods of day for certain applications such as pumps, motors in general and power supplies.

On the other hand water flow consumption determines the rate of motor speed according to affinity law [6,7] which in turn determines the elevation (static head) and consumed power. Variable Frequency Drive (VFD) can be applied to achieve up mentioned facts.

The proposed model consists of several modules as shown in Figure 1 with the following functions:

- **PV Photovoltaic Array** \((PV)\) that converts the solar irradiation into voltage \(V_{pv}\) and current \(I_{pv}\).
- **Buck-Boost DC Chopper** Module that boosts up the PV voltage to the predetermined levels. Conversely in case of high \(V_{pv}\) the output voltage is reduced.
- **MPPT**, maximum power point tracking unit that tracks the optimized operation point for power extraction by controlling the chopper duty cycle.
- **Variable Frequency Drive** that controls the speed and torque of three-phase induction motor driving centrifugal pump by controlling the voltage and frequency.
- **Speed-Flow Control Unit** that determines the required voltage and frequency aiming at regulating the motor speed and torque according to actual water flow consumption.
PV-Grid Tie System Energizing Water Pump

- **Power Estimator** that detects the available $P_{pv}$ power, the consumed motor power $P_L$ and the amount of power shortage $P_G$ that should be supplied from AC-grid.
- **PV-Grid Integrator** that provides the load with necessary power taken from either one of the sources PV or AC grid, or from both.
- Amount of power shortage $P_G$ that should be supplied from AC-grid.
- **AC-DC Converter** that converts the grid voltage into smoothed DC voltage that should be easily tied to the PV output terminal aiming at avoiding synchronizing procedures.

The proposed model differs from other models, where the system is consumed energy from the grid in case of energy shortages and night time operation. It is fully simulated using Matlab/Simulink, where the system parameters can be changed and investigated.

2. Modeling of Proposed Electrical Model

2.1. PV Performances

The application of Photovoltaic solar energy in energizing electrical load on-grid connected, where the pump power is controlled based on the extracted from the PV module power.

2.1.1. Photovoltaic Model Interpretation

Basically, PV cell is a P-N semiconductor junction that directly converts light energy into electricity. It has the equivalent circuit shown in Figure 2 [9,10].

The following are the simplified equations describing the cell output voltage and current:

$$V_o = \frac{A \cdot K \cdot T_o}{q} \ln \left( \frac{I_{ph} + I_d - I_o}{I_o} \right) - R_s \cdot I_o$$  \hspace{1cm} (1)

$$I_o = N_p \left( I_{ph} - I_d \left( e^{\frac{q \cdot V_o}{N_p \cdot K \cdot T_o}} - 1 \right) \right)$$  \hspace{1cm} (2)

$$I_d = I_w \left( \frac{T_o}{T_e} \right)^{\frac{1}{2}} \cdot e^{\frac{q \cdot V_o}{N_p \cdot K \cdot T_o}}$$  \hspace{1cm} (3)

$$I_{ph} = N_p \cdot \left( I_e \cdot \phi_n + I_c (T_e - T_c) \right) ; \phi_n = G/G_e$$  \hspace{1cm} (4)

The idealistic diode idealistic factors A & B are with values vary between 1 and 2 depending on I-V performance shaping and approximations.

2.1.2. Photovoltaic I-V Performance

In order to study the I-V performance of the PV circuit and to look for appropriate dc chopper for boosting up the output voltage to predetermined value it is necessary to illustrate the obtained PV voltage and current for boost chopper according to specifications given in Table 1 at
reference irradiation \( (G_r = 1000 \text{ W/m}^2) \). The PV Array voltage can be obtained by multiplying the module voltage and current by \( N_{sm} \) and \( N_{pm} \). **Figure 3** illustrates the proposed PV array built in Matlab/Simulink [11] with R-L load, where the obtained results for different variation levels are presented. From these performances it is shown that the total output PV voltage and current varies according to irradiation level with approximated 65 W maximum power at \( G = 1000 \text{ W/m}^2 \).

### Table 1. Data specification for PV Array.

<table>
<thead>
<tr>
<th>q</th>
<th>K</th>
<th>( I_{in} )</th>
<th>( I_{d} )</th>
<th>( R_{S} )</th>
<th>( R_{P} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.602e-19</td>
<td>1.38e-23</td>
<td>4 A</td>
<td>0.2 mA</td>
<td>1 mΩ</td>
<td>10 kΩ</td>
</tr>
<tr>
<td>( N_s )</td>
<td>( N_p )</td>
<td>( V_{oc} )</td>
<td>( V_{oc} )</td>
<td>( I_{sc} )</td>
<td>( V_{mpv} )</td>
</tr>
<tr>
<td>38</td>
<td>4</td>
<td>0.6 V</td>
<td>21.5 V</td>
<td>4 A</td>
<td>17.5 V</td>
</tr>
<tr>
<td>( I_{pp} )</td>
<td>( N_{sm} )</td>
<td>( N_{pm} )</td>
<td>( V_{pv} )</td>
<td>( R_{Load} )</td>
<td>( T_{c} )</td>
</tr>
<tr>
<td>3.7 A</td>
<td>6</td>
<td>1</td>
<td>130 V</td>
<td>44 ( \Omega )</td>
<td>25°C</td>
</tr>
</tbody>
</table>

**Figure 3.** PV model with I-V performances. (a) Proposed model for PV array in Simulink environment; (b) I-V performance of PV module.
2.2. The Integration of PV with Water Pumping System

A centrifugal pumps are used as electrical load [6], where the pump power, speed and torque are directly affected by either load-side parameters in form of water flow-rate, static head, water pressure, and line side in form of solar irradiation, weather conditions, and extracted power. Figure 4 illustrates PV solar system energized water pump installation, where the water pumping system can be directly energized from the PV or indirectly throughout battery bank [10]. Both configurations have their advantages and disadvantages.

Direct-coupled pumping systems illustrated in Figure 4(a) are sized to store extra water on sunny days so it is available on cloudy days and at night. Water can be stored in a larger-than-needed watering tank or in a separate storage tank and then gravity-fed to smaller watering tanks. Water-storage capacity is important in this pumping system.

While Figure 4(b) illustrates battery-coupled water pumping systems which consist of photovoltaic (PV) panels, charge control regulator, batteries, pump controller, pressure switch, tank, and AC water pump. The electric current produced by PV panels during daylight hours charges the batteries, and the batteries in turn supply power to the pump anytime water is needed. The use of batteries spreads the pumping over a longer period of time by providing a variable voltage and frequency depending on the water-consumption rate, which in turn reduces the pump losses and increases the battery discharging time which is an important factor during the night and low light periods, the system can still deliver a needed rate of water for livestock.

2.2.1. Centrifugal Pump Performances

According to [8] the power demand of the water pump is expressed using the following expression:

\[ P_p = \frac{\rho \cdot g \cdot Q \cdot H}{\eta_p} \]  \hspace{1cm} (5)

The pump operational performance which presents the relationships between total head including static head and friction head, water flow-rate, and pump efficiency are illustrated in Figure 5 for certain commercial pump.

By applying the principle of motor-pump power balance, Equation (5) can be integrated with motor speed-torque performance as:

\[ \rho \cdot g \cdot Q \cdot H = \eta_p \cdot T_m \cdot \omega \]  \hspace{1cm} (6)

Now referring to Figure 5 where the pump (H-Q) curve is illustrated, which normally used to locate the pump’s operation point. For exact determining the mentioned operation point there is a need to determine the total head of the installation \( H_s \), which is the sum of the static head \( H_s \) known as elevation difference, and the network hydraulic losses \( H_L \), thus:

\[ H_s = H_s + H_L = h + \xi \cdot Q^2 \]  \hspace{1cm} (7)

The friction coefficient \( \xi \) depends on the system installation, pipes section, and liquid viscosity. The operation point results by the application of the following equation:

\[ H = H_s \]  \hspace{1cm} (8)

This condition can be obtained by intersecting of the corresponding curves of Figure 5.

2.2.2. Electrical Motor Performances

Centrifugal pumps can be driven by either direct current motors [9] or alternating current motors, mainly induc-
According to [13] if the frequency is increased above rated value, the flux and torque would decrease. If the synchronous speed corresponding to the rated frequency \( f_n \) is called base speed \( \omega_{sn} \) or \( n_{sn} \), the synchronous speed at any other frequency becomes:

\[
\omega_s = K_v \omega_n \quad \text{or} \quad n_s = K_v n_n \tag{11}
\]

where \( K_v = \frac{f}{f_n} \).

Substituting Equation (11) in Equation (17) the electromagnetic torque can be expressed as:

\[
T_{em} = 2 \cdot k_p \frac{K_v^2}{R_s} \left( \frac{R_s}{f} \right)^2 + \left( \frac{X_m}{f} \right)^2 \left( \frac{X_m}{f} + \frac{X_m^2}{f_n} \right)
\]

where \( K_p = \frac{X_m}{2w_n} \).

According to [15] \( K_v = V_{sn}/f \) for \( f > f_n \); and \( K_v = f(T_{max}, R_1, X_1, f, X_m, R_{sh}, \ldots) \) for \( f < f_n \).

The electromagnetic power \( P_{em} \) and the losses can be defined as follow:

\[
P_{em} = \omega_s \cdot T_{em} = K_v \cdot \omega_s (1 - s) T_{em} = P_{mech} + P_{const} \tag{13}
\]

Varying the frequency of the motor causes significant change in the drawn by the motor current, and in turn the consumed power. According to Figure 6, the power and current can be given as follows:

\[
I_{L1} = \frac{V_{ph}}{Z_m} ; \quad P_{app} = \sqrt{3} V_{L} \cdot I_{L1} \cdot \cos \phi ; \quad \phi = \tan^{-1} \left( \frac{X_m}{R_{app}} \right)
\]

\[
Z_m = R_{app} + jX_{app} = R_1 + jK_v \cdot X_1
\]

\[
+ jK_v \cdot X_m \left( \frac{R_s^2}{s} + jK_v \cdot X_1^2 \right)
\]

2.2.2.2. Simulation Results

Considering the rated parameter values of the selected induction motor [15]:

\[
n = 2835 \, \text{rpm} ; \quad P_n = 1100 \, \text{W} ; \quad V_n = 127 \, \text{Vac} ; \quad R_1 = R_2 = 1.27 \, \Omega ; \quad X_1 = X_2 = 3.860 \, \Omega ; \quad X_m = 60 \, \Omega .
\]

Substituting the outlined motor parameters in the developed mathematical model, we obtain through simulation the motor torque as a function of speed (and slip) for different supply frequencies as shown in Figure 7. For a constant (V/F) ratio, the motor develops a constant maximum torque, except at low speeds (or frequencies). From this curve the motor develops two operation modes: constant torque modes for frequencies less than the rated where the torque is maintained constant; and constant power mode for frequencies greater than the rated where the speed exceeds the synchronous and the torque falls down keeping the power at constant levels.

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Figure 7. Simulation results of the mechanical performance of three-phase induction motor.

Having the mechanical performance of the motor at various frequencies, where two operation mode can be applied constant torque \((V/F = \text{const})\) & constant power \((V = \text{const}, \ f > f_n)\) throughout VFD inverter we can build the pump performance. Way out from the natural curve of the pump at rated motor speed, where \(f, H & Q\) are nominal values, and known from the pump data sheet.

Taking into consideration the affinity law and derived equation stated in [16,17] for various motor speeds the water flow-rate changes at various elevations (static head) as follows:

\[
\frac{H}{H_n} = \left( \frac{n}{n_n} \right)^2 = \left( \frac{f}{f_n} \right)^2; \quad \frac{P_{\text{mech}}}{P_{\text{mech},n}} = \left( \frac{f}{f_n} \right)^3 \tag{15}
\]

Applying Equation (15) in presented model requires to select the whether the pump operates at maximum efficiency where the water-flow rate has optimized value \((Q_{\eta,\text{max}})\), thus:

\[
\frac{H}{H_n} = \begin{cases} 
\left( \frac{f}{f_n} \right)^2 & \text{for } Q < Q_{\eta,\text{max}} \\
1 + \left( \frac{Q - Q_{\eta,\text{max}}}{Q_{\eta,\text{max}}} \right)^2 \left( \frac{f}{f_n} \right)^2 & \text{for } Q > Q_{\eta,\text{max}} 
\end{cases} \tag{16}
\]

where

\[
Q_{\eta,\text{max}} = Q_{\eta,\text{max}} \left( \frac{f}{f_n} \right); \\
Q_{\eta,\text{max}} = Q @ f_n = 50 \ \text{Hz} \ & \ \eta_{\text{max}} \tag{17}
\]

The simulated results are displayed in Figure 8, where the pump flow-rate and static heads changed at different frequencies. According to pump data sheet the value of \((Q_{\eta,\text{max}} = 9.5 \ \text{m}^3/\text{hr})\) is taken as a reference value obtained at maximum efficiency and 50 Hz frequency. Also it’s shown that regulating the source frequency directly affects the static head and water-flow rate.

On other hand regulating the frequency causes significant change in motor current as shown in Figure 9, where at low frequency the drawn by the motor current is the highest compared with others at both operation modes, starting and rated operation.

At different frequencies there is a stable operation points where the motor operates at its rated slip \((s_n)\) where the amount of pumped water depends on the mechanical torque developed at these frequencies and given head. Referring to Equation (6) and substituting the value of rated slip in Equations (12) and (14), the water flow-rate can be written as:

\[
Q = \frac{4\pi f (1-s)}{\rho \cdot g \cdot H \cdot P} \left( s = s_n \right) \tag{18}
\]

Figure 8. Simulation results of the pump performance \(H = f(Q)\).

Figure 9. Simulation results of the motor current at various frequencies \(I_{ph} = f(n)\).
The obtained simulation results at rated motor operation for various frequencies and elevation are given in Figure 10 for water flow-rates at three heads (10 m, 25 m and 40 m) where it can be seen that for frequencies below the rated ($f < 50$ Hz) $Q$ has quadratic relation with speed.

3. SIMULINK Model of Described Pump System

3.1. Simulation Model

A Matlab/Simulink for proposed mathematical model is presented for induction motor pump, taking into account that varying the motor voltage and frequency in accordance with water flow-rate level saves energy and operates the motor at maximum pump efficiency.

Figure 11 presents the whole Simulink model including solar PV model, Variable voltage-variable frequency inverter system, Pump system, and water flow-rate system, that predicts the water flow-rate and regulates both voltage and frequency by using the variable voltage-variable frequency (VFD) technology in order to keep the motor operating at constant torque.

3.2. Simulation Results

The obtained simulation results from above mentioned model are displayed in Figure 12 for various water flow-rate and corresponding reference and actual speed, where it’s shown that the motor adjusts its speed in accordance with the needed flow-rate, which in turn significantly reduces the power consumption.

While Figure 13 illustrates the generated by PV generator effective power at various radiations and consumed by the pump effective power at water elevation of

![Figure 10. Simulation results for pump performance at different heads (elevations).](image1)

![Figure 11. Matlab/Simulink model of induction-motor pump.](image2)
20 m. It can be seen that at various water consumption the PV system is capable to energize the pump system and the excess of power at light consumption rate can be used for energizing another loads. Furthermore applying (VFD) saves energy and gives the pump system the ability for normally operation even at light irradiations or cloudy weather.

3.3. Grid-Integrated Simulation Model

The proposed pump system is mainly energized from the PV source, while the AC utility serves to recover the energy shortages [17]. Figure 14 illustrates the complete simulation model including power estimator module, grid compensation module, grid-tie module, etc.

Avoiding synchronizing procedure when two AC sources are parallel connected, the AC utility is converted into DC and connected to the load based on switching commands sent by power estimator module to switch $Q_4$ by mean of the logic depicted in Equation (19).

The total power in form of voltage and current are converted into AC through out inverter circuit.

$$Q_4 = \begin{cases} 
\text{OFF} & \text{if } P_{pv} \geq P_L \cdots \text{Pure PV Source} \\
\text{ON} / \text{OFF} & \text{if } P_{pv} \left\{ \begin{array}{l} P_L \cdots \text{Combined} \\
\text{ON} & \text{for Night time.} 
\end{array} \right. 
\end{cases}$$

(19)

Figure 15 illustrates the results obtained from the mentioned simulation model, and proposed logic in Equation (19) where it’s shown that the grid will be switched on only when there are a power shortages ($P_{pv} < P_{load}$) and the load needs to be fully energized. Meanwhile, on-off grid connection can be realized in cases of load level fluctuation or cloudy weather. During the night time the load is energized from the AC utility. The proposed circuit can be applied for either AC load or pump system, single or three phase pumps.

4. Conclusions

A complete mathematical model has been developed for studying the pump behaviours at various elevations, water consumption rate and source voltage frequencies.

The proposed PV model consists of variable tracking module and voltage drop compensating module that can be used for either dc or ac loads with precise voltage tracking procedure.

The proposed Simulink model for induction motor
The saved energy due to applying VFD control may reach 30% of consumed power, therefore being more suitable to be energized from PV generator.

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doi:10.1109/TIA.2005.853371


Nomenclature

A,B diode idealistic factors

$E_g$ band gap energy of the semiconductor

$f_n$ rated supply voltage frequency

$g$ gravity acceleration (9.8 m/s²)

$G$ solar irradiation

$G_r$ reference solar irradiation

$h$ reservoir elevation (m)

$H$ total head (m)

$H_A$ total installation head (m)

$H_s$ static head (m)

$H_L$ network hydraulic losses (m)

$\rho$ water density (1000 kg/m³)

$\eta_p$ pump efficiency (%)

$I_d$ diode saturation current

$I_{MPP}$ PV module current at maximum power

$I_c$ cell current

$I_{ph}$ cell photo current

$I_{pv}$ Photovoltaic current

$I_{sc}$ short circuit current

$I_{ce}, I_{e}$ constants given at standard conditions

$I_{L1}$ motor line current

$K$ Boltzmann constant

$n$ motor speed in rpm

$n_e$ motor synchronous speed in rpm

$N_p$ number of parallel connected cells

$N_{pm}$ number of parallel connected PV modules

$N_s$ number of series connected cells

$N_{sm}$ number of series connected PV modules

$p$ number of motor poles

$P_c$ grid power

$P_{cont}$ constant losses power

$P_L$ load consumed power

$P_{em}$ electromagnetic power

$P_{mech}$ net mechanical power

$R_{L,load}$ load resistance

$R_p$ PV intercircuit shunt resistance

$R_s$ PV intercircuit series resistance

$R_1$ stator resistance of induction motor

$R_2'$ rotor resistance motor referred to stator

$R_{th}$ Thevinen resistance referred to stator

$R_{inp}$ total input stator resistance

$Q$ electric charge (Coulomb)

$Q$ water flow-rate (m³/hr)

$P_{pv}$ Photovoltaic generated power

$P_{PV}$ Photovoltaic

$P_{inp}$ motor input power

$T_e$ cell temperature in Kelvin

$T_{em}$ electromagnetic torque (N·m)

$T_m$ motor net mechanical torque (Nm)

$T_{th}$ reference temperature in Kelvin

$VFD$ Variable Frequency Drive

$V_{MPP}$ PV module voltage at maximum power

$V_c$ cell output voltage

$V_{OC}$ PV module open circuit voltage

$V_{ph}$ terminal phase voltage

$V_{pv}$ array photovoltaic voltage

$V_{th}$ Thevinen voltage

$X_m$ magnetic reactance

$X_1$ stator reactance of induction mptor

$X_2'$ rotor reactance of induction motor referred to stator

$X_m$ Thevinen reactance referred to stator

$X_{inp}$ total input stator reactance

$Z_{th}$ Thevinen impedance

$Z_{inp}$ total input stator impedance

$\Phi_n$ normalized insulation

$\phi$ motor phase shift angle

$\omega$ rotor speed in rad/s

$\xi$ friction coefficient