Study of Photovoltaic Water Pumping System using Scalar- DVC Based Control

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Abstract- This paper aims to achieve a control of a photovoltaic water pumping system. The study consists of a photovoltaic generator, an inverter, an induction motor and a centrifugal pump as mechanical load. The model used for global simulation is a closed loop model: the voltage output of PVG model is coupled with the voltage input of the inverter-induction motor model; the current output of this latter is coupled with the current entry of the PVG. The strategy control proposed in this study consist to i) pumping water with Solar energy, ii) drives the machine in constant flux and variable voltage for this subject a closed loop scalar based control law via a direct voltage control (DVC) inverter is used. The MPPT is given by the theory of conservation of energy ensures the control speed. The induction motor model is based on the classic dynamic model in the dq orthogonal Park reference frame. Simulations results confirm the working of the complete model and the effectiveness, feasibility and limits of such approach.

Keywords: Photovoltaic Generator (PVG), Scalar Based control (SBC); DVC inverter, Induction Motor, Centrifugal Pump.

1. INTRODUCTION

The use of the renewable energy source as the solar energy in the isolated sectors and the rural zones is a better solution to produce the needed electric energy for such applications as the pumping systems. So the Solar energy is one of the cleanest and environment-friendly non-conventional energy sources. With use of a PV panel solar energy is directly converters into electrical energy. The electrical energy produced by the PV panel can be extracted over time and used in the form of electric power. This electric power can be used to drive electric devices. Typically the power is extracted by using DC/DC up/down converter circuits and/or DC/AC inverter circuit. A PV panel in a uniform and constant irradiation has I-V characteristics, for irradiation there is only one operating point, known as the Maximum Power Point (MPP). For the latter, the PV panel operates at maximum efficiency and produces a maximum of power ($P_{\text{max}}$). When we connect a load directly to a PV panel, the operating point is not necessarily the MPP but it will be the intersection of the I-V characteristics with the load line, as it is represented in the figure 2. Then in the direct coupling of the loads, the PV panels are often oversized in order to ensure sufficient power to supply the load and this leads to a system excessively expensive. To overcome this problem, the tracking module can be used to maintain the operating of the PV panel at $P_{\text{max}}$, this can be done by means of the Maximum Power Point (MPP) by controlling the voltage or current generator independently of the load [1], [2].

Regarding to the widespread use of three phase electro pumps in industrial processes under variable loads, there is an obviously important need for a real model of pumping process powered by a photovoltaic generator in order to enhance of efficiency [1], and [3]. During the last two decades, AC variable speed drives have demonstrated increasing success. This is the result of technological progress in power inverters and their very fast and accurate drivers on the one hand and progress in digital signal processors such as DSP and dSPACE kits on the other. Various control schemes are in fact built, experimentally studied and commercialized for industrial purposes. Consequently the aim of this paper is to obtain a suitable control of an induction motor with a centrifugal pump as a load powered by a photovoltaic generator. The used method, labeled DVC (Direct Voltage Control), in the case of a closed loop scalar control structure. To ensure a good speed response, a PI controller is used. Several simulation results are presented and discussed and some concluding remarks are outlined. This paper is organized as follows. In section 2, a general description of the system is presented. Dynamic model of the photovoltaic panels, the converter DC/AC and the induction motor-pump are described. In this research on three phase squirrel-cage induction motor a closed loop Volts/Hertz voltage-fed a DVC inverter drive as scalar control technique is reviewed in section 3. Section 4, provides digital simulation results, and some discussions followed by the conclusion in section 6.
2. DESCRIPTION OF THE GLOBAL SYSTEM

The autonomous system consists of many subsystems. The first one is solar arrays, which produce electricity by converter sun’s energy; actual power generated by a solar device depends on the sun’s illumination, temperature, operation point and other conditions. The second is the inverter DC/AC, converts the DC voltage of internal DC link delivered by PV to a variable three phase alternating voltage with variable frequency. The third is the three phase induction Motor driving a centrifugal pump. In addition, a tank was used to simulate the well.

2.1 SYSTEM MODELING

For system modeling, we need study each subsystem. The following sections present the modeling of all subsystem of the photovoltaic water pumping system (PWPS).

2.2 PHOTOVOLTAIC ARRAY

The equivalent circuit model of a solar cell consists of a current generator $I_{ph}$ and a diode with series and shunt resistances as illustrated in figure 1; which have identified in previous work [4]. The array current $I_{PV}$ related to the array voltage $V_{PV}$ as in following equation:

$$I_p = I_p - I_n \left\{ \frac{v_p + r_s I_p}{v_{th}} - 1 \right\} - \frac{v_p + r_s I_p}{v_{th}} \exp \left[ - \frac{v_p + r_s I_p}{v_{th}} \right]$$

(1)

Figure 1. Equivalent circuit of a PVG

The cells are connected in series and in parallel combinations in order to form an array of the desired voltage and power levels. Figures 3and 4 represents the experiment characteristics of I-V characteristics of the solar-cell generator for several insulation levels and different temperature. The full model used in most literature is given by equations (1).

$$v_{th} = \frac{n_{om} A k_B T}{q}$$

(2)

$$I_{sc} = S_n (I_{sc} + k_r (T - T_r))$$

(3)

$$I_{sc} = \frac{I_{pm} I_{re}}{E_c} \exp \left[ E_c \left( \frac{1}{v_{th}} - \frac{1}{v_{th}(T)} \right) \right]$$

(4)

2.3 INDUCTION MOTO-PUMP

The induction motor is modeled using transformation of fixed abc coordination to rotating dqo coordination. The three phase induction motor model definitely formulated as mentioned in (5) to (9). [3]

$$\begin{align*}
V_{ad} &= R I_{ad} + \frac{d\phi_{ad}}{dt} - \omega \phi_{aq} \\
V_{aq} &= R I_{aq} + \frac{d\phi_{aq}}{dt} + \omega \phi_{ad}
\end{align*}$$

(5)

The stator flux and the rotor flux are respectively given by the following relations:

$$\begin{align*}
\Phi_s &= L_s I_s + M I_r \\
\Phi_r &= L_r I_r + M I_s
\end{align*}$$

(6)

In this case, the induction motor develops an electromagnetic torque $T_e$ expressed as follow:

$$T_e = p m_s (\Phi_{ad} I_{aq} - \Phi_{aq} I_{ad})$$

(7)
With \( m_r = \frac{M}{L_r} \),
d, q: axes corresponding to reference axes in Park mode.
The mechanical model of the induction motor is given in Eq. (8)
\[
\frac{J \frac{d \omega}{dt}}{p} = T_s - T_r (\omega_r)
\]  (8)

The centrifugal pump model described by equation (9), presents a model based on motor dynamics. Effects of pump flow rate and speed are shown in modeling equation. The equation is a form of Riccati equation where \( A_1, A_2 \) and \( A_3 \) are determinable constants from pump geometry.
\[
H = A_1 \omega_r^2 - A_2 \omega_r Q - A_3 Q^2
\]  (9)

This equation shows the influence of flow rate and speed on outlet pressure of the centrifugal pump; also it can match with steady - state conditions of pressure versus flow rate curve. The pump torque in a form of similar function of flow rate and speed may be modeled like as (10). [5], [6].
\[
T_L = A_{p1}\omega_r^2 + A_{p2}\omega_r + A_{p3}
\]  (10)

In our case \( H = 0.68 m \) to simulate the constant quantity of the equation (10); so we have:
\( A_1 = 0.039 \), \( A_2 = -0.3079 \), and \( A_3 = -0.0024 \) and
\( A_{p1} = 1.217 e^{-5} \), \( A_2 = 9.917 e^{-5} \), and \( A_3 = 5.939 e^{-5} \)

Note that the evaluation of the measured flow rate is made through a flow meter installed on the pump in the laboratory research.
Centrifugal pumps check the laws of similarities. For a rotational speed \( N \) of the pump wheel, we have an operating point characterized by a flow \( Q \) and manometric height \( H \), when we move to a speed \( N' \) ; we obtain another point of operation characterized by a flow rate \( Q' \) and a manometric height \( H' \) as follow:
\[
Q = \frac{N'}{N} Q , \quad H' = \left( \frac{N'}{N} \right)^2 H
\]  (11)

2.4 DIRECT VOLTAGE CONTROL (DVC) INVERTER

Be in agreement to consider that at some time, the control law requires a reference voltage \( v_{ref} \) located in the sector number one. Fig.5 gives a general view of voltage vectors generated by a standard inverter in the space of Concordia’s stationary reference frame.

![Inverter voltage vectors in Concordia’s reference frame.](image)

Average value of the voltage synthesized by the well known SPWM technique is expressed by Eq.12, where \( \rho \) and \( \xi \) are respectively voltage ratio and angle of \( v_{ref} \) with respect to the considered sector.
\[
\bar{v}_{ref} = \frac{\rho}{\sqrt{2}} e^{j \xi} \quad \text{avec} \quad \rho \in [0 ; 1] \quad \xi \in [0 \ 60^\circ]
\]  (12)

The first sector is limited by voltage vectors \( V_1 \) and \( V_2 \). When normalized by the admissible voltage limit, these vectors verify, respectively, the following equation:
\[
\begin{align*}
\bar{v}_1 &= 1 \\
\bar{v}_2 &= e^{j(60\xi - \zeta)}
\end{align*}
\]  (13)

In the sense of SPWM principle, these two vectors will be applied, respectively, during two time intervals \( \tau_1 \) and \( \tau_2 \) defined by:
\[
\begin{align*}
\tau_1 &= T_s \rho \sin(60^\circ - \zeta) \\
\tau_2 &= T_s \rho \sin(\xi)
\end{align*}
\]  (14)

It’s consider that time is computed by a discrete clock having a sampling period \( T_d \) chosen \( N \) time smaller then the period \( T_s \) used by the SPWM routine (\( T_s = N T_d \)). During the SPWM period \( T_s \), vector \( V_1 \) will be used respectively \( N_1 \) times while vector \( V_2 \) will be used \( N_2 \) times. Integers \( N_1 \) and \( N_2 \) are defined by their rounded values that verify:
\[
\begin{align*}
N_1 &= \text{round}(N \rho \sin(60^\circ - \zeta)) \\
N_2 &= \text{max}( \text{round}(N \rho \sin(\xi)), N - N_1)
\end{align*}
\]  (15)

Because of the sum (\( N_1 + N_2 \)) is not necessarily equal to \( N \), at the end of the SPWM period \( T_s \), there will be an error between the theoretical average voltage value and the actually synthesized one. The magnitude of this error is expressed by the following relation showing its dependence on the integer \( N \), the voltage ratio and angle:
\[
\varepsilon = \left| \int \frac{\rho}{\sqrt{2}} e^{j(60\xi - \zeta)} - \frac{N_1 + N_2}{2} \left(1 + j \sqrt{3}\right) \right| = f(\rho, N, \xi)
\]  (16)
It is marked that if \( N \) is great enough, we theoretically converge to the same result as SPWM solution \([7]\). In other words, the error will disappear. When analyzing the possibility to admit some error level, it is comprehensible to specify admissible limits on \( N \) and \( \rho \).

This means that by a compromise to be made between the demanded magnitude of the vector voltage and the period \( T_d \), an average vector voltage can be obtained with sufficient precision. By this we signify that instead of operating by SPWM technique with large period \( T_s \), we can directly select after some shorter time interval \( T_d \) one of the available inverter voltage vectors. Let’s designate by \( n(t) \) the selected one among the seven inverter voltage vectors. To induce the average voltage to converge to the command value, we select \( n(t) \) so that it minimizes the voltage error along time. This constraint is expressed by the following criterion:

\[
n(t) \rightarrow \min \int \mathcal{E}(t) dt = \int (v_{ref}(t) - v(n(t))) dt \quad (17)
\]

As the vector voltage is constant during the considered time interval, one can express the evolution of voltage error by Eq. (16) and select the best inverter vector voltage according to the standard minimization Eq. (17):

\[
\mathcal{E}(n(t)) = \mathcal{E} + j\omega = \mathcal{E}(t) + T_s (v_{ref}(t) - v(n(t))) \quad (18)
\]

\[
n(t) \rightarrow \min \left| \mathcal{E}(n(t)) \right| = \min \left( \mathcal{E}^2 + \omega^2 \right) \quad (19)
\]

The above minimization integral criterion must naturally respect at any time \( d \) and \( q \) components. As illustrative purposes of this test, we consider a voltage inverter powered by a photovoltaic DC voltage. We also propose to synthesize a reference voltage with the control of amplitude/pulse. In the case of a voltage supply, it suffices to impose to the DVC inverter the module of the voltage \( V_s \) proportional to the stator frequency relation by the constant \( V / Hz \) control described in section 3.

3. CONTROL STRATEGIES

3.1. SCALAR BASED CONTROL STRATEGY

The scalar control method is based on varying two parameters simultaneously. The speed can be varied by increasing or decreasing the supply frequency, but this result in change of impedances. The change of impedances eventuate the increase or decrease of current. If the current is small, the torque of motor decreases. If the frequency decreases or the voltage increases, the coils can be burned or saturation can occur in the iron of coils. To avoid these problems, it is necessary to vary the frequency and the voltage at the same way. In this way, the occurring disadvantages of changing frequency and voltage can be compensated. The supply voltage is given by the following relationship, which obtained after development of the equations governing the operation of the motor in steady state:

\[
V_s = \Phi_s \omega_s \left( 1 + \frac{1}{\tau_s \omega_s} \right)^2 \quad (20)
\]

In this expression, \( V_s \) is the effective voltage of the sinusoidal wave of the inverter. \( \omega_s \) is the statorique pulsation and \( \tau_s = \frac{L_s}{R_s} \) is the stator time constant and \( \Phi_s \) is the stator flux. If, moreover, the voltage drop due to the statorique resistance \( R_s \) is negligible, we have:

\[
V_s = \Phi_s \omega_s \quad (21)
\]

It should be noted here that the law \( \frac{V_s}{f_s} = \text{cste} \) is reduced to a constant flux operation. To keep the flow constant at its nominal value generally, the stator voltage must be adjusted in proportion to the supply frequency. This is the simplest approach to speed control of induction motors, called Constant Volts / Hertz method. It can be seen basically no loop regulation is necessary. In some practical applications the stator current is measured and forecasts are taken to prevent overload. For operation at low speed, the voltage drop in the stator resistance is no longer negligible with respect to the leakage reactance. The control structure must take into account the voltage drop to maintain a constant flux. Conversely, at a speed greater than that corresponding to the nominal frequency, the condition of constant V/Hz cannot be satisfied because this would amount to overvoltage. Therefore, the stator voltage must be adjusted according to the following rule:

\[
V_s = \begin{cases} 
(V_{sn} - V_{so}) \frac{f}{f_n} + V_{so} & \text{pour } f < f_n, \\
V_{sn} & \text{pour } f \geq f_n 
\end{cases} \quad (22)
\]

Where \( V_{so} \) denotes the effective value of the stator voltage at zero frequency. The relation (22) is shown in Figure (6).

![Figure (6): frequency-voltage relationship for constant V/Hz Control](image)
There are two types of scalar control in closed-loop the first provide control speed and the second provide control torque [8]. We treat here the case of scalar control speed. As shown in figure (7), the measured or estimated speed \( \omega_r \) can be controlled in a closed loop. It is compared to the reference speed \( \omega_{\text{ref}} \), which is proportional to the illumination emitted on the solar panel, to generate an error signal. Proportional integral PI controller is used to generate the slip pulse \( \omega_s \) to be added to \( \omega_r \) to determine the stator angular reference \( \omega_{\text{ref}} \), so the motor will reach the desired speed. This stator angular reference defines the reference voltage. With this control method the torque is accessible in all operating points up to the nominal value of speed and the motor can operate over the nominal speed. In the over speed range, the torque of the motor will decrease in inverse proportion to the increasing frequency because voltage cannot be higher than the value at which the driver electronics is able to operate.

![Figure (7): Structure of the global control scheme](image)

**3.2. THE PHOTOVOLTAIC ENERGY CONTROL**

The global model is based on a power balance at the conversion chain. The power absorbed by the pump unit from the inverter and the power supplied by the PVG to the inverter are respectively given by:

\[
P_{_{ps}} = v_s i_s = v_{_{ps}} i_{_{ps}} + v_{_{qs}} i_{_{qs}}
\]

(23)

And

\[
P_{_{p}} = v_p i_p
\]

(24)

\( P_s \) is the power absorbed by pumping system calculated using variables Park [9] (the Park transformation considered here preserves powers). We make the approximation that the power losses in the inverter are trivial. This approximation was used to model and validate by experiment the control of a photovoltaic pumping unit using the energy conservation law. We have then:

\[
P_{p} = P_s
\]

(25)

The current absorbed by the motor is used as input variable of the PVG and the output voltage of the PVG serves to feeding the inverter. In addition, the voltage system tensions generated and the load are balanced. The average value of the current in the DC bus is defined as follow:

\[
I_{_{dc}} = \frac{1}{T} \int_0^T (c_1 i_1 + c_2 i_2 + c_3 i_3) dt = i_s
\]

(26)

After development, this quantity is expressed in terms of the average value of the statoric current per phase. The current absorbed by the motor is used as input variable to the model of the PVG and output voltage of the PVG serves to feeding the inverter. To take this aspect into account, the current \( i_s \) measured must such that equation (25) is verified, and we will have to solve the following system:

\[
\begin{align*}
 iP &= i_s \\
 i_s &= I_m - I_{\text{ref}} \left( \frac{v_s + r_i i_s}{v_{_{th}} + r_i} - 1 \right) = \frac{v_s + r_i i_s}{v_{_{th}} + r_i}.
\end{align*}
\]

(27)

We note as follow the function that we should resolve it By Newton-Raphson method:

\[
f = i_p - I_{_{ref}} \left( \frac{v_s + r_i i_p}{v_{_{th}} + r_i} - 1 \right) + \frac{v_s + r_i i_p}{v_{_{th}} + r_i}.
\]

(28)

We successfully solve Eq. (28) and we deduce the value of \( v_s \) which serves as power supply for the inverter.

**4. SIMULATIONS RESULTS**

The models of the closed-loop constant V/Hz control were implemented in Matlab/Simulink. During the simulations the models were tested with changing speed that change with illumination. The simulation was prepared considering the characteristics of the PVG, installed on the roof of the laboratory, and using the characteristic of the pump unit in the Appendix. The inverter is controlled by DVC technique. The adjustment of the voltage and the angular speed is based on constant V/Hz control. To avoid the overcoming of operating limits of the moto-pump, we chose for a nominal frequency of 50 Hz, an equivalent illumination equal to 1000W/m². In order to test the good organization of the proposed method, we applied three levels of insulation as shown in figure 8, just to be sure that even in rapid
changing in atmospheric conditions (like insulation or temperature), the overall system can follow this change and is able to function around the optimal value. The figures below represent, for a fixed height \((H = 0.68m)\), the evolution of the angular speed, the electromagnetic torque, the general appearance of the stator current and the source voltage for conventional AC 50 Hz and for PVG 500V. We also present the power absorbed by the pump unit and the photovoltaic power provided by the PVG.
5. DISCUSSION

Initially, reference electric speed was chosen proportional to the illumination. The reference and measured speed given by figure 11. The system has been tested with the use of scalar-based motor control, V/Hz, by introducing DVC technique. This control method introduced in the photovoltaic water pumping system is very promising. To test the performance of the system described above, simulation results are presented.

As presented in figure 13, $\omega_{evolutes}$ as $\omega_{ref}$ following the variation in the illumination; we prove that the statorique flux is constant.

We note also as shown in Figure 8, 13 and 15, when the illumination decreases, the speed decreases, and the energy consumption by moto-pump is no longer the power supplied by the PV generator. The torque decreases also and the system move away from the nominal operating point. It’s shown that the measured speed converges strictly to the reference one. Also we note that the load torque converges to the electromagnetic one as shown in Figure (12).

6. CONCLUSION

The constant V/Hz control method has advantages and disadvantages. Scalar control is a cheap, well-implementable method. Because of these advantages and its simplicity, stability, many applications operate with this control technique in the industry. On the other hand, it is not satisfactory for the control of drives with dynamic behavior, since it gives slow response to transients. This study has allowed us to have a simulation model for photovoltaic pumping system that facilitate the design of any other similar system, in which the parameters of the constituent elements are defined in a set of specifications. The goal is eventually to dimension the PV generator to ensure proper system operation and avoid unnecessary costs in the realization of the pumping system. We presented in this theoretical study a model that allows analyzing performance of a pumping system.

NOMENCLATURE:

$I_{rs}$ : Reverse saturation current at reference temperature ($I_{rs} = 2.25e^{-4}$),

$S_r$: Solar irradiation normalized by reference irradiation ($1000W/m^2$),

$A$: Quality factor ($A = 2$ for Silicon diode)

$q$: Electronic charge ($q = 1.6e^{-19}$),

$k_B$: Boltzmann’s constant ($k_B = 1.38e^{-20}$),

$E_G$: Silicon band gap ($E_G = 1.8e^{-2}$),

$K_r$: short-circuit current temperature coefficient (Typical value is $K_r = 0.8$).

$S_r$: Solar insulation

$V_r$: PVG voltage

$r_s$: Series resistance of the PVG

$r_{sh}$: shunt resistance of the PVG

$v_{th}$: Thermal voltage of the PVG

$v_{sd}$: d-axis stator voltage

$v_{sq}$: q-axis stator voltage

$R_s$: Stator resistance per phase

$R_r$: Rotor resistance per phase

$L_s$: Stator self inductance

$L_r$: Rotor self inductance

$J$: Total inertia

$M$: Mutual inductance

$P$: Number of pole pairs

$T_s$: Electromagnetic torque

$P_n$: Motor output rated power

$B_m$: Viscose friction coefficient

$\Phi_r$: d-q axis rotor flux

$\Phi_r$: d-q axis stator flux

$\omega_s$: statorique angular speed

$\omega_r$: drive angular speed

$\sigma$: Leakage coefficient ($\sigma = 1 - \frac{\mu_s}{\mu_r}$)

$\tau_s$: Stator time constant ($\frac{L_s}{R_s}$)

$\tau_r$: Rotor time constant ($\frac{L_r}{R_r}$)

$A_p$: pump torque constant

$H$: total pump head

$Q$: Water discharge rate
$T_l$: load torque
$T_e$: Electromagnetic torque

7. ANNEX: PARAMETERS OF THE MODELED SYSTEM

Table 1: PV model Characteristics:

<table>
<thead>
<tr>
<th>$P_p$</th>
<th>50 w</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{opt}$ (A)</td>
<td>2.9</td>
</tr>
<tr>
<td>$V_{opt}$ (V)</td>
<td>17.2</td>
</tr>
<tr>
<td>$V_m$ (V)</td>
<td>21</td>
</tr>
<tr>
<td>$I_m$ (A)</td>
<td>3.4</td>
</tr>
<tr>
<td>Number of cell</td>
<td>36</td>
</tr>
<tr>
<td>Type of cell</td>
<td>Poly</td>
</tr>
<tr>
<td>efficiency</td>
<td>11.3%</td>
</tr>
</tbody>
</table>

Table 2: Pump Characteristics:

<table>
<thead>
<tr>
<th>$P_p$</th>
<th>0.71k w</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$ (lit/min)</td>
<td>30(min)- 80(max)</td>
</tr>
<tr>
<td>$H$ (m)</td>
<td>12.8(min)-20.1(max)</td>
</tr>
</tbody>
</table>

Table 3: IM Characteristics:

| Rated power $P_n$ | 0.61 Kw |
| Number of pair of poles $p$ | 1 |
| Statoric resistance $R_s$ | 17.68 Ω |
| Rotoric resistance $R_r$ | 19.1016Ω |
| Statoric cyclic inductance $L_s$ | 0.6877 H |
| Rotoric cyclic inductance $L_r$ | 0.6811 H |
| Mutual cyclic inductance $M$ | 0.65611 H |
| Moment d'inertie $J$ | 0.0001 kg.m² |
| Friction coefficient $B_m$ | 0Kgm2s |
| Nominal torque | 1.9 N.m |
| Voltage between phases | 400V |
| Nominal current | 1.45 A |

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