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Performance Determination of Photovoltaic AC Water-Pumping System Using a Boost Converter Controlled by PI Regulator

Eric Simonguy[1], Eric Korsaga[1], Jean M'boliguipa[2], Toussaint T. Guingané[1], Zacharie Koalaga[1]

[1]*Laboratoire de Matériaux et Environnement (LAME), UFR/SEA, Université Ouaga 1 Pr Joseph Ki-Zerbo, 03 BP 7021 Ouagadougou 03, Burkina Faso.*

[2]*Laboratoire d'Energétique Carnot (LEC), Université de Bangui, Centrafrique.*

Abstract

This work studies the performance of a Photovoltaic (PV) Alternating Current (AC) pumping system using a centrifugal pump, driven by a cage Asynchronous Motor (AM) fed through a three-phase voltage inverter. The boost converter control strategy based on the use of Proportional Integral (PI) regulator ensures the operation of the AM with rated voltage and frequency. The simulation results in Matlab/Simulink software show the operation limits and the dynamic performance of the proposed structure.

Keywords: PV pumping system; asynchronous motor; Centrifugal pump; PI regulator; dynamic performance.

1. INTRODUCTION

The use of the solar energy for pumping water is particularly well adapted to the rural areas and isolated sites. The increasing demand of water in these zones made that a growing interest is done to the utilization of photovoltaic (PV) generator as energy source for several motor-pumps.

There are two configurations of the photovoltaic standalone water pumping systems: direct coupled PV pumping systems and PV pumping systems with battery storage [1].

Although it is more reliable than photovoltaic pumping system with battery storage, direct coupled photovoltaic water-pumping system provides a flow that depends on solar radiation during the day. To have a flow independent of the sun, we chose to use a PI regulator. Its role is to regulate the input voltage of the inverter, thus enabling it to supply the three-phase asynchronous motor with rated voltage and frequency. Therefore, the pump will be driven at constant speed and will provide a constant flow.

The role of this pumping system is to store water in an elevated tank in order to produce by gravitation irrigation water in a rural zone.

This work is organized in two sections: the first section describes methods and material used and the second presents the results and analysis.

2. MATERIAL AND METHODS

2.1. System description

The water pumping system considered is constituted by a photovoltaic array, a boost converter with his PI control, a three-phase voltage inverter, a centrifugal motor-driven pump and a water storage tank. Its synoptic diagram is presented in the Figure 1:

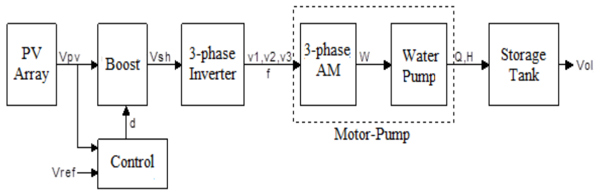

Figure 1: Synoptic diagram of the system

2.2. PV array model

The PV array is composed of a several modules connected in series and in parallel, themselves constituted of PV cells. Many models of PV cells are used in the literature [2, 3]. Among which, the simplest is the single diode model [4]. It will be used in this study because it provides fairly accurate results.

The mathematical model which characterizes a photovoltaic module consisting in n_p cells in parallel and n_s in series is given by the following equation:

$$I = I_{ph} - I_s \left[exp\left(\frac{q(V + IR_s)}{akT_C} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \qquad (1)$$

$$I_{ph} = n_p i_{ph},\ I_s = n_p i_s,\ R_s = \frac{n_s}{n_p} \mathrm{r_s},\ R_{sh} = \frac{n_s}{n_p} \mathrm{r_{sh}} \qquad (2)$$

where I, V, I_{ph}, I_s, R_s and R_{sh} are respectively the current, the voltage, the photocurrent, the reverses saturation current, the series resistance and the parallel resistance of the PV module. Then, a is diode ideality factor, k is the Boltzmann constant (1.3854 10^{-23} J/K) and q is the electron charge (1.602 10^{-19} C).

2.3. Boost converter and his control

The boost converter is needed to efficiently convert a Direct Current (DC) voltage from a lower level to a higher level. It's much used in photovoltaic applications [5], particularly in the solar pumping. The rigorous control of its duty ratio (d) allows optimizing the photovoltaic power by forcing the PV array to work at the maximum of the P-V characteristic.

By using the simplified model, the input value and the output value are related to the duty ratio d by the following expression [6]:

$$V_{sh} = \frac{V_{eh}}{1-d} \tag{3}$$

$$I_{sh} = (1-d) \cdot I_{eh} \tag{4}$$

where V_{eh} and V_{sh} are respectively the input voltage and the output voltage of the converter; I_{eh} and I_{sh} are respectively the input current and the output current.

- **Operation strategy of the PI regulator**

So as to manage the transfer of energy between the PV source and the voltage inverter, the boost converter is controlled by the PI regulator. It block diagram is shown in Figure 2.

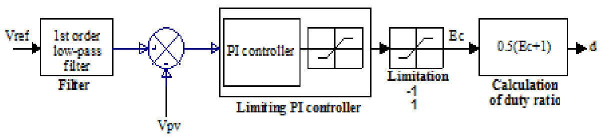

Figure 2: PI regulator

The signal Ec is determine by proportional-integral treatment between the reference voltage V_{ref} and the photovoltaic voltage V_{pv}. The Limitation block is used to limit the value of Ec between -1 and 1, and the last block calculates the duty ratio value d according to equation (5).

$$d = 0.5(E_c + 1) \tag{5}$$

The PI regulator parameters are determined by the simulation for a reference voltage V_{ref} equal to 500 V. They are given in the table 1.

Table 1: Regulator parameters

Proportional gain (K_p)	0.004
Integral gain (K_i)	13
Time-constant of filter (τ)	10^{-4} s

2.4. Voltage inverter model

To model the inverter, we will consider that the electronic switches are ideals and operating in complementary regimes which have two possible states and the switching are carried instantaneously.

In considering the medium point 0 of the continuous source as reference point, the voltages v_{m0} (m = a, b, c) take the value $V_{cc}/2$ when the superior switch placed on one arm is in conduction and respectively $-V_{cc}/2$ when the inferior switch placed on the same arm is in conduction [7]. So we get:

$$v_{m0} = \frac{S_m \cdot V_{CC}}{2}, m = a, b, c \tag{6}$$

where S_m is the command function of the inverter arms and $S_m = \pm 1$ (state of the switch).

The line to neutral output voltages can write under the following form [8]:

$$\begin{cases} v_{aN} = \frac{V_{CC}}{6} \cdot (2.S_a - S_b - S_c) \\ v_{bN} = \frac{V_{CC}}{6} \cdot (2.S_b - S_c - S_a) \\ v_{cN} = \frac{V_{CC}}{6} \cdot (2.S_c - S_a - S_b) \end{cases} \tag{7}$$

where V_{cc} is the continuous voltage, S_a, S_b et S_c are the command functions of the inverter arms.

2.5. Motor pump model

2.5.1. Asynchronous motor model

The asynchronous machine is presented by a model brought back to a system of axis *d*, *q*, obtained by a Park transformation of a three-phase system into a two-phase system, in a reference frame turning at the synchronism speed [9, 10].

The voltage equations of the asynchronous machine in the (*d*, *q*) axis systems are given as follows:

$$\begin{cases} V_{sd} = R_s I_{sd} + \frac{d\emptyset_{sd}}{dt} - \omega_s \cdot \emptyset_{sq} \\ V_{sq} = R_s I_{sq} + \frac{d\emptyset_{sq}}{dt} + \omega_s \cdot \emptyset_{sd} \\ 0 = R_r I_{rd} + \frac{d\emptyset_{rd}}{dt} - (\omega_s - \omega) \cdot \emptyset_{rq} \\ 0 = R_r I_{rq} + \frac{d\emptyset_{rq}}{dt} + (\omega_s - \omega) \cdot \emptyset_{rd} \end{cases} \tag{8}$$

where V_{sd} and V_{sq} are the d-axis and q-axis components of the stator voltage, I_{sd} and I_{sq} are the d-axis and q-axis components of the stator current, I_{rd} and I_{rq} are the d-axis and q-axis components of the rotor current, R_s and R_r are respectively stator resistance and rotor resistance, Φ_{sd} and Φ_{sq} are the d-axis and q-axis components of the stator flux, Φ_{rd} and Φ_{rq} are the d-axis and q-axis components of the rotor flux, ω_s and ω are respectively stator pulsation and mechanic pulsation.

The Park components of stator flux may be expressed by the equations:

$$\emptyset_{sd} = L_s \cdot I_{sd} + M_{sr} \cdot I_{rd} \quad (9)$$

$$\emptyset_{sq} = L_s \cdot I_{sq} + M_{sr} \cdot I_{rq} \quad (10)$$

where L_s and M_{sr} are respectively the stator inductance and the mutual inductance between the stator and the rotor.

And those of rotor flux are given by:

$$\emptyset_{rd} = L_r \cdot I_{rd} + M_{sr} \cdot I_{sd} \quad (11)$$

$$\emptyset_{rq} = L_r \cdot I_{rq} + M_{sr} \cdot I_{sq} \quad (12)$$

where L_r is rotor inductance.

The following equation gives the electromagnetic torque:

$$C_{em} = p \cdot M_{sr} \cdot \left(\mathrm{I}_{rd} \cdot I_{sq} - \mathrm{I}_{rq} \cdot I_{sd}\right) \quad (13)$$

where p is the pair pole number.

The mechanic equation is given by (14).

$$J \cdot \frac{d\Omega}{dt} + f \cdot \Omega = C_{em} - C_r \quad (14)$$

where C_r and C_{em} are respectively resistant and electromagnetic torques, f is the coefficient of viscous friction and J is the inertia moment of motor.

2.5.2. Centrifugal pump model

The centrifugal pump model is based on the similitude laws [11, 12] associated to the equation of the resistant torque.

The similitude laws are expressed by (15).

$$Q = Q_n \cdot \left(\frac{N}{N_n}\right), \qquad H = H_n \cdot \left(\frac{N}{N_n}\right)^2, \qquad P = P_n \cdot \left(\frac{N}{N_n}\right)^3 \quad (15)$$

where Q and Q_n are water flow(m^3/h) respectively corresponding to the speed N and N_n, H and H_n are the manometric height respectively corresponding to N and N_n, P and P_n are the mechanic power (kW) respectively corresponding to N and N_n.

And the load torque of the centrifugal pump can be described by (16).

$$C_r = k\Omega^2 \quad (16)$$

where k is the pump torque coefficient (Nm/ $(rad/s)^2$) and Ω the rotation angular velocity (rd/s).

2.6. Storage tank model

The volume of the water in the tank is related to the pumping flow Q as follows:

$$Vol(t) = \int_0^t Q(t)\,dt + Vol_0 \quad (17)$$

where t is the simulation time (seconds) and Vol_0 is the water reserve. For this study, Vol_0 is fixed at 16 m^3.

3. SIMULATION RESULTS

Figure 3 presents the complete model of the pumping system implemented in Matlab/Simulink.

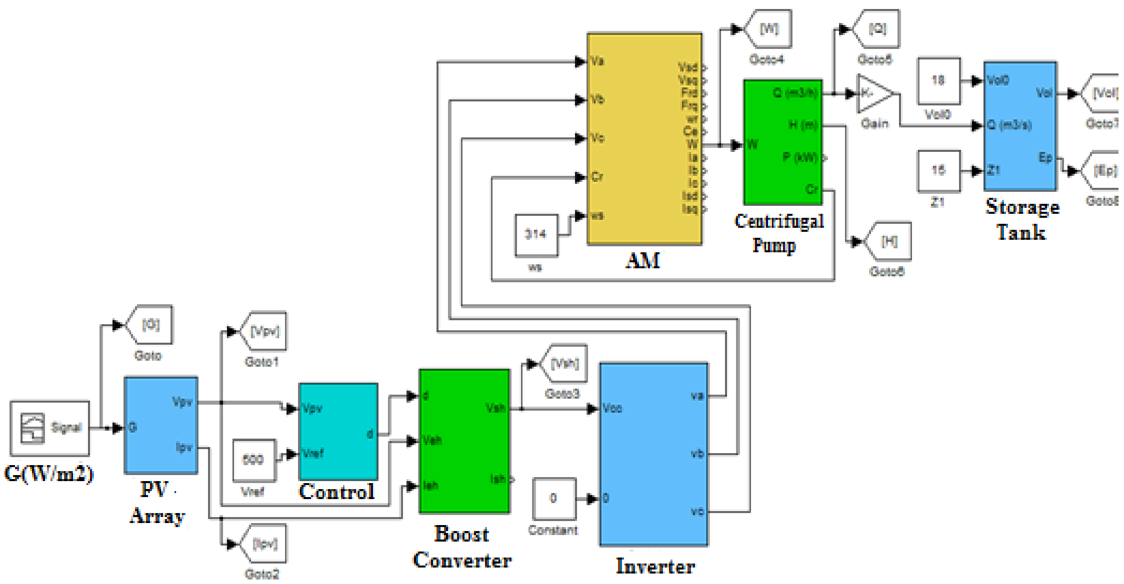

Figure 3: Matlab/Simulink model of PV pumping system

To study the performance of the system during meteorological disturbances, we apply to the entry the illumination profile of figure 4. The operating temperature is considered constant and equal to 25ºC.

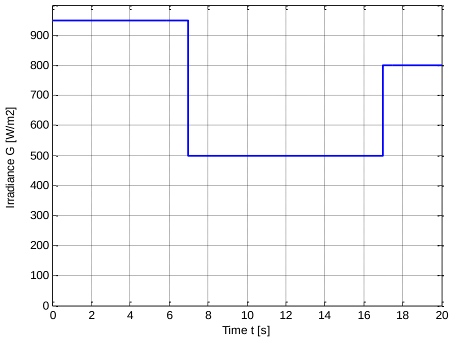

Figure 4: Illumination profile

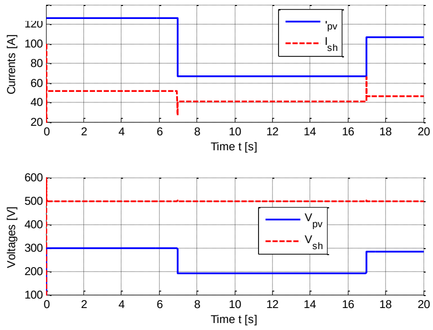

Figure 5: PV array parameters and Boost converter's output parameters

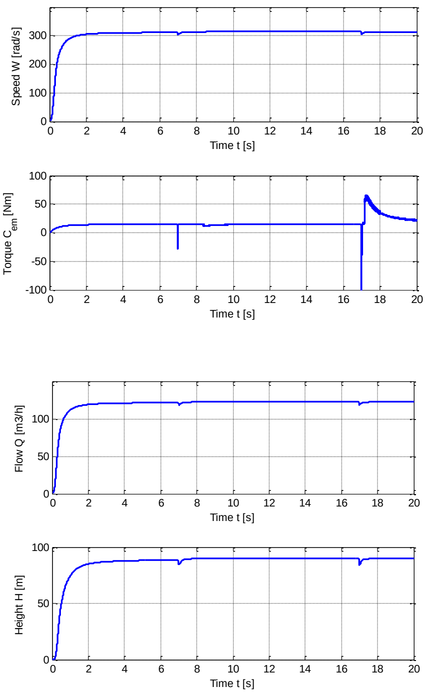

Figure 6: Motor-pump parameters

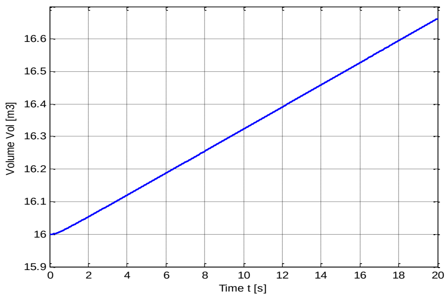

Figure 7: Water volume in the tank

Figure 5 shows the response of the PV array and the boost converter to a sudden variation of illumination. It proves that the variation of illumination influences the current and the voltage of the PV array. However, the output voltage of the boost converter is maintained constant and equal to the reference voltage V_{ref}.

Figure 6 presents the motor-pump parameters. The torque variations at the different points of illumination changes are very large and are followed of disturbances. That induces significant increases of the feeding currents of the motor, noise and mechanic vibrations. However, the rotation speed, the water flow and the manometric height respond instantaneously by transient variations to the illumination changes and return very quickly to their optimal values.

Figure 7 shows the volume of the water in the tank. The initial volume is 16 m^3 and we noted that the water volume increases and is not affected by the illumination changes.

- ***Influence of change of asynchronous motor parameters***

The parameters of the asynchronous machine can change during operation. It is significant to compare the performance of pumping system when one varies the parameters of the machine. Figures 8, 9, 10 and 11 respectively show the influence of varying the parameters of asynchronous machine R_s and J on the response of the rotation speed and electromagnetic torque.

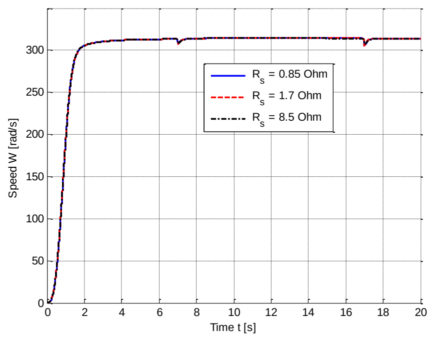

Figure 8: Influence of stator resistance variations on rotation speed

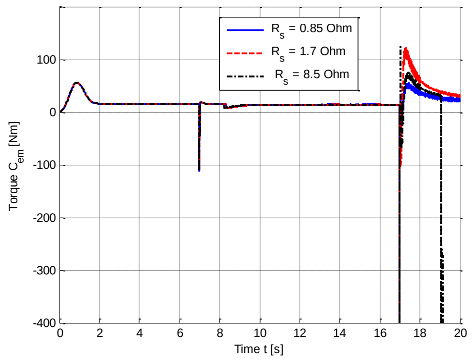

Figure 9: Influence of stator resistance variation on electromagnetic torque

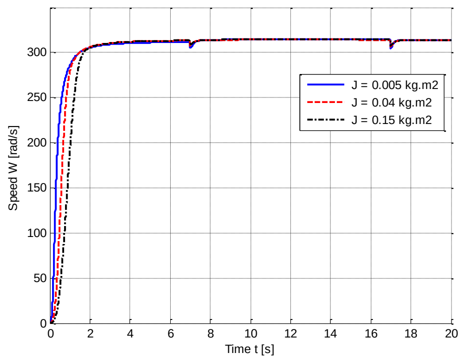

Figure 10: Influence of inertia moment variations on rotation speed

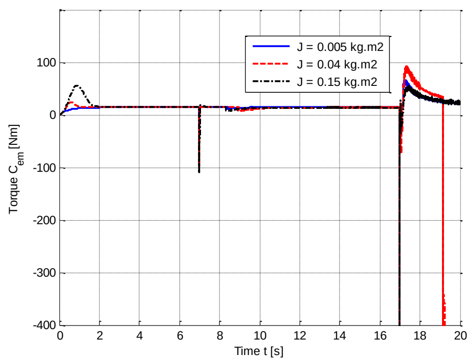

Figure 11: Influence of inertia moment variations on electromagnetic torque

Figures 8, 9, 10 and 11 show the influence of the variations of stator resistance and rotor inertia moment on the rotation speed and electromagnetic torque. It is noted that the rotation speed and consequently the water flow and the manometric height are practically insensitive at the variations of the motor parameters R_s and J. However, the electromagnetic torque and consequently the stator currents are very sensitive to their variations.

4. CONCLUSION

This work analyzes the dynamic performance of a PV pumping system using a boost converter controlled by a PI regulator.

The simulation results show that the speed is controlled perfectly. Consequently, the water flow and the manometric height are maintained at their optimal values. However, the electromagnetic torque is very unstable, which causes very significant variations of the stator currents of the asynchronous motor.

It is noted that, when the electrical and mechanical parameters of the motor R_s and J vary, the speed is always maintained at its optimal value. Whereas, the electromagnetic torque continues to be degraded.

As a prospect to this work, we intend to develop a system allowing to controlling also the electromagnetic torque by the stator currents.

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APPENDIX

Table 2: PV module data

Maximum power (P_{max})	180 W
Voltage at P_{max} (V_{mp})	35.14 V
Current at P_{max} (I_{mp})	5.12 A
Open circuit voltage (V_{oc})	43.2 V
Short circuit current (I_{sc})	5.48 A
Number of cells (N_{cel})	72

Table 3: Asynchronous Motor parameters

Phase-phase voltage (U)	380 V
Frequency (f)	50 Hz
Stator resistance (R_s)	0.85 Ω
Stator inductance (L_s)	14 mH
Rotor inductance (L_r)	23 mH
Mutual inductance (M)	58 mH
Number of pairs of poles (p)	1
Inertia moment (J)	0.15

Table 4: Centrifugal Pump parameters

Performances at 2500 tr/mn	
Nominal flow (Q_n)	100 m^3/h
Nominal height (H_n)	90 m
Torque coefficient (k)	19 10^{-5} Nm/(rad/s)^2

Table 5: Storage tank

Volume (C)	668 m^3
Water reserve (Vol_0)	16 m^3

Table 6: List of symbols

Symbol	**Signification**
i_{ph}	PV cell photocurrent
i_s	PV cell reverses saturation current
r_s	PV cell series resistance
r_p	PV cell parallel resistance
V_{cc}	Inverter DC voltage
V_{ref}	Reference voltage