



Modelling and simulation of a pumping system fed by photovoltaic generator within the Matlab/Simulink programming environment

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Abstract

In spite of poor efficiency of the photovoltaic systems developed up to date and the high cost of the installations of the equipment of this kind of station of solar energy conversion into electric power, this did not stop the researchers to continue to make efforts in this field in order to minimize the expenses of installation of equipment and to increase the output efficiency of the photovoltaic systems. In order to make solar energy competitive with the other forms of renewable energies, a better exploitation of its advantages especially environmental side, this will be possible only with the development of the less expensive and high output efficiency systems. The objective of this work is to bring a contribution to the study of the behaviours of the photovoltaic generators and converters used to feed a well defined load, in our case an asynchronous machine actuating a centrifugal pump, this through modelling and simulation of the various stages that constitute the overall system.

Keywords: Photovoltaic; Pumping system; Modelling; Matlab

1. Introduction

The classification of solar energy in the world as one of the promising renewable energies

has become irreversible, for several reasons such as

- It is considered the cleanest energy.
- The technology of solar cells is growing fast
- The solar energy can be exploited in the whole world.

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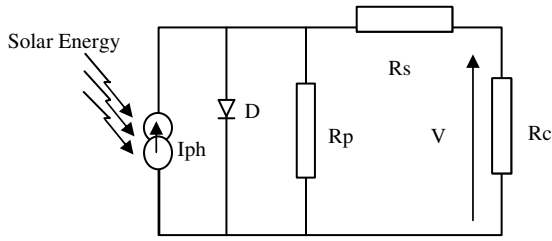


Fig. 1. The simplified equivalent electric circuit of a photovoltaic cell.

The photovoltaic pumping systems are more and more used for irrigation, particularly in the isolated areas. The study of such a system through modelling and simulation of the various stages that constitute it, this in the aim of bringing a contribution to the study of the behaviour of the photovoltaic generator and converters used to feed a load composed from a motor-driven centrifugal pump, the system is defined as follows:

- Photovoltaic generator.
- Direct current-direct current converter (DC/DC).
- Direct current-alternating current converter (DC/AC).
- Asynchronous machine.
- Centrifugal pump.

Therefore the work is based upon the knowledge of the action of the various parts of the system models.

2. Modelling of the photovoltaic generator

The direct conversion of sunlight into an electric power, without any intermediary, is defined as being the photovoltaic effect. The solar cell is the basic element in charge of the solar energy transformation into electric power. Fig. 2 represents the simplified equivalent electric circuit of a photovoltaic cell [1,5] defined by the following equations:

$$I = I_{sc} - A \left[e^{(V + IR_{ss})/B} - 1 \right] \quad (1)$$

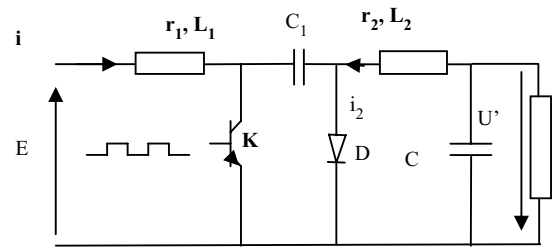


Fig. 2. Buck-Boost chopper circuit.

$$A = (I_{sc} - I_{op}) e^{(-V_{op} + I_{op} R_{ss})/B} \quad (2)$$

$$B = (V_{op} + I_{op} R_{ss} - V_{oc}) / \log(1 - I_{op} / I_{sc}) \quad (3)$$

where I_{sc} , short-circuit current; I_{op} , optimal current; V_{oc} , open circuit voltage; V_{op} , optimal voltage; R_{ss} , series resistance; R_p , parallel resistance.

Knowing that several parameters of the Eq. (1) vary proportionally with the sunning and the temperature [1], considering a current of short-circuit I_{sc} for a reference sunning $J_{ref} = 1000 \text{ W/m}^2$ [1], the I - V characteristic is obtained and can be resumed in the following Eqs. (4) and (5).

$$I' = I + \Delta I \quad (4)$$

$$V' = V + \Delta V \quad (5)$$

where

$$\Delta I = -(1 - J/J_{ref}) I_{sc} \quad (6)$$

$$\Delta V = -R_s I \quad (7)$$

J , luminous flow in W/m^2 ; J_{ref} reference luminous flow supposed $1000 (\text{W/m}^2)$.

Therefore from the previous equations which govern a photoelectric cell, the model of the photovoltaic generator was developed.

3. Modelling of the dc/dc converter

The capacitive accumulation chopper shown in Fig. 2, allows the supply of a current load starting from a current source, where the capacitor C_1 plays the role of an auxiliary source of voltage. During the charging of C_1 , there is a current generator outputting in voltage receiver, as in a parallel chopper. When C_1 discharges, it constitutes a voltage generator outputting in a current receiver, as in a series chopper. The circuit is equivalent to a cascade of parallel and series choppers, from where its name *Buck–Boost* converter [3].

For the modelling of the *Buck–Boost* chopper, we have chosen a simple model connecting the input voltage, the voltage of the photovoltaic generator, with the output voltage of the chopper used to supply the voltage inverter [2].

It is supposed that the losses on the level of the chopper are negligible and $P_{\text{input}} = P_{\text{output}}$. Therefore the equation which governs the chopper is given by

$$U' = Ud/(1-d) \quad (8)$$

where U' , the output voltage; U , the voltage of the photovoltaic generator; d , cyclic ratio.

4. Modelling of the voltage inverter

The three-phase voltage inverter modelled is shown in Fig. 3.

Knowing that if the sinusoidal currents forms a balanced system [3], the voltages V'_a , V'_b and V'_c have necessarily a null sum. In order to obtain their instantaneous values we start from the voltages $V_a - V_o$, $V_b - V_o$ and $V_c - V_o$ between the three terminals of the inverter and the fictitious point (0) of the direct voltage source then removes from it the instantaneous homopolar component of this system of voltage.

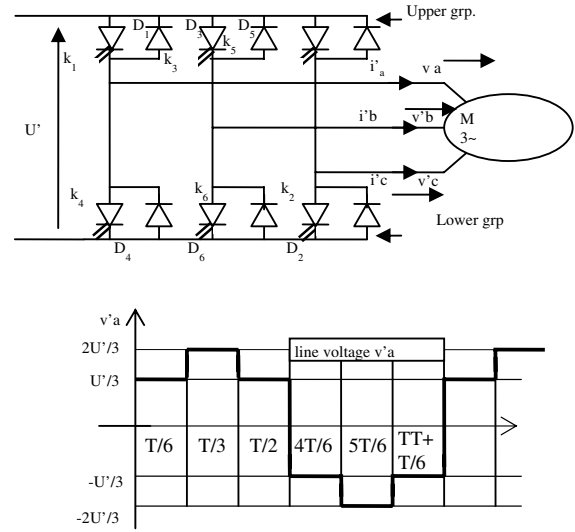


Fig. 3. Quasi-square voltage inverter.

For the phase (A), we have

$$V'_a = V_a - V_o - 1/3[(V_a - V_o) + (V_b - V_o) + (V_c - V_o)] \quad (9)$$

and the same as for the voltages of the other phases, which are given by

$$V'_a = 2/3(V_a - V_o) - 1/3[(V_b - V_o) + (V_c - V_o)] \quad (10)$$

$$V'_b = 2/3(V_b - V_o) - 1/3[(V_a - V_o) + (V_c - V_o)] \quad (11)$$

$$V'_c = 2/3(V_c - V_o) - 1/3[(V_a - V_o) + (V_b - V_o)] \quad (12)$$

The line-to-line voltages at the inverter terminals are given by

$$V_{ab} = V'_a - V'_b \quad (13)$$

$$V_{bc} = V'_b - V'_c \quad (14)$$

$$V_{ca} = V'_c - V'_a \quad (15)$$

In order to obtain the voltage supply of the asynchronous machine in a two-phase system (d, q), the Park transformation is used.

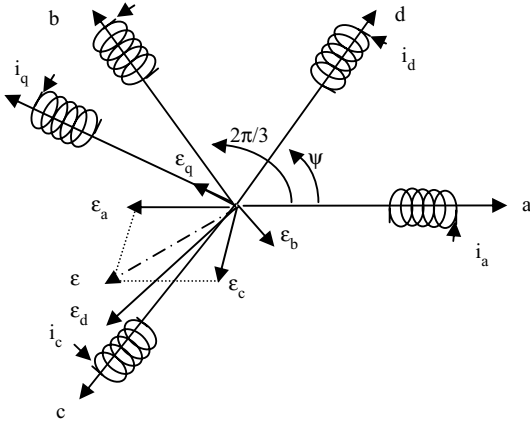


Fig. 4. Three phase system (*Oabc*) and bi-phase system (*Odq*).

$$[V_{dq}] = [P(\psi)][V'_{abc}] \quad (16)$$

where $[P(\psi)]$ is known as matrix of park given by the relation below.

$$P(\psi) = \frac{1}{\sqrt{3}} \begin{bmatrix} \cos \psi & \cos(\psi - 2\pi/3) & \cos(\psi + 2\pi/3) \\ -\sin \psi & -\sin(\psi - 2\pi/3) & -\sin(\psi + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (17)$$

5. Modeling of the asynchronous machine

The asynchronous machine is presented by a model brought back to a system of axis *d*, *q*, as shown in Fig. 4, obtained by a transformation of Park of a three-phase system into a two-phase system [4].

For simplification purpose, we put thereafter $[P] = [P(\psi)]$, and by applying the linear transformation $[P(\psi)]$ we obtain

$$[P]^{-1}[V_{dqo}] = [R][P]^{-1}[i_{dqo}] + (d/dt)\{[P]^{-1}[\phi_{dqo}]\} \quad (18)$$

After simplification, we obtain

$$[V_{dqo}] = [R][i_{dqo}] + (d/dt)[\phi_{dqo}] + [P](d[P]^{-1}/dt)[\phi_{dqo}] \quad (19)$$

where

$$[P](d[P]^{-1}/dt)[\phi_{dqo}] = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} (d\psi/dt) \quad (20)$$

Thus we obtain the system of Park equations which constitutes a dynamic model for a diphasic winding.

$$V_d = ri_d + d\phi_d/dt - (d\psi/dt)\phi_q \quad (21)$$

$$V_q = ri_q + d\phi_q/dt + (d\psi/dt)\phi_d \quad (22)$$

$$V_o = ri_o + d\phi_o/dt \quad (23)$$

It is supposed that the *D* axis is interdependent with the $\vec{O}_a$ axis from where $\Psi = 0$, thus the Eqs. (21), (22) and (23) become

$$V_d = ri_d + d\phi_d/dt \quad (24)$$

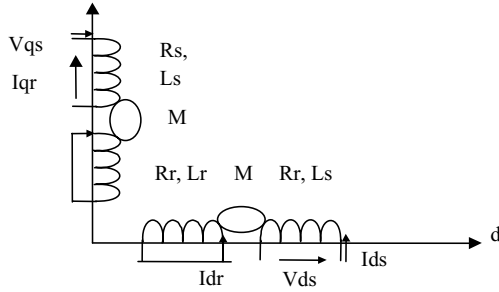
$$V_q = ri_q + d\phi_q/dt \quad (25)$$

$$V_o = ri_o + d\phi_o/dt \quad (26)$$

The V_o component is cancelled when the system is balanced, i.e. the sum of the components (*a*, *b*, *c*) is null.

After establishment of the relations between flux, the currents of the *d*, *q* axes and the (*a*, *b*, *c*) axes [4], we obtain

$$\begin{bmatrix} \phi_{sd} \\ \phi_{sq} \\ \phi_{rd} \\ \phi_{rq} \end{bmatrix} = \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \quad (27)$$

Fig. 5. Fictitious winding of (d, q) axes.

where L_s , L_r and M are respectively stator inductance, rotor inductance and the mutual inductance between the stator and the rotor. This leads us to represent fictitious winding of the D and Q axes in Fig. 5.

The voltage equations of the asynchronous machine (Fig. 6) in the (d, q) axes system are given as follows:

$$V_{sd} = R_s i_{sd} + d\phi_{sd} / dt \quad (28)$$

$$V_{sq} = R_s i_{sq} + d\phi_{sq} / dt \quad (29)$$

$$V_{rd} = R_r i_{rd} + (d\phi_{rd} / dt) - (d\theta_r / dt) \phi_{rq} = 0 \quad (30)$$

$$V_{rq} = R_r i_{rq} + (d\phi_{rq} / dt) + (d\theta_r / dt) \phi_{rd} = 0 \quad (31)$$

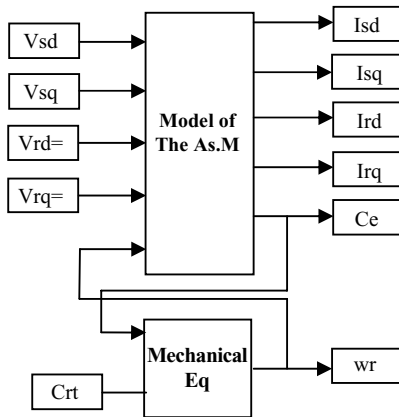


Fig. 6. Functional scheme of the model of the asynchronous machine and its mechanical load.

θ_r the electrical angle of the rotor relatively to the D axis.

In our model θ_r is null ($\theta_r = 0$), i.e. the case of the study of stator sizes.

After developing the flux as functions of currents, the final model of the asynchronous machine is represented by the following equations:

$$V_{sd} = R_s i_{sd} + L_s (di_{sd} / dt) + M (di_{rd} / dt) \quad (32)$$

$$V_{sq} = R_s i_{sq} + L_s (di_{sq} / dt) + M (di_{rq} / dt) \quad (33)$$

$$0 = V_{rd} = R_r i_{rd} + L_r (di_{rd} / dt) - M (di_{sd} / dt) + (L_r \omega_r i_{rq} + M \omega_r i_{sq}) \quad (34)$$

$$0 = V_{rq} = R_r i_{rq} + L_r (di_{rq} / dt) - M (di_{sq} / dt) + (L_r \omega_r i_{rd} + M \omega_r i_{sd}) \quad (35)$$

The electromagnetic couple is given by:

$$P_m = C_e \Omega \quad (36)$$

where C_e , the electromagnetic couple; ($\Omega = \omega_r / p$: angular velocity of rotation); ω_r , angular velocity of the rotor; p , numbers of pair of poles; the scalar expression of the electromagnetic couple is found as

$$C_e = pM [i_{sq} i_{rd} - i_{rq} i_{sd}] \quad (37)$$

6. Modelling of the centrifugal pump

Any pump is characterized by its absorptive power which is obviously a mechanical power on the shaft coupled to the pump, which is given by [6,7]

$$P = \frac{\rho g H Q}{\eta} \quad (38)$$

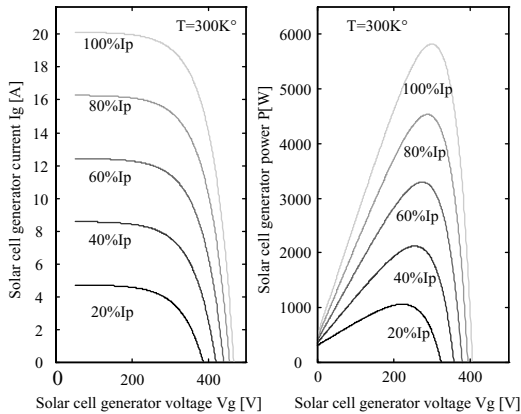


Fig. 7. Characteristics of a solar cell generator.

Useful power: power consumed of the absorptive power is given by

$$P_u = \rho g H Q \quad (39)$$

where η , the total output.

$$\eta = \frac{P_u}{P} \quad (40)$$

where ρ , density (Kg/m^3); G , acceleration of gravity (m^2/S); H , height of rise (m); Q , flow (m^3/S).

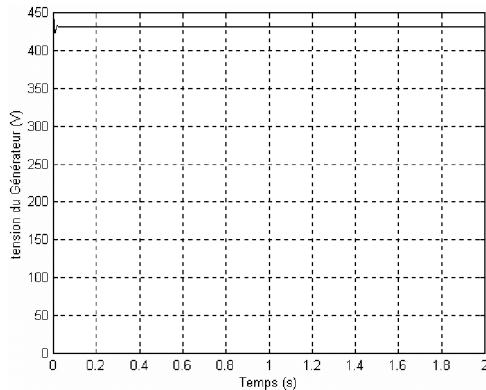


Fig. 8. Voltage of the photovoltaic generator.

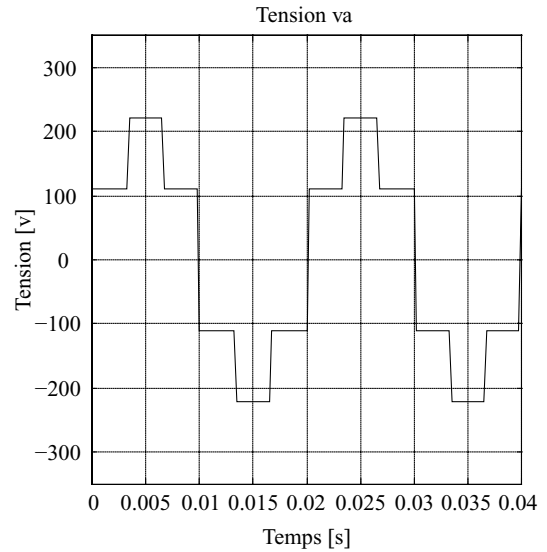


Fig. 9. Line voltage of the inverter.

7. Results of simulation

By modelling and simulating separately each part of the system under a specific condition, we had an idea on each part a side the results of the simulations are shown in Figs. 7–14. The interconnection between the various parts constituting the system can be simulated under the same conditions. In order to validate the results obtained,

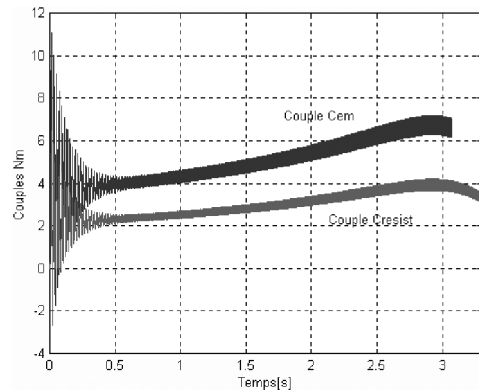


Fig. 10. Electromagnetic torque.

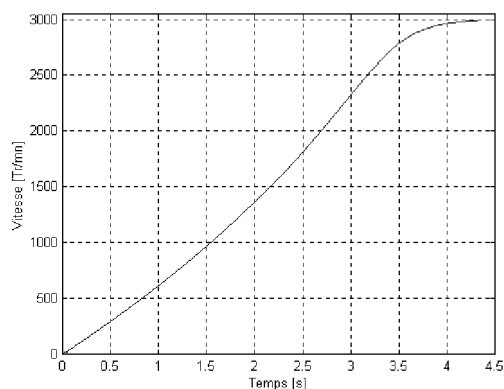


Fig. 11. Rotation speed (r/min).

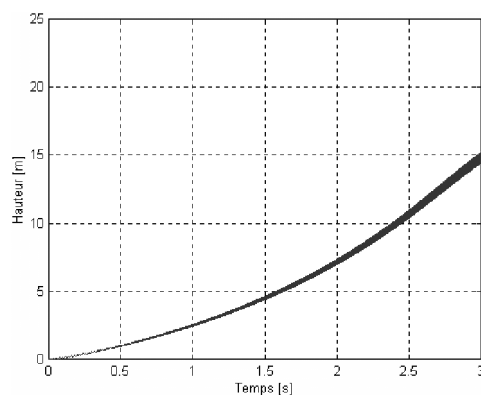


Fig. 13. Height (m).

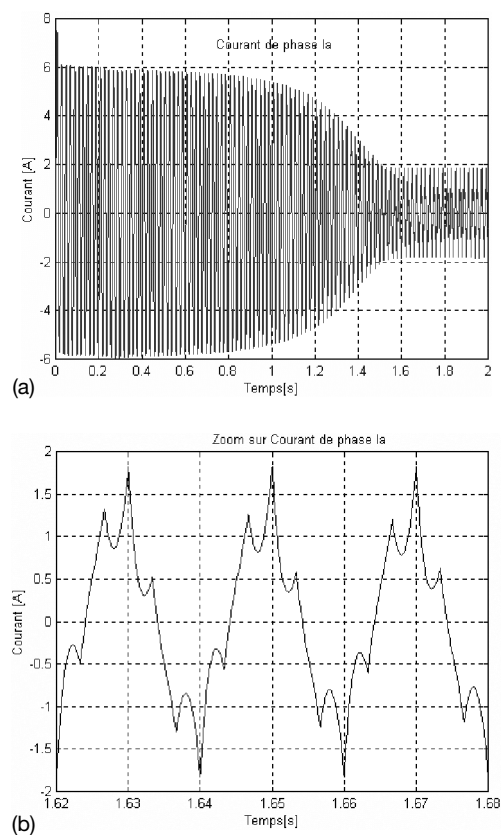


Fig. 12. Stator current (A).

a comparison was made with the results of ref. [8].

8. Conclusion

- This work opens a window on the modelling and simulation of the photovoltaic pumping systems using Simulink under Matlab programming environment.
- The results obtained from the simulation of the system are satisfactory.

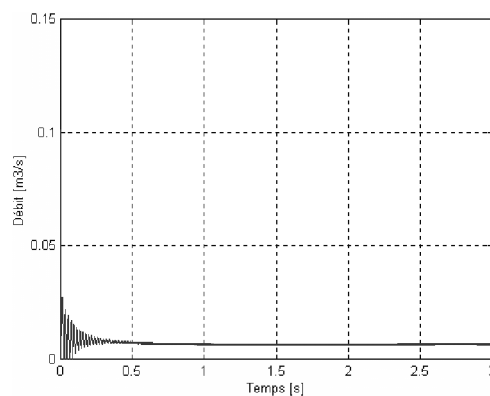


Fig. 14. Flow (m³/h).

- We estimate that this work will be a contribution to the analysis of the photovoltaic pumping system with regards to the results of simulation of the model.

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