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Water Pumping Using Solar Energy

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ABSTRACT

This article defines a simulation model of a simple system based essentially solar pumping of a photovoltaic generator and a DC motor with permanent magnet type of load as the centrifugal pump, in order to optimized the whole system it is necessary introduce a boost converter

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1. INTRODUCTION

The use of solar energy as a means of water pumping is one of the most promising applications of solar energy.

A greater focus has been devoted to ensure that solar pumping operation is reliable and economical, to do so, we must extract the maximum solar energy possible and have a good system design.

Solar pumping by a DC motor via a DC-DC converter is commonly used since the DC motor is simple to use and more efficient with low loads. Furthermore it can be connected directly without any inverter because the energy produced by the photovoltaic generator is considered continuous.

The solar pumping system generally includes the PV generator, a DC-DC converter, the DC motor and the pump. Before starting the modeling of the entire system, we model each component alone.

The use of solar energy for pumping means to determine the solar radiation for a variety of angles with the horizontal, and a variety of angles with respect to the solar south. Radiation on inclined surfaces must be calculated, while measures of radiation on horizontal surfaces are available for many places.

We will discuss the main basic concepts for solar pumping.

1.1. Radiation

The data of global radiation measured each day are available for multiple locations and latitudes in most industrialized countries, these data are then reduced by the monthly average brightness index
The extraterrestrial radiation is the solar radiation before it reaches the atmospheric layer. The extraterrestrial radiation on a horizontal surface H_0 for the given day n is obtained by the following equation [1] [2]:

$$H_0 = \frac{86400 G_{SC}}{\pi}\left(1+0.033\cos\left(\frac{2\pi}{365}\right)\right)\left(\cos\psi\cos\delta\sin\omega_s + \omega_s\sin\psi\sin\delta\right) \quad (1)$$

While G_{SC} is the solar constant which is equal to 1367 W/m^2 ψ is the hour angle of the sun which depends on latitude of the project location specified by the user.
δ is the declination angle, it is function of the day *n* of the year and is given by *Coper* formula [1][2].

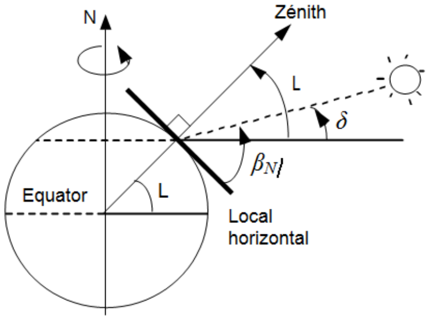

Figure 1. Importants Angles Solaires

$$\delta = 23.45 \sin\left(\frac{2\pi(284+n)}{365}\right) \quad (2)$$

For January the first *n*=1. ω_s is the hour angle of the sun at sunset, is given by the following equation:

$$\omega_s = \cos^{-1}\left(-\tan(\delta)\tan(\psi)\right) \quad (3)$$

$$\text{The clarity index } \overline{K}_T = \frac{\overline{H}}{\overline{H}_o} \quad (4)$$

$\overline{H}$ is the monthly average of daily solar radiation on a horizontal plane [kWh/m^2/j]
$\overline{H}_o$ is the monthly average of extraterrestrial radiation on the same horizontal surface [kWh/m^2/j].

Solar radiation has two components direct sunlight, emitted by the solar disk and diffuse solar radiation emitted by the rest of the sky.

The theory of computation on an inclined surface requires knowledge of direct and diffuse solar access for each hour on an average day.

The monthly average of the daily diffuse solar radiation from the monthly average of the daily global insolation H and using the correlation of Erbs [1] [2]:

for $\omega_s \le 81.4^o$ et $0.3 \le \overline{K}_T \le 0.8$

$$\frac{\overline{H}_d}{\overline{H}} = 1.391 - 3.56\overline{K}_T + 4.189\overline{K}_T^{\,2} - 2.137\overline{K}_T^{\,3} \quad (5)$$

and for $\omega_s > 81.4^o$ et $0.3 \le \overline{K}_T \le 0.8$

$$\frac{\overline{H}_d}{\overline{H}} = 1.311 - 3.022\overline{K}_T + 3.427\overline{K}_T^{\,2} - 1.821\overline{K}_T^{\,3} \quad (6)$$

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\left(\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s}\right) \quad (7)$$

$$a = 0.409 + 0.5016 \sin\left(\omega_s - \frac{\pi}{3}\right) \tag{8}$$

$$b = 0.6609 - 04767 \sin\left(\omega_s - \frac{\pi}{3}\right) \tag{9}$$

r_t is the ratio of the hourly value of the total daily global insolation.

ω_s Is the hour angle of the sunset in radians.
ω is the sun angle for the middle of the hour with the formula of Liu and Jordan for diffuse radiation H global horizontal insolation.
diffuse and direct components (H_d and H_b) are given by the following three formulas:

$$H_b = H - H_d \tag{10}$$

$$H_d = r_d \overline{H}_d \tag{11}$$

$$H = r_t \overline{H} \tag{12}$$

The hour insolation in an inclined plane of the PV array is obtained by using a model described in the manual of Duffie and Beckman [2]

$$H_t = H_b R_b + H_d \left(\frac{1+\cos\beta}{2}\right) + \rho H \left(\frac{1-\cos\beta}{2}\right) \tag{13}$$

ρ represents the coefficient of ground diffuse light reflection (ground albedo)
β PV array inclination.
R_b is direct insolation on the PV array divided by direct insolation on the horizontal.

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{14}$$

θ is the direct insolation incidence angle on the PV array and θ_z is the sun zenith angle.

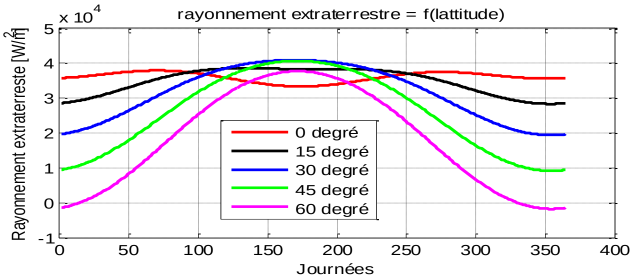

Figure 2. Extraterrastrial radiation

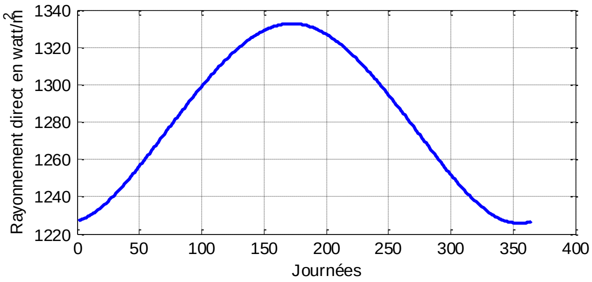

Figure 3. Direct Radiation (W/m^2)

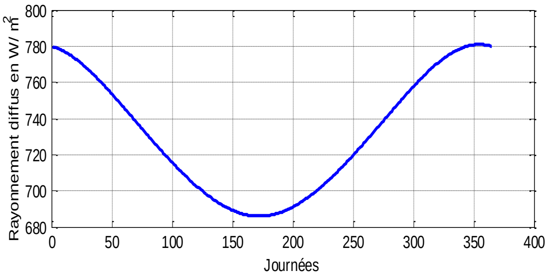

Figure 4. Diffuse Radiation (W/m2)

2. PHOTOVOLTAIC GENERATOR MODLING

The scientific community offers several models for the photovoltaic generator. The standard model with a single diode and a single cell, then generalizing to a PV module by considering it as a set of identical cells connected in series-parallel (commonly used) Figure (5a).

The equivalent circuit of the general model consists of a current source, a diode, a parallel resistor due to leakage currents and a series resistance and describing a current flow internal resistance as shown in "Figure 5a".

The voltage-current characteristic equation of a photovoltaic cell is given as follows:

$$I_g = I_{ph} - I_D - I_{sh} = I_{ph} - I_0\left(\exp\left(\frac{q\left(V_g + R_S I_g\right)}{nkT_C}\right) - 1\right) - \frac{\left(V_g + R_S I_g\right)}{R_{Sh}} \quad (15)$$

For a photovoltaic generator made up of series cells *Ns* and parallel cells *Np*. (15) becomes [3]:

$$I_g = N_P\left(I_{ph} - I_0\left(\exp\left(\frac{q\left(\frac{V_g}{N_S} + R_S\frac{I_g}{N_P}\right)}{nkT_C}\right) - 1\right) - \frac{\frac{V_g}{N_S} + R_S\frac{I_g}{N_P}}{R_{sh}}\right) \quad (16)$$

V_g, I_g Panel output voltage [V] and current [A].
I_{ph} Photocurrent in ampère.
R_S series resistance in ohm, R_{Sh} shunt resistance in ohm.
q electron charge q=1.602.10^{-19} coulomb
k Boltzmann constant = 1.381.10^{-23} J/K.
n Quality factor of the diode, between 1 et 2.
the shunt resistance R_{sh} is considered of high value, the current I_{sh} tends to zero, the previous equation becomes [Figure 1-c]:

$$I_g = I_{ph} - I_D = I_{ph} - I_0\left(\exp\left(\frac{q\left(V_g + R_S I_g\right)}{nkT_C}\right) - 1\right) \quad (17)$$

For an ideal cell « Fig1.d » R_{sh} and R_s can be neglected. (17) can be simplified to [3]:

$$I_g = I_{ph} - I_D = I_{ph} - I_0\left(\exp\left(\frac{qV_g}{nkT_C}\right) - 1\right) \quad (18)$$

$$I_g = N_P \left(I_{ph} - I_0 \left(\exp\left(\frac{qV_g}{N_S nkT_C} \right) - 1 \right) \right) \quad (19)$$

Provided that each cell has the same parameters, the terminal voltage can be rewritten from the above equation.

$$V_g = \frac{N_S nkT_C}{q} \ln \left(\frac{I_{PH} - \frac{I_g}{N_P}}{I_0} + 1 \right) \quad (20)$$

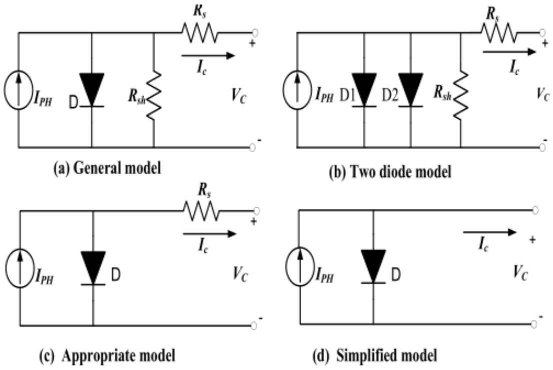

Figure 5. Different Models of the PV Generator

The current source depends mainly on radiation and operating cell temperature, which is described as follows:

$$I_{PH} = \frac{G}{G_{ref}} \left[I_{sc} + \mu_{I,SC} \left(T_c - T_{c,ref} \right) \right] \quad (21)$$

while *Isc* represents cell short circuit current at 25 °C and 1kW/m^2
$\mu_{I,SC}$ short circuit cell temperature coefficient $T_{c,\ ref}$ is the cell reference temperature and G is the solar radiation in W/m^2, on the other hand the saturation current varies with the temperature of the cell, it is described as follows:

$$I_0 = I_{0,ref} \left(\frac{T_c}{T_{c,ref}} \right)^3 \exp\left[\frac{qe_{gap}}{nk} \left(\frac{1}{T_{c,ref}} - \frac{1}{T_c} \right) \right] \quad (22)$$

$I_{0,ref}$ reverse saturation current at the reference temperature. The width of the band gap e_{gap} for the semiconductor material, for silicon equal to 1.11 eV.
The temperature of the cell is calculated by:

$$T_c = T_a + \frac{G}{800} \left(NOCT - 20 \right) \quad (23)$$

T_a Ambient temperature °C.
$NOCT$ Nominal operation cell temperature in °C.
The two diodes model is widely used, its equivalent circuit is shown in Figure 5-b. [3] [4] the *I(V)* characteristic is :

$$I_g = I_{PH} - I_{D1} - I_{D2} - I_{Rh} = I_{PH} - I_{s1}\left(\frac{q\left(V_g + R_S I_g\right)}{n_1 k T_C}\right) - I_{s2}\left(\frac{q\left(V_g + R_S I_g\right)}{n_2 k T_C}\right) - \frac{\left(V_g + R_S I_g\right)}{R_{Sh}} \quad (24)$$

3. CENTRIFUGAL PUMP

The centrifugal pump is highly appreciated in a solar pumping system, in fact the driving torque of the pump is virtually zero at startup, the pump runs while sunlight is very low.

Manufacturers of pumps provide the performance characteristic *H=f(Q).* [4]

The hydraulic network characteristic is given by :

$$h = h_0 + K_h Q^2 \quad (25)$$

h_0 is the static height and K_h is the canalization constant taking into consideration laminar and singular load losses.

The daily hydraulic power corresponds to the power needed for rising a daily volume Q (m^3/s) to the height H (en m).

$$P_H = \rho\ g\ Q\ H \quad (26)$$

g is the gravitation (9.81 m/s^2), ρ the water density (1000 kg/m^3).

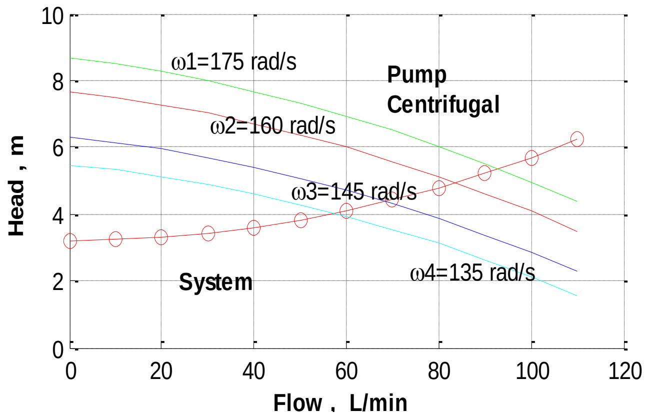

Figure 6. H (Q) Curve of the Pump and the Fluidic Network

The required absorbed power for its mechanical drive, is expressed by the relation

$$P_H = \frac{\rho\ g\ Q\ H}{\eta_p} \quad (27)$$

η_p is the pump efficiency.

4. BOOST CONVERTER

A boost converter increases the voltage supplied by the photovoltaic generator and decrease the number of cells needed to achieve the desired voltage level.

$$\frac{V_o}{V_i}=\frac{1}{1-\alpha} \tag{28}$$

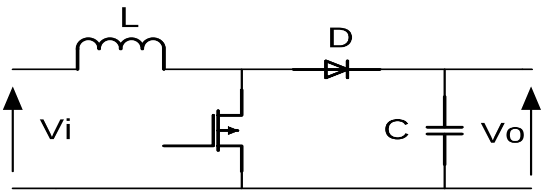

Figure 7. Convertisseur Survolteur

5. GLOBAL SYSTEM MODELING

The solar pumping system not optimized is a combination of three subsystems: a photovoltaic generator coupled directly to the DC motor with permanent magnet which drives the centrifugal pump.

This system is widely used because it does not require any storage battery, static converters or regulators; it has a simple control while brush collector system requires an alternate maintenance.

In transient regime, the resulting equations by this direct coupling are: [4] [5]

$$\begin{aligned} V_m &= e(\omega)+R_a i_a + L_a\frac{di_a}{dt} \\ T_m(i_a) &= T_l + J\frac{d\omega}{dt} \\ e(\omega) &= k_e\,\omega \\ T_m(i_a) &= k_e\, i_a \end{aligned} \tag{29}$$

By coupling the motor to the photovoltaic generator we have $V_m = V_g$ *and* $i_m = I_g$ as well $V_m i_a = V_g I_g$, in steady state, the torque-speed equation is given by:

$$\omega=\frac{V_g-\left(\frac{T_m}{k_e}\right)R_a}{k_e} \tag{30}$$

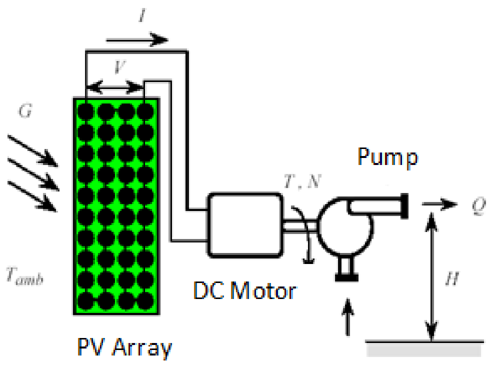

Figure 8. Diagram of Solar Pumping System Driven Directly by a DC MOTOR

The resistive torque of the centrifugal pump T_l is given by:

$$T_l = k_r \omega^2 + T_s \quad (31)$$

T_s The static torque

k_r Proportionality factor [N.m/(rd/s)^2]

6. CONCLUSION AND RESULTATS

The points Imax(1) and Imax(2) in the Figure9 designate the maximum power point (MPP) and is composed of the optimum voltage (VMPP) and the optimal current (IMPP) [4]. Maximum Power Point Tracking (MPPT) is an essential element in the photovoltaic system, which ensures optimal utilization of solar energy available. The problem considered by MPPT techniques is to find the voltage or current that should work to extract the maximum power.

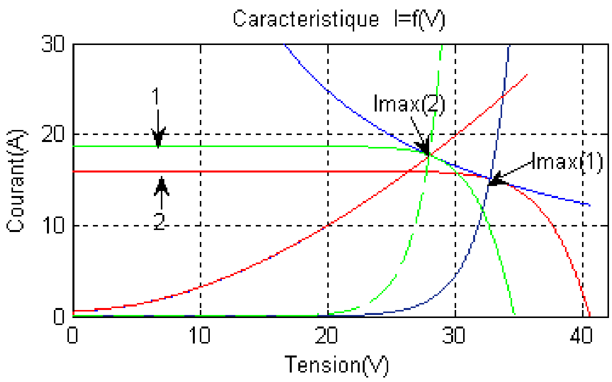

Figure 9. I-V Characteristic Before and After Optimization. (1), (2) Load Current and Maximal Current Curve Respectively for Two Levels of Illumination and Temperature. (E=800W/m2), (T=25°C)

The flow curve as a function of the illumination of the solar pumping system shows that a pump requires a threshold level of radiance to begin pumping water. This value changes from one system **to** another (in our case G = 400 W/m2).

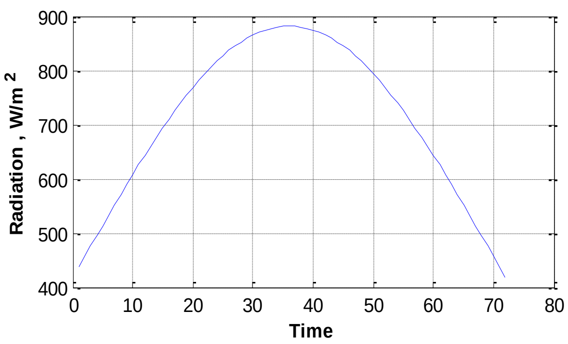

Figure 10. Irradiance as a Function of Time

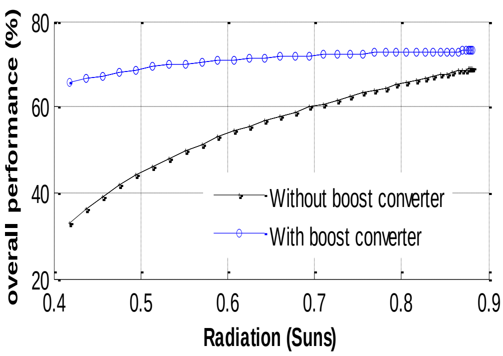

Figure 11. Overall Performance Based on Irradiance

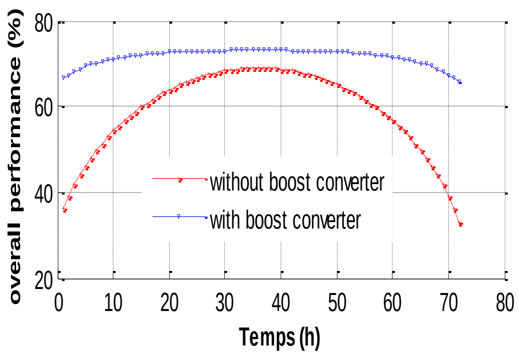

Figure 12. Overall Performance as a Function of Time

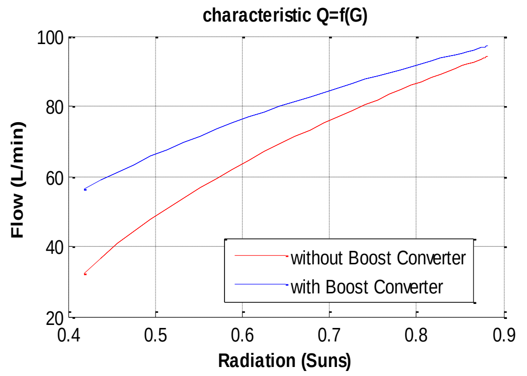

Figure 13. Water Flow Function of the Irradiance

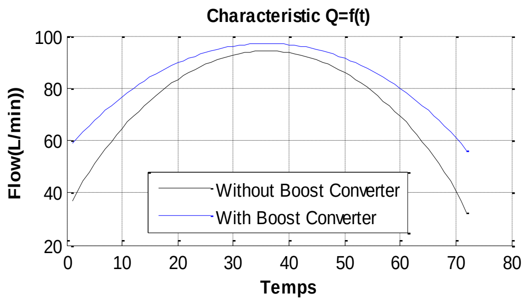

Figure 14. Water Flow in Function of the Time

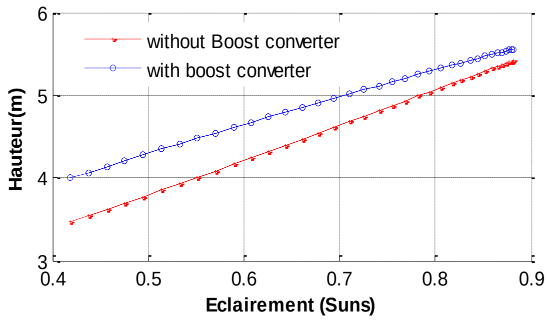

Figure 14. Height in Function of the Irradiance

The optimization system with the boost converter corrects the output of the motor that will work around an optimal operating point. The flow of water pumped is therefore improved.

The maximum power point tracking (MPPT) plays an important role in photovoltaic power systems because it maximizes the performance of photovoltaic system. The MPPT can also minimize the overall system cost, we also find that the optimization works best when the generator operates to low light during the nominal operation of the motor.

Appendix

Photovoltaic Generator Caracteristics (MSX60)

Paramètre	valeur
Maximal power	60 Watt
Voltage at maximum power	16.8V
current at maximum power	3.55A
Short circuit current	3.87A
Open circuit voltage	21 V

Electrical Motor Caracteristics

Paramètre	Valeur
Rated power	651 Watt
Rated voltage	31V
Rated curent	21A
Minimal current	9A
Rated speed	1700 (tr/min)
Motor constant Ke	0.0167 (V/t.m)
Torque constant Kt	0.0153(Kg.m/A)
Motor resistance Ra	0.24(Ω)

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