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Research Article

Design and Management of a Photovoltaic Pumping System

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Abstract – Solar energy is recognized as one of the most important renewable alternatives to electricity, especially in remote areas where solar energy is not available due to high line costs. This innovative and sustainable solution is becoming increasingly popular in many parts of the world due to its environmental and economic benefits.

The purpose of this research is to study water pumping using photovoltaic energy. Optimization algorithms are used to track the maximum power point and apply it to control step-ups in order to operate the photovoltaic system at maximum capacity and predict the impact of climate change on system performances. Powering the converter, powering the frequency converter and analysis of motor pump operation under the influence of climate change is presented and discussed however the control system credibility and effectiveness is proved by simulation results under MatLab/Simulink software.

Keywords –Renewable Energy, Photovoltaic Power Generation, Optimal Control, Asynchronous Machine, Centrifugal Pump, Simulation

I. INTRODUCTION

Power generation will be a big topic in the next few years. This is important in all sectors as developed countries have steadily increasing energy demands and developing countries have constant energy demands [1]. However, the world's electricity generation is largely based on fossil fuels, and depletion is inevitable due to the drastic depletion of these energy sources. Unfortunately, this power generation technology emits greenhouse gases and pollutes the atmosphere [2,3]. Starting from this problem, the best alternative solutions have focused on so-called renewable resources. Renewable resources represent a key strategic sector that dominates in terms of research and development[1][4-6]. Among renewable resources, photovoltaic solar systems are increasingly being used in various applications [7]. Let's take this opportunity to design a remote pumping system. The work presented in this document focuses on the application and development of motion analysis for photovoltaic pump systems. In fact, using solar energy to pump water in remote areas is an innovative and sustainable solution that is gaining popularity in many parts of the world. Photovoltaic systems, which convert solar energy into electricity, offer a reliable alternative to traditional energy sources such as fossil fuels and grid power. Solar pumps can help irrigate crops, provide drinking water to remote communities, and support other economic activities in areas with limited or no access to electricity. Furthermore, the technology is environmentally friendly and helps reduce greenhouse gas emissions, making it an attractive solution in the fight against climate change [8].

Installation of these systems depends on several factors, including the amount of water required, the depth of the well or groundwater source, the distance between the water source and water tank. Solar panels should be installed in sunny, non-shaded areas to ensure optimal energy production. The pump used in this work is a centrifugal pump. Installing and maintaining a solar water pump system requires some expertise, but is relatively easy and inexpensive compared to other energy sources. The advantages of this technology, such as low environmental impact and long life, make it an attractive solution for remote areas with limited or no access to electricity.

II. Structure of the Proposed Pumping System

The solar-powered water system under consideration, basically and as shown by figure. 1, consists of a solar panel, a power converter, a motor pump, and a storage tank for the pumped water. The considered pumping system consists of connected asynchronous machine (*AsM*) and a centrifugal pump. The *AsM* is often used for speed control operation because it has a frequency converter power supply [9]. For voltage-fed three-phase asynchronous motors case, the stator voltage components U_{ds} and U_{qs} and the rotating field speed are considered as control variables, and the resistant torque C_r is considered a disturbance variable [10].

These systems are relatively easy to operate. Solar panels convert the sun's energy into electricity, powering pumps that draw water from wells and groundwater sources. Water is stored in tanks for later use, such as irrigation or human consumption cases.

III. Modelling of the Photovoltaic Generator

The equivalent circuit diagram of a real solar cell considering the manufacturing-related parasitic resistance effects is shown in Figure 2 [11],[12]. This equivalent scheme consists of a diode (*D*) characterizing the interior *PN* junction, a current source (I_{ph}) characterizing the photocurrent, a series resistance (R_s) representing Joule effect losses, and a shunt resistor (R_{sh}) representing leakage. The chip-to-chip current, representing the gate and back contacts, is typically much higher than R_s value.

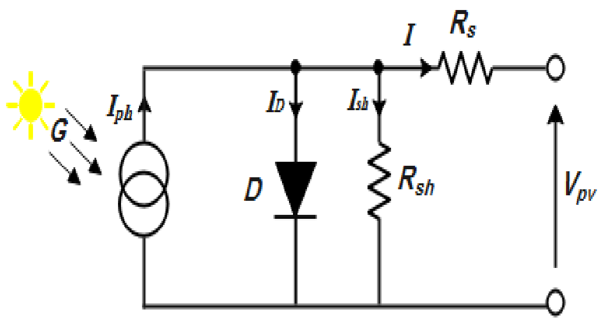

Fig. 2 Electrical circuit of a real photovoltaic cell

According to the circuit and applying Kirchhoff's law, we find that [13],[14]:

$$I = I_{ph} - I_D - I_{sh} \quad (1)$$

As long as I_ph is proportional to the solar irradiance as shown in equation [15]:

$$I_{ph} = [I_{rs} + K_i(T - T_r)]\frac{G}{G_r} \quad (2)$$

where;

$$I_{rs} = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left(\frac{q\,E_g}{K\,A}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right) \quad (3)$$

On the other hand, the current through the diode I_D is explained in the following relationship [16]:

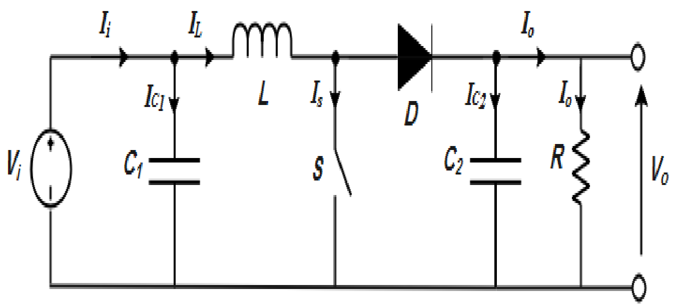

Figure. 3 Basic electrical circuit of a boost converter

$$I_D = I_s\left[exp\left(\frac{q(V+IR_s)}{KT_cA}\right) - 1\right] \quad (5)$$

According to Kirchhoff's law, the current in the shunt resistor is expressed as:

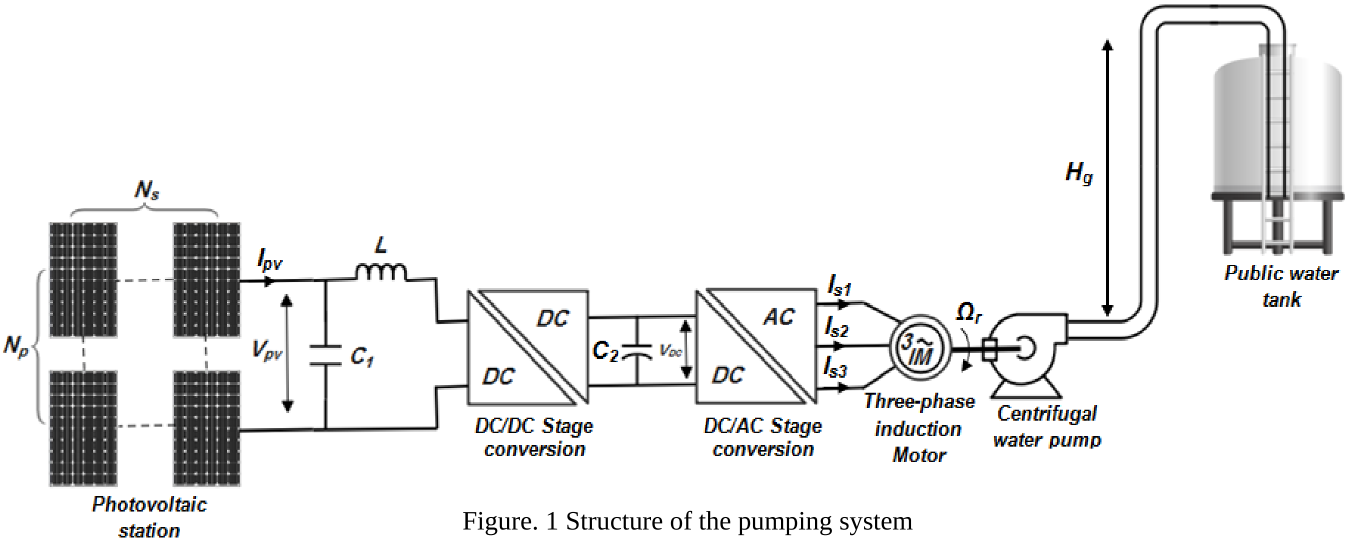

Figure. 1 Structure of the pumping system

$$I_{sh} = \left[\frac{V+IR_S}{R_{sh}}\right] \quad (6)$$

Solar cells generate low voltage (approximately 0.5*V*) and consume little power, so multiple cells must be combined. So, to form a solar panel, multiple cells are connected in series, parallel, or series-parallel (mixed) combinations to form a photovoltaic generator. When constituting of a solar panel, the model considers the number of cells grouped according to the formula:

$$I = N_p I_{ph} - N_p I_{rs}\left[e^{\frac{q\,(V+R_S\,I)}{A\,K\,T\,N_S}} - 1\right] - N_p\left(\frac{q\,(V+R_S\,I)}{R_S * R_{sh}}\right) \quad (7)$$

$$I_{rs} = \frac{I_{sc}}{\left[exp\left(\frac{q\,V_{OC}}{N_S\,K\,A\,T_C}\right)-1\right]} \quad (8)$$

With,

I: Cell current; *V*: Cell voltage; I_{ph}: Photoelectric current(sensitive to solar photon); R_s and R_{sh}: Resistances representing losses and material resistance; I_{rs}: Saturation current of the diode; I_{rr}: Short circuit current of the cell; *q*: Electron charge($1,6.10^{-19}$ *C*); *A*: Ideality factor of the diode; *K*: Boltzmann constant($1,38.10^{-23}$ *J/K*); *T*: Ambient temperature; T_r: Reference temperature (25°*C*); K_i: Short circuit temperature coefficient; *G*: Ambient irradiance; G_r: Reference irradiance (1000W/m^2); and E_g: Threshold energy.

IV. DC/DC and DC/AC control stages

The diagram in Figure 3 shows the circuit of a boost converter. Here, during the first time interval (αT), the transistor (*S*) closes and the current in the inductor gradually increases, storing energy until the end of the first period. The transistor is then open for (*T-αT*) and the inductance (*L*) across the current sink (I_L) produces a voltage that is added to the source voltage (V_i) applied to the load (*R*) via the diode (D) [17].

To get the maximum power from the solar panel, a maximum power point tracker (*MPPT*) is used to control the variation of the cell's current-voltage characteristic *I(V)*. MPPT control is therefore an important part of most PV systems [18]-[20]. In this work, a Perturb and Observe (*P&O*) control is used as the most widely used technique. This is due to its simplicity with few measured parameters. *MPPT* control based on *P&O* technology operates according to the following flowchart [21]-[22]

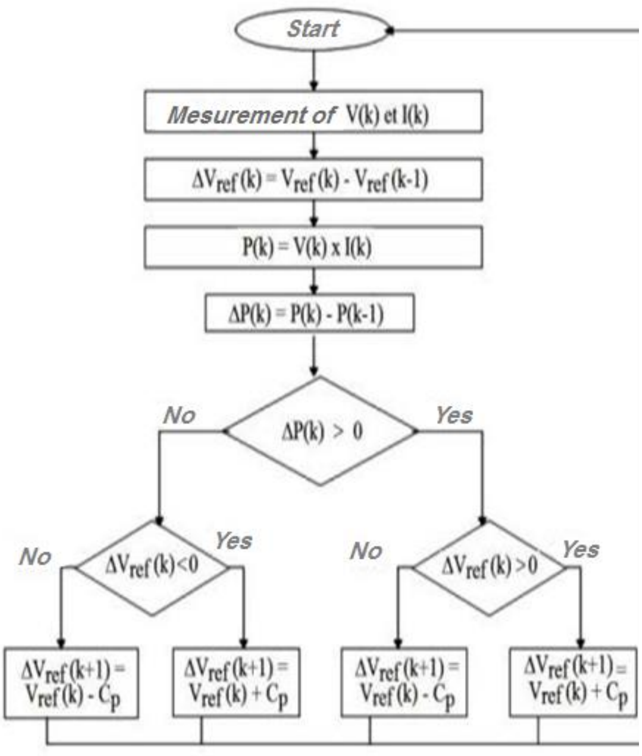

Figure. 4 Flowchart of the Perturb & Observe MPPT algorithm

Also, an inverter is used to convert the constant DC voltage supplied by the solar generator into an AC voltage with adjustable amplitude and frequency. The modelling of the three-phase voltage inverter is based on the interruption of the upper stage thyristors S_a, S_b, S_c and the intermediate circuit voltage V_{dc}, from which the simple voltage is obtained [23].

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (9)$$

The above model can be reformulated by the following system of equations:

$$\begin{cases} V_{an} = \frac{V_{dc}}{3}(2S_a - S_b - S_c) \\ V_{bn} = \frac{V_{dc}}{3}(-S_a + 2S_b - S_c) \\ V_{cn} = \frac{V_{dc}}{3}(-S_a - S_b + 2S_c) \end{cases} \quad (10)$$

Pulse Width Modulation (*PWM*) control consists of comparing two control signals (reference and carrier). It is characterised by the modulation index "*m*", equal to the ratio $m = f_p / fm$ and the voltage adjustment index $r = A_m / A_p$ where, (f_p) carrier frequency, (f_m) reference frequency, (A_m) reference amplitude and (A_p) carrier amplitude.

V. MODELLING OF THE PUMPING SYSTEM

Since, the stator voltages (U_{ds} and U_{qs}) and the speed of the rotating field are the control variables of the three-phase voltage-fed asynchronous machine, and the resistant torque C_r is the disturbance variable, the *AsM* state model can be expressed by the flowing expression [24],[25].

$$\dot{X} = A \,.\, X + B \,.\, U \quad (11)$$

With;

$$\dot{X} = \begin{bmatrix} di_{ds} \\ di_{qs} \\ d\phi_{dr} \\ d\phi_{qr} \end{bmatrix}$$

and,

$$A = \begin{bmatrix} -\lambda & \omega_s & \frac{K_s}{T_r} & \omega_r K_s \\ -\omega_s & -\lambda & -\omega_r K_s & \frac{K_s}{T_r} \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & \omega_s \omega_r \\ 0 & \frac{M}{T_r} & -(\omega_s \omega_r) & -\frac{1}{T_r} \end{bmatrix}$$

$$X = \begin{bmatrix} i_{ds} \\ i_{qs} \\ \phi_{dr} \\ \phi_{qr} \end{bmatrix} \quad \text{and,} \quad B = \begin{bmatrix} \frac{1}{\delta L_S} & 0 \\ 0 & \frac{1}{\delta L_S} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

and the control variable matrix *U*:

$$U = \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix}$$

We can also express the mecanical equations for both torque and speed by:

$$\begin{cases} C_e = \frac{3\,P\,M}{2\,L_r}\Big(\big(\phi_{dr} - i_{qs}\big) - \big(\phi_{qr} i_{ds}\big)\Big) \\ \frac{d\Omega_r}{dt} = \frac{1}{J}\big(C_e - C_r - (K_f \Omega_r)\big) \end{cases} \quad (12)$$

Where;

$T_r = \frac{L_r}{R_r}$; $\delta = 1 - \frac{M^2}{L_s\, L_r}$; $K_s = \frac{M}{\delta\, L_s\, L_r}$; $\lambda = \frac{R_s}{\delta\, L_s\, L_r} + \frac{R_r M^2}{\delta\, L_s\, {L_r}^2}$

As a definition, centrifugal pump is a hydraulic machine that transfers energy to fluids (especially liquids) by centrifugal force. These types of pumps differ in design, but the principle of operation is the same and the fluid dynamics are always the same. The main purpose of centrifugal pumps is to increase pressure and pump liquids [26].

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Centrifugal pumps are designed for a relatively fixed full load (*HMT*). Pump displacement (*Q*) varies proportionally with engine speed. Its torque increases very rapidly at this speed and the head is a function of the square of the motor speed. Therefore, very high engine speeds are required to ensure good flow. Besides, the energy consumption, which is proportional to *Q* and *HMT*, changes proportionally to the cube of the velocity. Centrifugal pumps are typically used at medium or shallow depths (10-100 meters) with high flow rates [27]-[29].

The operation of the centrifugal pump involves her three parameters: Lift, flow rate and speed.

$$f(H, Q, P) = 0 \quad (9)$$

During pump operation, the main types of losses are noted, in particular the normal pressure drop and the singular pressure drop, each of which is mathematically represented by the relationship:

$$\Delta H_1 = \lambda.\frac{V^2}{2.g}.\frac{L}{D} \quad (10)$$

$$\Delta H_2 = \varepsilon\frac{V^2}{2g} = \varepsilon\frac{8Q^2}{\pi^2 D^2 g} \quad (11)$$

With;

λ: Coefficient of linear pressure drop; *D*: Internal diameter of the pipe [*m*]; *V*: Average velocity of the fluid [*m/s*]; *g*: Acceleration of gravity [*m/s2*]; *L*: Length of the pipe [*m*]; ε: Coefficient of local pressure drop and *Q*: Volume flow [m^3/h].

Furthermore, a pump is defined by its total head (*H*), volumetric flow (*Q*), and power, hydraulic power (H_P), given by the relations [30]:

$$H(t) = H_m \cdot \left(\frac{N(t)}{N_m}\right)^2 \quad (12)$$

$$Q(t) = Q_m \cdot \left(\frac{N(t)}{N_m}\right) \quad (13)$$

$$H_P = \rho * g * Q * H \quad (14)$$

H: Total head achieved by the pump [m]; H_m: Maximum head [*m*]; *N(t)*: Instantaneous speed [*rpm*]; N_m: Maximum speed [*rpm*]; *Q(t)*: Instantaneous flow rate [*m3/s*]; Q_m: Maximum flow rate [*m3/s*]; ρ: Density of the liquid [*kg/m3*]; *g*: Acceleration of gravity [m/s^2].

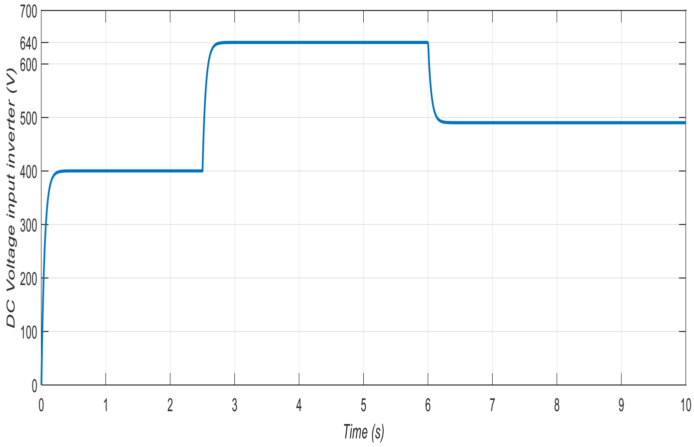
The centrifugal pump parameters introduced from our work are defined in the table below.

Table. 1. AsM and pump parameters

Nominal speed Ω_n	1500 *tr/min*
Nominal frequency F_n	50 *Hz*
Stator resistance R_s	4.850 *Ohm*
Rotor resistance R_r	3.805 *Ohm*
Cyclic stator inductance L_s	0.274 *H*
Cyclic rotor inductance L_r	0.274 *H*
Mutual inductance *M*	0.258 *H*
Moment of inertia *J*	0.031 $Kg.m^2$
Viscose friction coefficient K_f	0.00114 *N.m.s/rd*
Maximal flow Q_m	0.001 m^3/s
maximum height H_m	35 *m*
Nominal speed N_m	2800 *tr/min*
density of the liquid ρ	1000 kg/m^3
acceleration of gravity *g*	10 m/s^2

VI. Simulation Results and Discussion

This section is devoted to the verification of the proposal by analysing the behaviour of the whole photovoltaic pump system under varying solar irradiance conditions through numerical simulations. To do so, we considered a three-stage irradiance profile, as shown in Fig. 5, which ensures the variation of the DC voltage supplied by the photovoltaic array across the boost chopper. Under these climatic conditions, Figure 6 shows the evolution of the stator currents of an asynchronous motor driving a centrifugal pump. Note that they react according to the changes imposed. Two zooms are shown directly below. These were recorded as the lighting and DC voltage varied, sometimes 0.5 s and 6 s. Figures 7 and 8 show the pumped flow and hydraulic power respectively. This demonstrates an acceptable operation under the conditions of the climatic changes made during operation time.



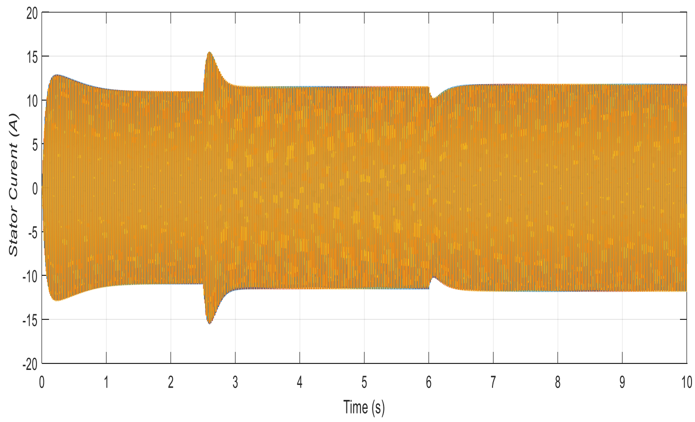
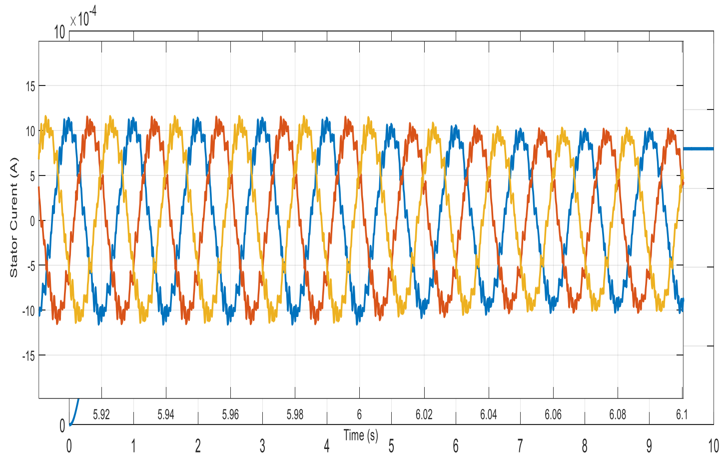


Fig 5. Input DC voltage of inverter



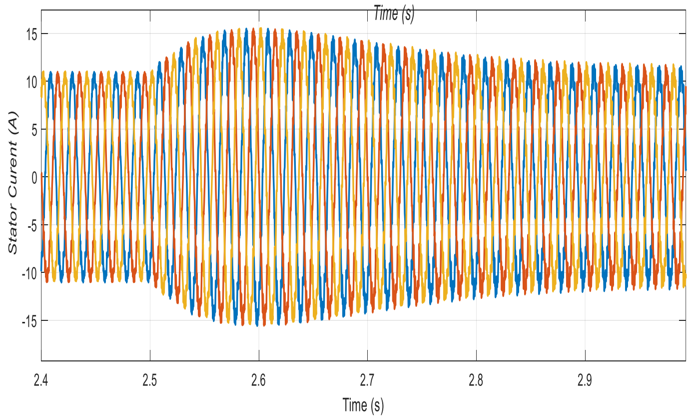


Fig 7. Pump water flow

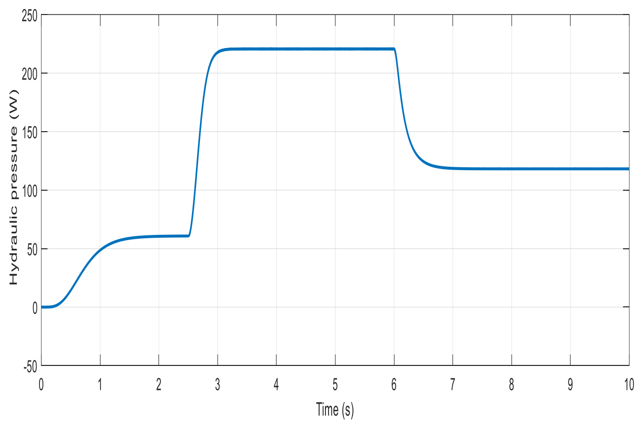


Fig 8. Hydraulic power

VII. Conclusion

Installing and maintaining a solar powered water collection system is relatively easy and inexpensive compared to other energy sources. This technology is an attractive solution for remote areas with limited or no access to electricity. Advantages of this technology include a lower carbon footprint, longer service life, and lower operating costs compared to traditional energy sources. Installing and maintaining a solar powered water collection system is relatively easy and inexpensive compared to other energy sources. This technology is an interesting solution for remote areas with limited or no access to electricity.

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