Modeling the Performance of the Photovoltaic (PV) Water Pumping Systems

نمذجة أداء نظم ضخ المياة الفوتوفولتية

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الملخص

يقترح البحث نموذج رياضي يمثل أداء منظومة ضخ المياة الفوتوفولتية .المنظومة المقترحة تعتبر من أفضل النظم المستخدمة لأنتاج الطاقة الكهربية النظيفة واللازمة لتشغيل مضخات المياة .تم أستنباط النموذج المقدم بأستخدام المعادلات الرياضية الأساسية والمعبرة عن أداء مكونات منظومة الضخ والممثلة بمصفوفة الخلايا الفوتوفولتية ومجموعة المحرك-طلمبة المياه .أيضاًتم أستنتاج نموذج رياضي أخر بمساعدة الماتلاب سميولنك .قد تطابقت النتائج المستخلصة من كلا النموذجين وهذا يثبت صحتهما.منظومة ضخ المياة الفوتوفولتية تحتوي على محرك تيار مستمرذو مغناطيس دائم يغذى مباشرةً من مصفوفة الخلايا الفوتوفولتية ،ومضخة المياة المستخدمة في المنظومة المقترحة من النوع المركزي . النماذج الرياضية يمكن أستخدامها بطريقة عامة لأي مكان معلوم خصائصه الشمسية لتحديد حجم المياة التي يمكن ضخها لمنظومة الضخ المستخدمة .وقد تم تطبيق المنظومة في قرية موجودة بالقرب من القاهرة .النموذج المقترح يمكن أستخدامة في تحديد مكونات المنظومة المقترحة وتحديد حجم المياة وحجم خزان المياة المستخدم لهذا الغرض .

Abstract

The research suggests a mathematical model which represents the performance of photovoltaic water pumping system. The suggested system is considered one of the best used systems for producing clean electric power that is necessary for operating water pumps. The proposed system has been extrapolated by using main mathematical equations which expressing the performance of pumping system's components which are represented the photovoltaic cells and the group of the water motor-pump. A Mat Lab/Simulink used to construct a same numerical model. The extracted results are the same from both model and these results approved their validity. The photovoltaic water pumping system includes permanent magnet DC motor (PMDM) that is fed directly by the photovoltaic cells. And the water pump used in this purposed system is (centrifugal) type. The mathematical models can be used generally for any place which their solar characteristic is known to determine the amount of water that can be pumped to the used pumping system. And the system was applied at a village near Cairo. The suggested model can be used in determining the components of the suggested system and determining the amount of water and the size of tank that will be used for this purpose.

Keywords:

PV model, Pump set model, PMDM, Minimum water tank design

List of symbols

I_D	:Diode saturation current (A)	G_o	:Nominal value of irradiance normally $1kW/m^2$
n	:Curve fitting constant	T_F	: Motor friction constant.
q	:Electron charge (1.602×10^{-19})(EV)	A_l	:Damping constant in (Nm s/ rad)
k	:Boltzmann's constant (1.381×10^{-23})(J/k)	ω	:Motor angular speed (rad/s)
T	:Cell temperature (k°)	T_{FL}	:Pump friction torque constant
I	:Cell current (A)	K_e	:Voltage constant in (V s/rad)
V	:Cell voltage (V)	Q	:Flow rate (m^3/s)
I_{LTr}	:Current in datasheet (measured at radiation of $1kW/m^2$)	ρ	:Water density 1000 (kg/m^3)
T_{ref}	:Reference temperature of PV cell (k°), usually (298k) (25c°)	g	:Earth gravity 9.81 ($m\ s^{-2}$)
a	:Temperature coefficient	D	:load speed dependent constant ($Nm\ s^2$)
K_T	:Torque constant (Nm/A)	A_l	:Damping Constant motor(Nm s/rad)
T_e	:Friction Constant for motor (Nm)	T_m	:Motor torque (Nm)
N_S	number of series cells	N_P	:Number of parallel cells

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I- Introduction

From food and energy security to human and environmental health, water contributes to improvements in social well-being and inclusive growth, affecting the livelihoods of billions [1]. Due to rich solar radiation and mild ambient temperature the stand –alone (PV) system is considered as one of the most promising application of renewable energy source to supply power areas [2]. Developing the grid system is often too expensive. Rural villages are frequently located too far away from existing grid lines; also depending on an imported fuel supply is difficult and risky, even if fuel is available. Transporting this fuel to remote rural villages is difficult. In rural areas of many developing countries, transportation of renewable energy systems, such as PV pumps is much easier than other types because they can be transported in pieces and assembles on site [3]. There are two types of water pumping systems classifications depending on the type of the pump used (AC or DC) and configuration of the system. There are two configurations: stand-alone and hybrid systems. Hybrid systems used two energy sources like wind or diesel generator with PV system. The most commonly utilized motor type with PV pumping systems is the Permanent Magnet Dc Motor (PMDM) [4]–[5]. Other brushed dc motors such as series, shunt, and separately excited motors have also been investigated [6]–[8].

Centrifugal and positive displacement is two types of pumps. Centrifugal is used in this paper due to capability to match with output of solar array. DC motor is a good choice that is not need an inverter (cost-effective) and used PMDM because there is no field current required for the development of magnetic field for motion and development of mechanical power [9]. DC motor pump set directly connected to PV generator is used in this paper.

II-PV Model

The solar array is considered the core of PV system that used to convert the solar radiation into electrical power. It is a few square inches in size and produces about one watt of power. The solar array or panel is a group of several modules electrically connected in series and parallel combinations to generate the required current and voltage.

Model generally consists of a current source I_L, a diode and series resistance R_s, and shunt resistance R_{sh} as shown in Figure1 [5].

Where the output terminal current I is equal to the difference between the light-generated current I_L, the diode current I_d and the shunt leakage current I_{sh} as shown in equation 1.

$$I = I_L - I_d - I_{sh} \qquad (1)$$

The series resistance R_s represents the internal resistance to the current flow and depends on the p-n junction depth, the impurities and contact resistance.

The shunt resistance R_{sh} is inversely related with leakage current to the ground. In an ideal PV cell, it is considered that there is no series or shunt resistance (R_s=0and $R_{sh}=\infty$). The PV conversion efficiency is sensitive to small variation in R_s but is insensitive to variation in R_{sh}. A small increase in R_s can decrease the PV output significantly .The open circuit voltage V_{oc} of the cell is obtained when the load current I equal zero and is given by the following [10]:

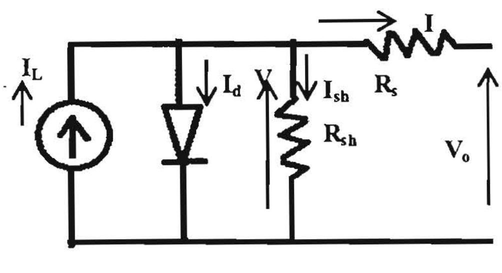

Figure 1: Equivalent circuit of PV array module.

$$V_{oc} = V + IR_S (2)$$

The diode current is given by the classical diode current expression:

$$I_d = I_D\,[\exp(qV_{oc}/nkT)-1] \quad (3)$$

Therefore the load current is given by the expression:

$$I = I_L - I_D\,[exp(qV_{oc}/nkT) - 1] - (V_{oc}/R_{sh}) (4)$$

The last term, the ground leakage current I_{sh}, in practical cells is small compared toI_L and I_D

and can be ignored then the load current equation becomes:

$I = I_L - I_D\,[exp\,(q\,(V + IR_S)/nkT) - 1]$ (5)

It is known that the current powered from array affected by the temperature and irradiance. Therefore the new I_L current at temperature T should be calculated by:

$I_{LTs} = I_{LTr}.\,[1 + a(T - T_{ref})]$ (6)

Also the short circuit current I_L is proportional to the amount of irradiance G which can be calculated by:

$I_{LG} = (G/G_o)\,I_{LGo}$ (7)

The value of I_D at the reference temperature T_{ref} is given by equation 8.

$I_D = [I_L/\,(exp\,(qV_{oc}/nkT)) - 1]$ (8)

The output voltage V_{ay} of the array can be calculated by:

$V_{ay} = N_s nkTq^{-1} ln[(1 + I_D^{-1} I_L G G_o^{-1}[1 + a(T - T_{ref})]) - I_D^{-1} N_p^{-1} I_{ay}] - N_p^{-1} I_{ay} R_s$ (9*)

Where; I_{ay} is the array current. It is noted from equation 9* the output voltage is considered as a function of G, T, N_S, N_P

III- Modeling the Pump set

The pump set generally consists mainly of an electrical DC motor coupled with a pump. Each one will be discussed as follow.

a -DC Motor

The permanent magnet DC motors are considered the best choice for the PV pumps systems located in remote applications where the minimum maintenance is required [2].

The motor torque load equation $T_M$is given by equation 9.

$T_M = T_F + A_1\omega(9)$

b- Centrifugal pump

This type of pump contains multi-stages to accommodate higher total head and higher volume flow rate [3].Centrifugal pumps are the best suited for PV direct coupling. The load torque T_L of the used centrifugal pump is given by:

$T_L = T_{FL} + D\omega^2$ (10)

The electric torque T_{elc} must be equals the sum of the load motor torque T_M and the load pump torque T_L which is given by the following equations.

$T_{elc} = T_e + A_1\omega + D\omega^2$ (11)

$T_e = T_F + T_{FL}$ (12)

$T_{elc} = K_T I$ (13)

The motor current I can be calculated by

$I = \frac{V_a - K_e\omega}{R_a}$ (14*)

The input terminal voltage V_a of the electrical motor of the pump set is given by

$V_a = R_a K_T^{-1}[(A_1 + K_e K_T R_a^{-1})\omega + D\omega^2 + T_e]$ (14**)

Equation 14 shows that the input voltage is function of R_a, T_e, A_1, K_e, K_T, D, ω.

The useful power P_u required for lifting the water and the discharge flow rate Qare given by equations 14 and 15 respectively:

$P_u = D * \omega^3$ (14)

$Q = P_u/(3600 * \rho * g * H)$ (15)

IV-PV directly coupled with Water Pump set

Figure 2 shows the schematic diagram of the pump set coupled with the PV.

On the case of the PV directly coupled with the pump set the voltages of PV and motor pump set are equals and are computed by equaling the equations 9* and 14**. The operation point of the whole system will be obtained (Figure3).

Also from the intersection point all performance of the system could be investigated such as the input and output power, the useful power Pu and the flow rate Q.

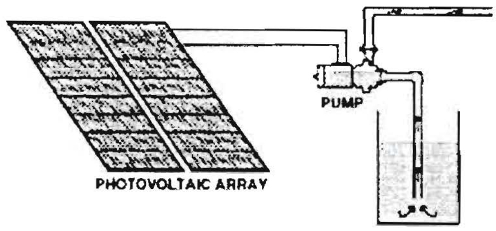

Figure 2: The system proposed.

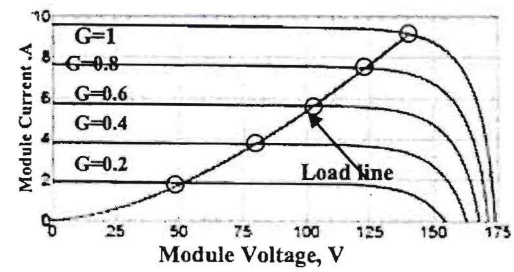

Figure 3: Operation points of PV water pump system at different solar radiation levels

In the following section the authors used the previous equations of the systems for building a Mat lab model Simulink for the system.

V- Mat lab Simulink Model of PV Water Pumping System

The proposed PV pump set models simulated by Mat lab Simulink and demonstrated in Figure 4. The built model takes into account the effect of irradiance G, temperature T and number of series parallel combination of photovoltaic modules N_S and N_P.PV pump set parameters which are listed in Table 1 are used as an input for the simulation.

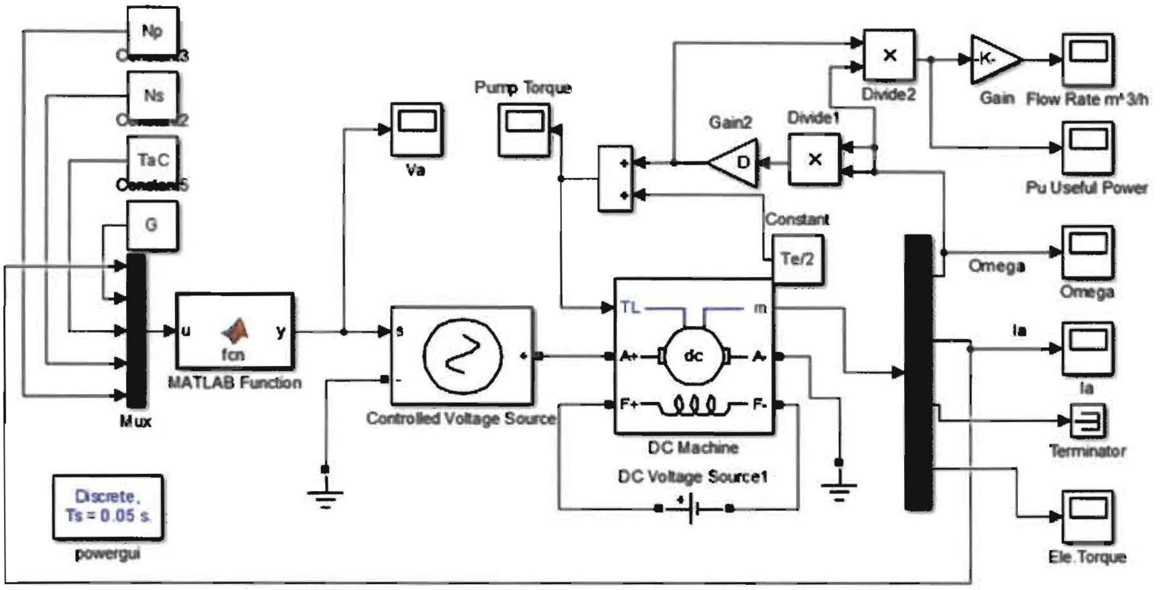

Figure 4: Simulink model of photovoltaic water pump system.

Table 1: PV Pump set Parameters [11]

Variable	R_a [Ω]	T_e [Nm]	A_l [Nm s/rad]	$K_e(=K_T)$ [Nm/A]	D [Nm s^2]	G [kW/m^2]	T [C°]	N_P	N_S
Value	**4.24**	**3.67x10^{-2}**	**3.82x10^{-3}**	**0.9212**	**6.57x10^{-4}**	**1**	**25**	**2**	**288**

VI- Case Study and Results Discussion

The transient results of the PV pump set system are given in Figures 5 to 10.The system needs 40 second to reach its steady state value. This time depends on the electrical and mechanical time constants of the PV pump set system.

The starting current of any dc machine is too high so it must be usually a method of reducing this current. In the proposed PV pump set system there is no need to use a method of starting at the moment at which the load current goes to be more than the PV short circuit current the PV voltage goes to zero value, this leads to reduce the load current. This process is repeated several times until it reaches to steady state as demonstrated in Figures 5 and 6.

The PV works like a constant current controller as shown in Figure 5. The variation of the voltage due to the previous oscillations is shown in Figure 6.

The pump speed, the electrical torque, the useful power and the corresponding flow rate of water versus time are given in Figures 7, 8, 9 and 10 respectively.

The I-V curves for the PV at different radiation levels G with temperature are shown in Figures11 and 12.

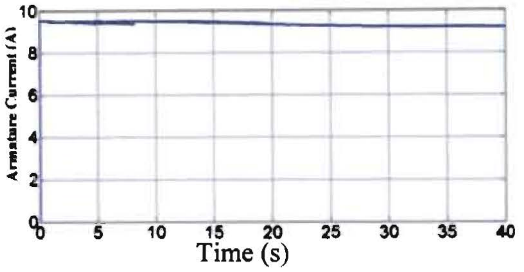

Figure 5: Armature current (Ia) versus time.

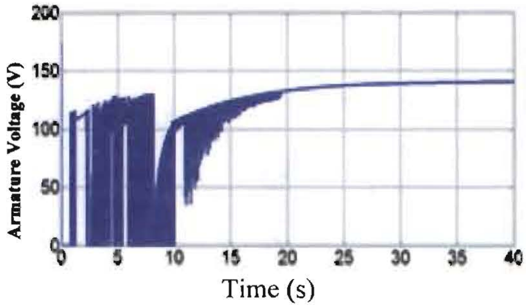

Figure 6: Armature voltage versus time.

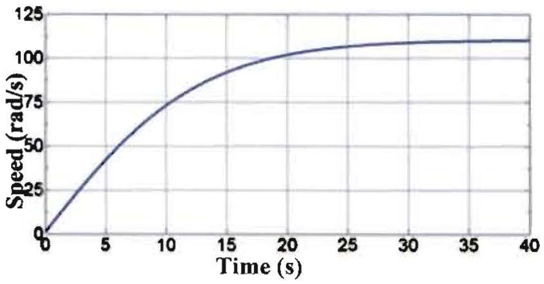

Figure 7: Pump Speed versus time.

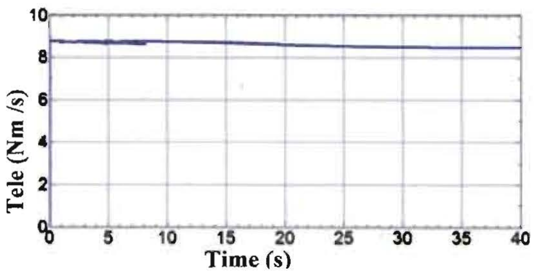

Figure 8: Electric Torque versus time.

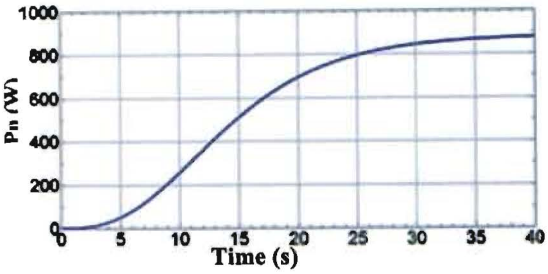

Figure 9: Useful power versus time.

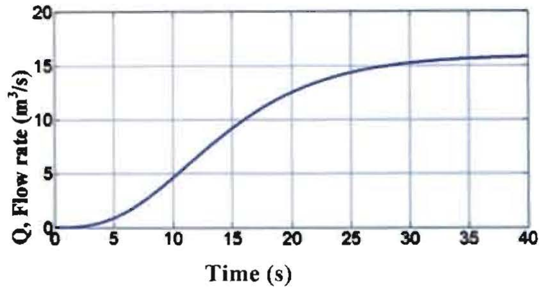

Figure 10: Flow rate versus time.

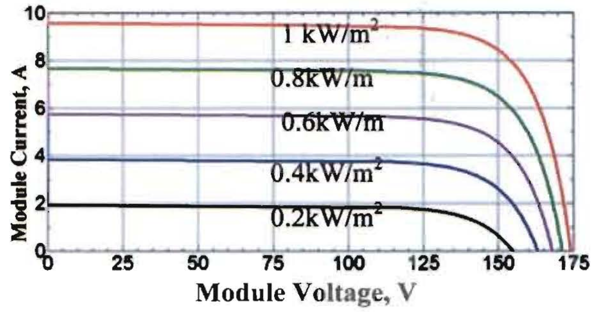

Figure 11: IV curves at different solar radiation levels ($T=25c^0$)

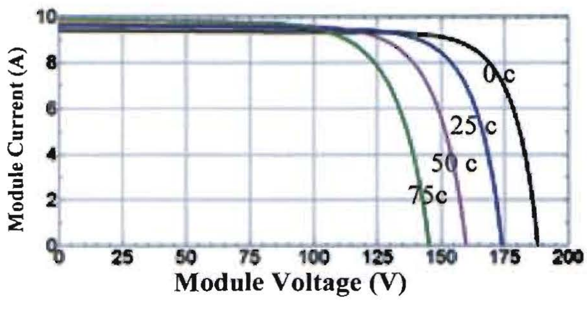

Figure 12: IV curves at different ambient temperatures T,($G=1kW/m^2$)

Evaluation of the produced quantity of the pumped water using the proposed PV water pump system is the main objective of this paper. A PV water pump system is required to be installed at Egyptian village which contains about 1000 persons near Cairo is taken as a case study.

The average radiation in kw/m^{2}and the length of day time data for this site is given in Table2according to NASA data [12].

Table 2: Geographical Site Information.

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
G(kw/m^2)	0.47	0.56	0.67	0.78	0.84	0.87	0.88	0.85	0.77	0.64	0.52	0.47
Daytime(hr)	10.4	11.1	11.9	12.8	13.6	14.0	13.8	13.2	12.3	11.4	10.6	10.2

Table 3: Different flow rate throughout one year.

	day	G	SL	Q_{av}	Q_p	Q_d	Q_{diff}
Jan.	15	0.49	10.4	1.52	36.6	50	-13.3
Feb.	45	0.56	11.1	2.00	48.0	50	-1.9
Mar.	74	0.67	11.9	2.82	67.8	50	17.8
Apr.	105	0.78	12.8	3.82	91.7	50	41.7
May	135	0.84	13.6	4.52	108.6	50	58.6
June	166	0.87	14	4.89	117.5	50	67.5
July	196	0.88	13.8	4.90	117.7	50	67.7
Aug.	227	0.85	13.2	4.46	107.2	50	57.2
Sep.	258	0.77	12.3	3.60	86.5	50	36.5
Oct.	288	0.64	11.4	2.52	60.6	50	10.6
Nov.	319	0.52	10.6	1.70	40.9	50	-9.0
Dec.	349	0.47	10.2	1.40	33.6	50	-16.3

The daily requirement volume of water for this village is calculated taken into consideration the following considerations [13]:

- 20 liters/day/person are required as the human needs.
- 20 liters/day/person are required for the animals (0.5 units of cattle per person)
- 10liters/day/person are required for the irrigation area (2m^2 for vegetable crops)

Then the total water needs for (1000) persons are about (50) m^3/day.

The proposed simulation program is used for calculating the instantaneous and average water flow rate over the year. The calculations are done for every day using the same input data which are given in Table 1.The value of the radiation is estimated and listed in Table 3.

The obtained results are tabulated in Table 4. The second column of the output results is the day number. For each raw the maximum value of the radiation G and the length of daytime in hours are found. The average Q_{av}, the produced Q_p and the demanded Q_d flow rate (m^3/hr) are calculated. The Q_{diff} is considered as the difference between Q_p and Qd which should be added or taken from the reservoir.

Figure 13 shows the daily volume of water throughout one year. Table 4 shows the important of using a storage tank because the water produced and demanded not equals during the service.

The question now what is the optimal volume of the tank? The answer will be obtained if the system is redesigned with an objective function is to minimize the absolute of Q_{diff}.

Figure 14 shows the variation of N_S with the average value of Q_{diff}.

It is found the minimum volume of the tank is corresponding to (N_S=180) and (Q_{diff}= 201 m^3) and equals to the positive area of the Q_{diff} curve figure 15. This will be the minimum volume of the tank.

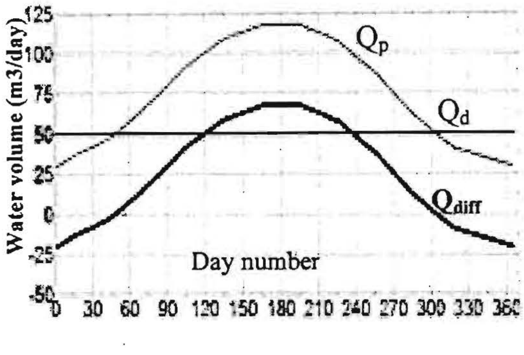

Figure 13: The daily volume of water throughout one year.

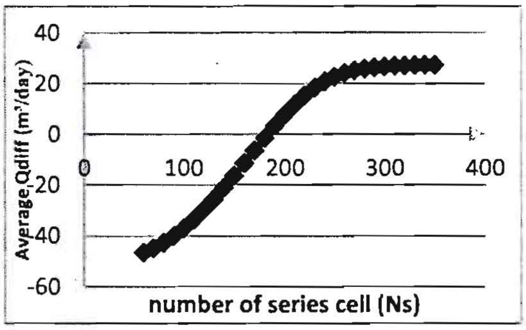

Figure 14: The variation of N_S versus the average value of Q_{diff}

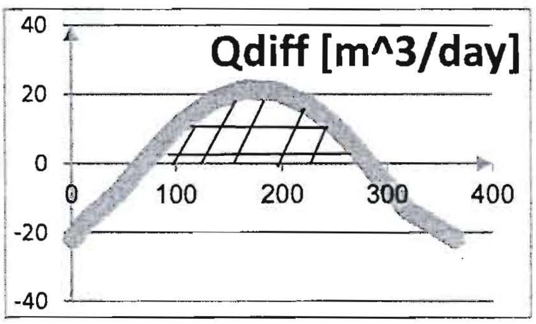

Figure 15: The positive area of Q_{diff} curve.

VII Conclusion

This paper proposed a mathematical model for the PV water pump system using the original equations for the different components. The obtained results from this model are compared to that obtained by Mat lab Simulink. The operation of the PV motor pump system during the transient and steady-state operation is deduced in this research. The mathematical study demonstrated and presented in this proper proves that, this paper can be used in general in designing the PV motor pump system at any site according the solar data of the site and the required volume of water.

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