OPTIMUM OPERATION OF COMBINED PV-DC MOTORS SYSTEMS USING A GRAPHICAL ANALYSIS TECHNIQUE

التشغيل الأمثل لمنظومات الخلايا الكهروضونية المتصلة بأنواع مختلفة من محركات التيار المستمر باستخدام الطريقة البيانية

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خلاصة

فى الأعوام الأخيرة ازداد الأهتمام بتطبيقات الخلايا الكهروضونية فى أنظمة الرى وضخ المياه، ولما كانت الخلايا الشمسية هي الأكثر تكلفة في المنظومة الشمسية كان من الضروري الاستفادة القصوى من طاقة الخلايا الشمسية ودراسة مواءمة الأحمال المختلفة لاختيار الأنسب والأفضل توافقاً مع الخلايا الشمسية الكهروضونية.

يستخدم هذا البحث طريقة التحليل البياني لأي منظومة شمسية تغذى أحمال ميكانيكية وقد تم من خلاله تمثيل المنظومة رياضيا من خلال المعادلات الممثلة لكل جزء منها ومن ثم استنباط العلاقات المختلفة التى تربط أجزاء هذه المنظومة معا ثم استنتاج مجموعة من الخصائص المميزة كأوجه مقارنة لبيان مدى توافق هذه الأحمال مع الخلايا. وقد تم تطبيق هذه الطريقة على نماذج مختلفة لمجموعة من الأحمال الميكانيكية متصلة مع أنواع مختلفة من محركات التيار المستمر مغذاة من خلايا شمسية كهروضونية، ويقدم البحث دراسة تأثير إضافة بطاريات التخزين على أداء المنظومة السابقة، وتم التطبيق عدديا على تسعة حالات لأنواع مختلفة من محركات التيار المستمر تغذى أحمال ميكانيكية مختلفة عند وجود وعدم وجود البطاريات، ومن ثم المقارنة بينها للوصول إلى أفضل أداء للمنظومة، حيث تعتمد المقارنة على كل من جودة المواءمة بين الخلايا والحمل ومستوى الإشعاع الذى يبدأ عنده تشغيل المحرك وكذلك كفاءة المنظومة. ومن خلال المقارنة بين الحالات المختلفة تم تحديد أفضل حمل يتم توصيله مع كل نوع من أنواع المحركات المستخدمة كما تم تحديد تأثير إضافة البطاريات لكل حالة.

ABSTRACT

Electrical motors powered by solar cell array (SCA) generators have important applications such as water-pumping for irrigation or water supply. Good matching of loads to solar cell generators is so important for optimum operation of the PV system and maximum utilization of solar energy. This paper applies a graphical technique to analyze the performances of directly coupled PV electro-mechanical systems for dc motors (that is, series separately excited and shunt motor) coupled to ventilator, centrifugal or constant loads. The technique depends on simulating the electrical characteristics in (I, V) plane, the mechanical characteristics in (T,ω) plane, and the hydraulic characteristics in (H,Q) plane. A comparison between different case studies is introduced to indicate the appropriate motor type for each load. The comparison depends on: quality of load matching, system efficiency and the insolation level at which the motor starts up. The effect of connecting a storage battery for each case study is also, investigated.

1- INTRODUCTION

With the continuous decrease of photovoltaic cell cost, there is an increasing interest in PV systems applications. Electrical motors powered by solar cell array are one of PV important applications. They can be used as water-pumping systems for irrigation or water supply, where the motors derive volumetric or centrifugal pumps. Good matching of loads to solar cell generators is so important for optimum operation of the PV system and maximum utilization of solar energy. Many researchers have investigated different methods for designing and optimizing the photovoltaic power systems (PVPS) to improve

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dc motors types powered by SCA and loaded with constant or ventilator load were analyzed in Ref. [2]. The performance and quality of matching of different load types connected to SCA were analyzed in Ref [3]. Matching of dc motors to PV generators for maximum daily gross mechanical energy was investigated in Ref. [4]. The effects of maximum power point tracking (MPPT) on the operation of loads powered by separate sources or a common source of SCA were investigated in Ref. [5]. Whereas, the calculation of the starting to rated current ratio and starting to rated torque ratio of the permanent magnet, separately, shunt and series excited motor with and without MPPT were explored in Ref. [6]. A load matching approach for sizing PVPS with short-term energy storage was evaluated in Ref [7]. An investigation of directly coupled photovoltiac-pumping systems connected to a large absorber field was presented in Ref. [8]. Matching of separately excited dc motors to PV generators for maximum power output was investigated in Ref [9]. Modelings of PV water pumping systems were analyzed in Ref. [10]. Optimal utilization of the solar energy using EMTP computer program has been investigated in Ref. [11]. A method for increasing the daily output mechanical energy supplied by series dc motors directly connected to solar cell arrays is presented in Ref. [12]. The performance of a stand-alone directly coupled PV electro-mechanical system, without battery bank, has been analyzed for dc permanent magnet, series, and shunt motors coupled with centrifugal and constant loads at different solar intensities and corresponding cell temperatures [13].

This paper presents a comprehensive study of the graphical analysis technique used for load matching in PVPS. The technique depends on modeling electrical characteristics in (I,V) plane, the mechanical characteristics in (T, ω) plane, and the hydraulic characteristics (in case of pumps) in (Q, H) plane. Finally the maximum power at each insolation level is plotted in (P, G) plane. This technique helps to graphically analyzing different load types, and improving the utilization of PV generated power. The technique is applied to different load types (constant load, ventilator load, and centrifugal pump load) connected to different dc motor types (series, shunt and separately excited motors) to investigate the suitable motor type for each load. The effects of adding storage battery to improve the matching quality are also investigated.

2- SCA EQUIVALENT CIRCUIT

The solar cell is a semiconductor device that converts solar insolation directly to electrical energy. The cell is a nonlinear device represented by its I-V terminal characteristics, or by an approximate electrical equivalent as shown in Fig. 1.

The solar cell is an electrical cell of low voltage and power levels therefore; the cells have to be connected in series and parallel combinations in order to obtain the desired voltage and power levels. The I-V equation representing a single solar cell can be represented as [2]:

$$V = -I\,R_s + A\ln\left(1 + \frac{I_{ph} - I}{I_o}\right) \tag{1}$$

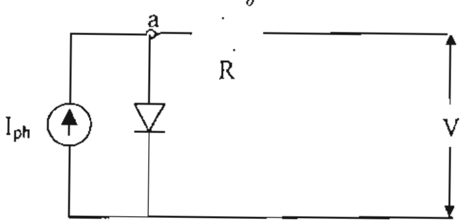


Fig. 1 Solar cell array equivalent circuit

A solar cell generator consists of N_s series cells and N_p parallel cells can be characterized as [7]:

$$V_g = -I_g R_{sg} + A_g \ln(1 + \frac{I_{phg} - I_g}{I_{og}}) \quad (2)$$

This equation can be defined for series-parallel combination as:

$I_{phg} = N_p I_{ph}$, $I_{og} = N_p I_o$ $A_g = AN_s$ $R_{sg} = R_s (N_s/N_p)$

3- DEFINITION OF THE PROBLEM

Different load types may be connected to the SCA generator-motor combination according to the required application. The main purpose of this study is to indicate the appropriate motor type connected to each load for optimum utilization of solar radiation. The dc motors can be classified according to the type of excitation field to: series, permanent magnet, shunt and separately excited motors. Permanent magnet dc motors have identical performances (equations) as separately excited motors for constant field. The widely used mechanical load types can be categorized as: constant load torque, ventilator load torque and centrifugal pump load. Fig. 2 illustrates a schematic diagram of the studied system.

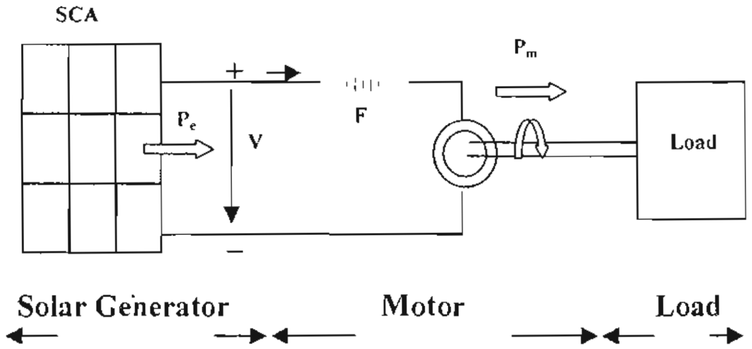


Fig. 2 A schematic diagram of the studied system

3-1 PV Array Sizing

The dc motors used in this study are 120 V, and 9.2 A [2]. A series-parallel connection of the array is needed to generate the required power. The studied solar cell array consists of 18 strings in parallel with 9 panels in series per each string. Each panel consists of 36 cells in series. The data of a solar cell used in this study (100 percent insolation = insolation of 1000 W/m²) are shown in Table 1 [2].

Table 1 Solar cell data

Symbol	Value	Nomenclature
I_o	$8.1*10^{-3}$ A	Reverse Saturation current
I_{ph}	0.756 A	Cell photocurrent
R_s	0.05 Ω	Cell series resistance
A	0.0731 V	Thermal voltage

The solar cell generator consists of 18 strings in parallel with 324 cells in series generates maximum voltage and current equal to 129.5 V and 9 A respectively at 100 %

insolation. The equation represents the solar cell generator can be evaluated by substituting in Eq. (2):

$$V_g = -0.9I_g + 23.68\ln(1 + \frac{I_{ph} - I_g}{0.0081}) \qquad (3)$$

3-2 Maximum Power Points Determination

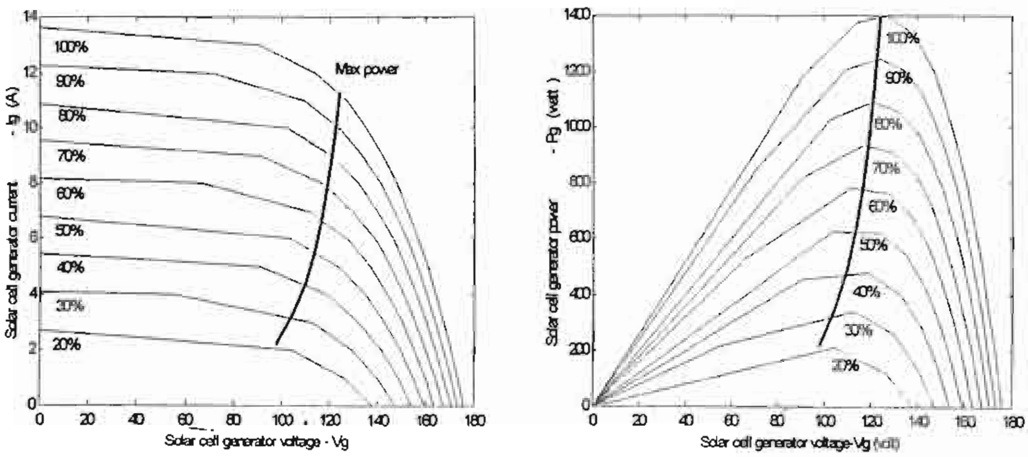
The maximum power points of the SCA generator can be evaluated by differentiating Eq. (3) as follow:

$$\frac{d}{dI_g}(V_g I_g) = 0 \qquad \text{Hence,} \qquad V_g + I_g \frac{dV_g}{dI_g} = 0 \qquad (4)$$

To get max power points: let I_{MP} the current value (for each insolation level) at which the power is maximum and substitute by Eq. (3) in Eq. (4) so that:

$$\ln\left(\frac{I_{ph} - I_{MP} + I_o}{I_o}\right) - 0.076 I_{MP} - \frac{I_{MP}}{I_{ph} - I_{MP} + I_o} = 0 \qquad (5)$$

Equation (5) is then, solved for I_{MP} using an iterative numerical solution method taking I_o as a constant value. Figs. 3-a and 3-b show the (I,V) and (P,V) characteristics of the studied SCA generator. Table 2, illustrates PV maximum power points for the studied SCA generator.



a- I-V Characteristics *b- P-V Characteristics*

Fig. 3 Solar cell array characteristics

Table 2 PV maximum power points for the studied SCA at different insolation levels

	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
I_{MP}, Amp.	1.1	2.19	3.32	4.46	5.595	6.735	7.873	9.01	10.15	11.279
V_g, Volt	82.1	97.66	105	110	113.8	116.7	119.1	121.1	122.7	124.12
P_m, Watt	90.3	213.9	348.6	490.6	636.7	786	937.7	1091	1245	1402

3-3 Characteristics of DC Motors

To study the suitable dc motor for different loads, the characteristics of dc motors have to be studied. The following assumptions are made for formulating dc motors equations [2]:

- Linear dependence of the magnetic flux on the field current;
- Constant armature- and field- self inductance;
- Negligible iron losses and armature reaction;
- The mechanical losses consist of static and viscous friction i.e.

$$T_{m\text{-}loss} = A + B\omega$$

The main characteristics of each dc motor type can be summarized as follows [2]:

3-3-1 Series motor:

The series motor voltages (V_m) and torque (T_m) in steady state can be expressed as:

$$V_m = M_{af}\, i_a\, \omega + R i_a \tag{6}$$

$$T_m = T_L + A + B\,\omega \tag{7}$$

$$T_m = M_{af}\, i_a^2 \tag{8}$$

Where:

R : Combined field and armature resistance, Ω

M_{af}: Mutual inductance between field and armature, H

T_L : Load torque, Nm.

By coupling the motor to the SCA generator:

$$V_m = V_g, \qquad i_a = I_g$$

Where V_g can be calculated by Eq. (3)

From the previous equations the motor speed-torque equation is evaluated as:

$$\omega = \frac{V_g - \left(\frac{T_m}{M_{af}}\right)^{\frac{1}{2}} R}{M_{af}\left(\frac{T_m}{M_{af}}\right)^{\frac{1}{2}}} \tag{9}$$

The steady state speed–torque characteristics in the mechanical plane (ω,T) can be established by solving Eq. (9) and the load equation as will be explained latter.

3-3-2 Separately excited motors:

The separately excited motor voltages and torque equations in steady state can be expressed as:

$$V_m = C_e\,\omega + R_a i_a \tag{10}$$

$$T_m(i_a) = C_e\, i_a \tag{11}$$

By coupling the motor to the SCA generator (Eq. (3)):

$$V_m = V_g, \qquad i_a = I_g$$

The motor speed equation is evaluated as:

$$\omega = \frac{V_g - (T_m\ C_e) R_a}{C_e} \tag{12}$$

The system's operating points can be determined by solving Eq. (12) and the load torque equation.

3-3-3 Shunt motors

The shunt motor voltages and torque equations in steady state can be expressed as:

$$V_m = M_{af}\ i_f\ \omega + R_a\ i_a \qquad (13)$$

$$V_m = R_f\, i_f \qquad (14)$$

$$i = i_a + i_f \qquad (15)$$

$$T_m = M_{af}\, i_a\, i_f \qquad (16)$$

By coupling the motor to the solar cell generator, we obtain:

$$V_m = V_g \quad \text{and} \quad i = I_g$$

The torque speed equation is given as:

$$\omega = \frac{V_g - (T_m / M_{af} i_f) R_a}{M_{af} i_f} \qquad (17)$$

The system's operating points can be determined by solving Eq. (17) with the load torque equation.

4- LOAD MATCHING ANALYSIS FOR DIFFERENT MOTOR TYPES

This section analyzes each of the three load categories with the different dc motor types to compromise suitable matching with the SCA generator. The indices of comparison are: quality of matching, system efficiency, and start up insolation level. Finally the effect of connecting a storage battery to the system in each case study is analyzed. The dc motors data used in this study are shown in Table 3.

Table 3 DC motors data

Type	Symbol	Value	Nomenclature
General Data	V	120 V	Rated Terminal Voltage
	I_a	9.2 A	Rated Armature current
	ω	157.1 rad/sec	Rated Shaft speed
	T_m	5.7 N.m	Rated Electromagnetic torque
Series Motor	R_{as}	2.2 Ω	Armature and Series Field Resistance
	M_{af}	0.0675 H	Mutual inductance
Separately Excited Motor	R_a	1.5 Ω	Armature Resistance
	C_e	0.621 V/rad/s	Flux coefficient at I_f = 9.2 A
Shunt Motor	R_a	1.5 Ω	Armature Resistance
	M_{af}	0.518H	Mutual inductance
	R_f	100 Ω	Field Resistance

4-1 Constant Load Torque

The widely used application of constant load torque is the volumetric pump. In steady state operation, the electromagnetic torque value is the summation of the constant load torque (TL) plus mechanical losses. The data used for the studied constant load is given in Table 4.

Table 4 Data for studied constant load

Symbol	Value	Nomenclature
A	0.2 N.m	Toque constant of rotational losses
B	0.0023 N.m/rad/s	Viscous Torque Constant
T_L	4.0 N.m	Load Torque

The steady state speed-torque characteristics in mechanical plane (T,ω), can be evaluated by solving the motor speed-torque equation with the load torque equation (Eq. (17)). The speed-torque equations for series, separately excited and shunt motors are evaluated before as Eq. (9), (12) and (17) respectively. The speed-torque values are computed for each motor type. The load line T_m in the mechanical plane (T,ω) can be transformed into the (I-V) plane by Eqs. (8) and (9) for a series motor and Eqs. (11), (12) for separately excited one as shown in Fig. 4. The SCA generator cannot produce sufficient torque to start up the shunt motor even at full insolation level

4-1-1 Comparison between different motors types supplied by SCA

As stated before the comparison indices are: start up insolation level, system efficiency, and quality of matching.

- **Start up insolation level:**
  It defines the minimum insolation level at which the motor starts to rotate. The start up insolation level can be computed as a percentage ratio of referred current at ω =0 to short circuit current at full insolation.
- **System efficiency:**
  It is defined as the average ratio between the mechanical output power and electrical input power (the output of the SCA generator) at each insolation level.
- **Quality of load matching:**
  It is a factor that determines the quality of photovoltaic systems performance and the degree of the solar cell utilization. The quality of load matching is defined as the ratio of the load input power to the SCA generator maximum power as a function of the solar insolation [2]:

$$Q_l = \frac{\int_{\text{Start up insolation level}}^{\text{Full insolation level}} P(G)dG}{\int_{0}^{\text{Full insolation level}} P(G)dG} \tag{18}$$

where: G Irradiance, kW/m²
P(G) SCA generated power at irradiance G, kW

In good matched systems the operation of the load line should be close to the maximum power line of the SCA generator:
The quality of load matching can be determined as the ratio between the area under the load curve supplied by SCA with respect to the maximum power line curve as shown in Fig. 5. The values of the quality of load matching for the different motors types are shown in Table 5.

Table 5 Comparison between different motors types connected to a constant load

Motor Type	Start up Insolation level	Matching Quality	Efficiency
Series motor	57.94%	62.73%	89.96%
Separately motor	49.68%	65.84%	92.05%

It can be seen that the separately excited motor is the appropriate type for a constant mechanical load. Its efficiency and matching quality are better than the series motor. It is not applicable to use shunt motors with constant mechanical loads. The full insolation level cannot produce sufficient torque to start up the shunt motor for this case study.

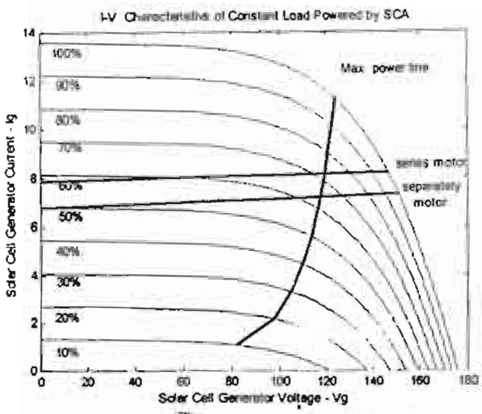


Fig.(4) I-V plane for SCA supply series and separately excited motors connected to constant load torque

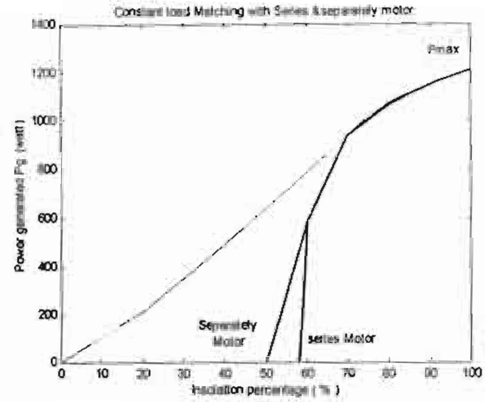


Fig.(5) Utilization curve for constant load torque connected to series and separately excited motors

4-1-2 Effect of storage battery:

Many PV systems incorporate storage batteries to improve system performance and reliability. This section will analyze the effect of connecting storage battery to a combined SCA generator-dc motor system. The I-V characteristics of a storage battery may be written as [3]:

$$V = V_B + I\,R_b \qquad (19)$$

Where V is the battery e.m.f and R_b is the internal resistance. By neglecting the internal resistance, V_B =constant. The Minimum and maximum voltage can be represented by the two vertical lines intersect with the I-V characteristics of the solar cell generator for various insolation levels. The two voltage values are assumed as 115 and 135 V, respectively according to the voltages of the studied SCA generator. The operating points are the intersection points of the two vertical lines with the I-V curve at different insolation levels.

a) Series motor

Constant load directly supplied by a SCA generator through dc motor results in poor matching quality as evaluated in the preceding section. The different types of dc motors start up at about 60% of the insolation level. Addition of storage battery to the system can enhance the quality of load matching. The charging and discharging cycles of the storage battery are analyzed, and applied to the studied system to evaluate the effect of adding storage battery.

- **Charging cycle:**
  The battery is fully charged to its maximum voltage (V_{max} =135 V) and then it is discharged to its minimum voltage (V_{min}=115 V) as shown by Fig. 6. During the daytime, the constant load is supplied either by the SCA generator and the storage battery, or by the storage battery only. During nighttime, the load is supplied only through the storage battery, therefore its voltage decreases until it reaches 115 V (the rated voltage of the motor, point *a*). As the sun rises, the load is supplied again by

both the SCA generator and the battery; the battery continues to discharge at slower rate. With increasing the insolation level, the operating point moves along ***a-b*** line until it reaches point ***b*** (70% of insolation level). At point ***b***, the SCA generator starts to supply the load and charge the storage battery

As the insolation increases the operating point reaches point *c* which is near to the rated current of the motor The battery now reaches its maximum voltage value and it is disconnected (at 90% insolation). The operating point moves from point *c* along the 90% insolation curve until it reaches point *d*. As the insolation varies the operating points move along the constant load line (points ***d - e - d - b***).

- **Discharging cycle:**

When the operating point reaches point b ($I = I_{min}$), the battery is reconnected and the operating point shifts to point f, where the load is supplied by both the SCA generator and the battery again. The battery starts to discharge with an increasing rate until it reaches point g, where the 'dark' time starts. The described trajectory a-b-c-d-e ...b-f-g, represents one cycle operation of the system.

Figure 7, shows the utilization curve, charging points [*a b c d e*] and discharging points [*b f g*] for a constant load connected to a series motor in presence of a storage battery.

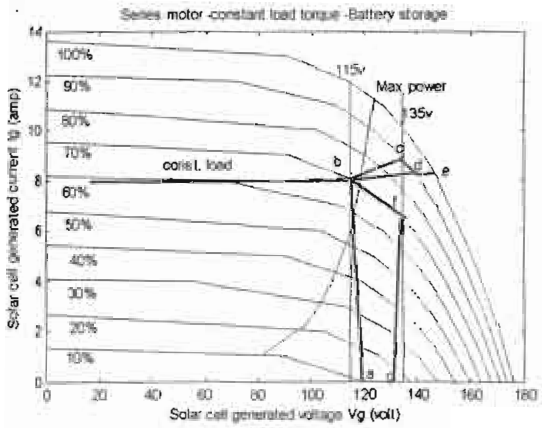


Fig. (6) Battery storage characteristics for a constant load torque connected to series motor supplied by SCA

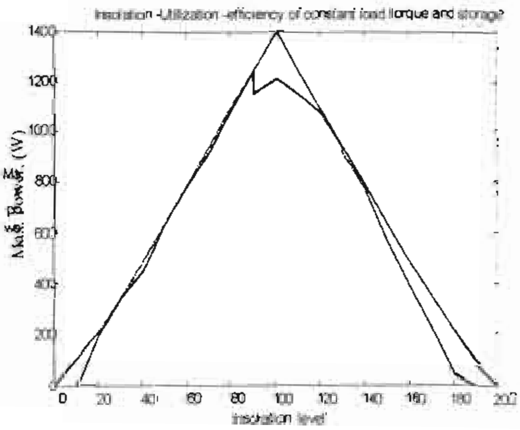


Fig. (7) Utilization curve for a constant load torque connected to a series motor supplied by SCA with battery storage

The start up rotation in this case is improved from 57.94 % without battery to 9.38 % after connecting a battery, which yields to improve the quality of matching from 62.73% to 93.25%.

b) Separately excited motor

The previous analysis is applied to the case study of a constant load torque connected to a separately excited motor and storage battery.

The start up isolation level in this case is improved from 49.68% without battery to 9.38 % after connecting a battery, which yields to improve the quality of matching from 65.84% to 94.65%.

Table 6, shows the effect of storage battery on constant load torque for series and separately excited motors.

Table 6 Effect of storage battery on constant load torque for different motor types

Motor Type	Without Storage Battery		With Storage Battery	
	Start up insolation	Matching Quality	Start up insolation	Matching Quality
Series motor	57.94 %	62.73%	9.38%	93.25%
Sep. excited motor	49.68%	65.84%	9.38%	94.65%

c) Shunt motor

For a shunt motor the full insolation level cannot produce sufficient torque to start up the motor even in case of adding storage battery

4-2 Ventilator Load Type

The widely used application of ventilator load is the centrifugal fan. The electromagnetic torque equation at steady state can be defined as:

$$T_m = a_f + b_f \omega^{c_f} + A + B\omega \tag{20}$$

The data used for the studied ventilator load is given in Table 7.

Table 7 Ventilator load data

Symbol	Value	Nomenclature
a_f	0.3 N.m	Static torque constant
b_f	0.00039	Dynamic torque constant
c_f	1.8	C factor

The motor speed-torque equations for the different motor types are solved with ventilator torque equation to get steady state speed-torque characteristics in the mechanical plane (T,ω) for this load type. The speed-torque equations for series, separately excited and shunt motors were evaluated before as Eq. (9), (13) and (19) respectively.

The load line T_m in the mechanical plane (T, ω) can be transformed into the (I-V) plane using Eq. (8) and (9) for series motors, Eq. (11) and (12) for separately excited, and Eq. (16) and (17) for shunt motors as illustrated by Fig. 8. The starts up insolation level, quality of load matching and system efficiency are computed for this case study. Fig. 9, and Table 8 illustrate the results.

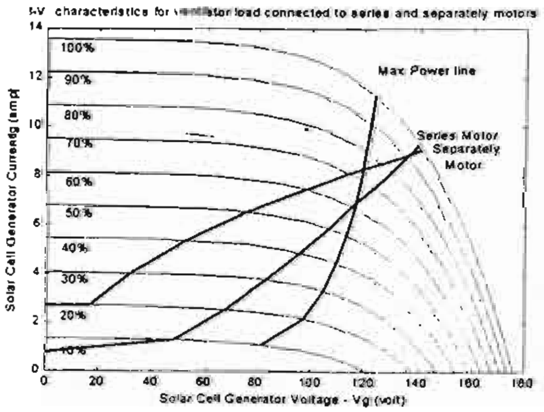


Fig. (8) I-V Plane for a ventilator load connected to series and separately excited motors

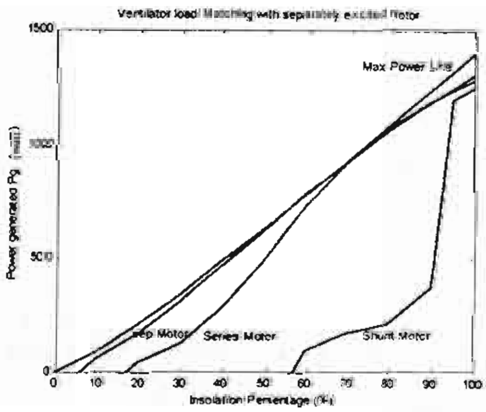


Fig.(9) Utilization curves for a ventilator load torque connected different motor types

Table 8 Comparison between different motor types connected to a ventilator load

Motor Type	Start Up insolation level	Matching Quality	Efficiency
Series motor	19.99%	83.84%	84.17%
Sep. Motor	5.9%	96.07%	92%
Shunt Motor	59.6%	32.25%	81%

In this case study:

- The start up insolation level for the separately excited motor is the lowest one (5.9% compared to 19.99% for series and 59.6% for shunt motor). Consequently the quality of load matching of the separately exited motors are 96.07% compared to 83.84% and 32.25% for series and shunt motors)
- The separately excited motors are the best choice for the ventilator loads supplied by SCA generator, the utilization of SCA output energy is 96.07% of its maximum output power.
- In contrast to the constant load torque the SCA generator can produce sufficient torque to start up the shunt motor to supply this load type (at 59.6% of insolation level). Although the shunt motor has the best efficiency, it has a poor quality of load matching, because of its high starting torque value

4-2-1 Effect of storage battery

The quality of load matching can be improved by connecting a storage battery to the studied system. Fig. 10, shows the charging and discharging cycles for a storage battery connected to a series motor, whereas, Fig. 11 shows the utilization curve, charging points [*a b c d*] and discharging points [*b f g*]. Fig. 12, shows the charging and discharging cycles for the battery and Fig. 13, shows the utilization curve, charging points [*a b c d*] and discharging points [*b f g*] for a separately excited motor. For a shunt motor the same curves are shown in Figs. 14, and 15. A summary of the storage battery effect on the studied system is presented in Table 9.

The results show that: connecting the storage battery has a reasonable effect on the shunt motor system. It improves the quality of load matching from 32.25% to 92.25%. On the other hand the storage battery has a little effect on the separately excited motor system. It improves the quality of load matching from 96.07% to 98.65%

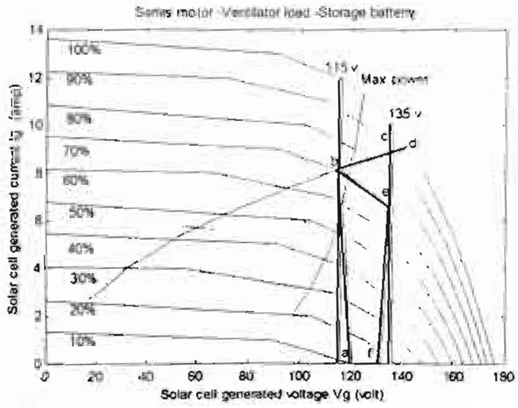


Fig. (10) Battery storage characteristics for a ventilator load torque connected to a series motor supplied by SCA

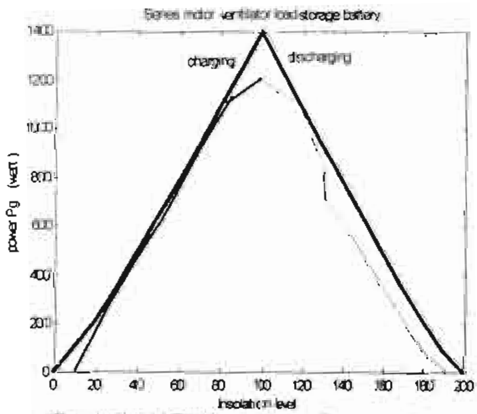


Fig. (11) Utilization curves for a ventilator load torque connected to a series motor supplied by SCA with battery storage

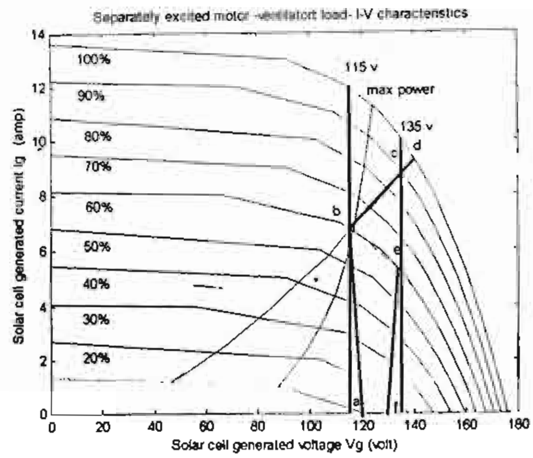


Fig. (12) Battery storage characteristics for a ventilator load torque connected to a separately excited motor supplied by SCA

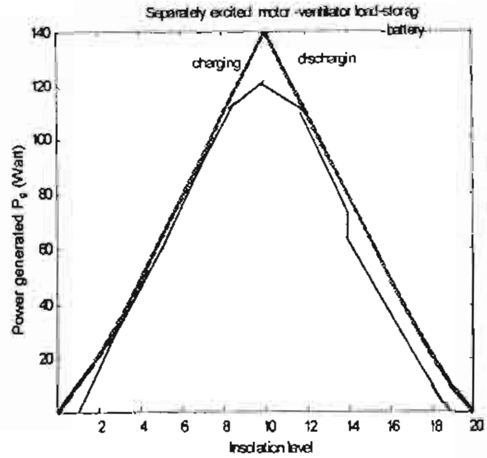


Fig. (13) Utilization curves for a ventilator load torque connected to a separately excited motor supplied by SCA with battery storage

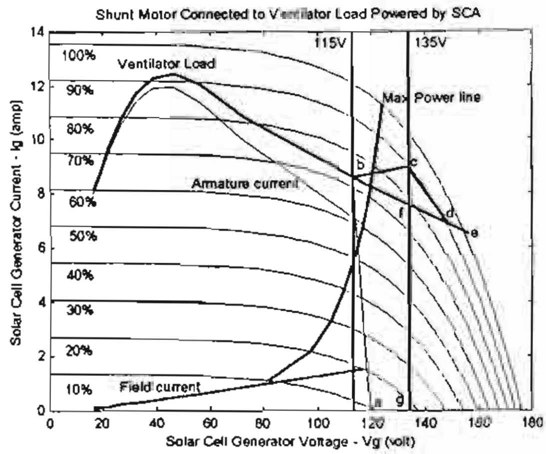


Fig. (14) Battery storage characteristics for a ventilator load torque connected to a shunt motor supplied by SCA

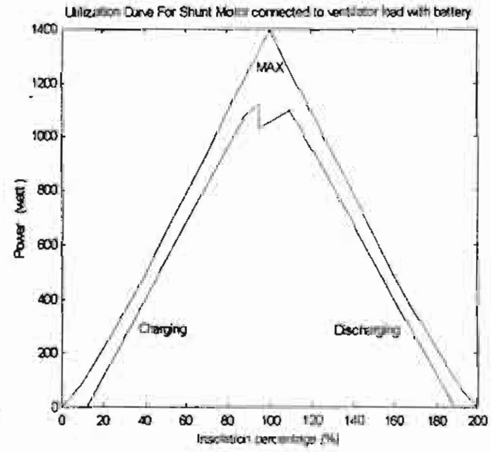


Fig. (15) Utilization curves for a ventilator load torque connected to a shunt motor supplied by SCA with battery storage

Table 9 Effect of storage battery on ventilator load

Motor Type	Without Storage Battery		With Storage Battery	
	Start up Insolation Level	Matching Quality	Start up Insolation Level	Matching Quality
Series Motor	19.9 %	83.54%	9.38%	97.7%
Sep. Motor	09.6%	96.07%	9.38%	98.65%
Shunt Motor	59.6%	32.25%	9.38%	92.25%

4-3 Centrifugal Pump

The centrifugal pump is the most popular type used in a PV-pumping system. The centrifugal pumps are simple, low cost, low maintenance and are available in a wide selection of designs for a range of flow rates and heads. The motor converts the electrical energy (I,V) into mechanical energy (T,ω) The pump converts mechanical energy (T,ω) into hydraulic energy (H,Q) with static head H_{static}. The terminal equations to represent the operation of the pump can by given by [14].

$$\omega = \omega_{ref} \sqrt{(H - bQ^2 / a} \tag{21}$$

$$Q = \frac{\eta \tau \omega}{.\rho g H} \tag{22}$$

By neglecting dynamic factor where $bQ^2 << H$, the static head can be obtained as:

$$H = a * (\omega / \omega_{ref})^2 \tag{23}$$

4-3-1 Centrifugal pump connected to different types of motors

The load of the centrifugal pump consists of the head created by the flow path (h_{path}) and the static head distance (h_{static}) [14]. The flow path h_{path} is so small compared with h_{static}. For simplifying the calculations the effect of the flow piping losses is neglected The centrifugal force of the pump is similar to the ventilator load (centrifugal force of the fan). The difference between them is nature of the fluid. In centrifugal fan the fluid is air, whereas in centrifugal pump it is water that is related to static head and water flow rate. The centrifugal pump data used for this study is shown in Table 10.

Table 10 Centrifugal pump data

Sym.	Value	Nomenclature
H	37.795 m	Rated Head
Q	80 liter/min	Flow rate charge
η	0.55%	Pump Efficiency
P	1000 kg/m^3	Fluid density
G	9.8 N/m/s^2	Gravitational constant
A	37.795 m	Static a factor

The centrifugal torque is supplied by the SCA generator through the three types of motors. Using equations (22) and (23), the H-Q curves are evaluated and graphed for series, separately excited and shunt motors respectively A comparison between the three motor types supplied by SCA generator at different insolation levels is shown in Fig. 16 whereas, the utilization curves for this case study is Fig. 17.

A comparison between different motor types connected to a centrifugal pump load is shown in Table 11

Table 11 Comparison between different motor types connected to a centrifugal pump

Motor Type	Start up Insolation	Quality of Load Matching	Efficiency
Series Motor	20%	81.73%	82.75%
Sp. Excited Motor	6%	93.5%	90.7%
Shunt Motor	59%	29.66%	81.08%

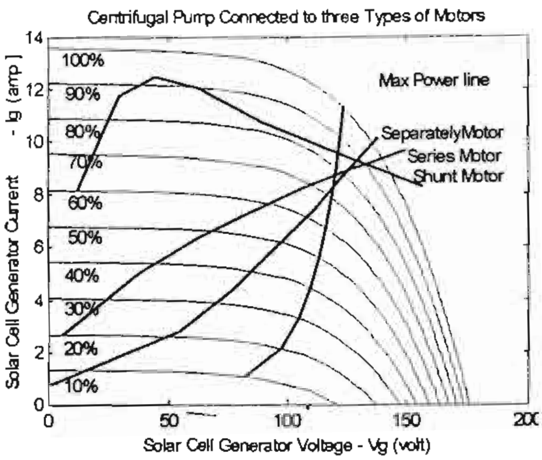


Fig. (16) I-V Plane for a centrifugal pump connected to different motor types

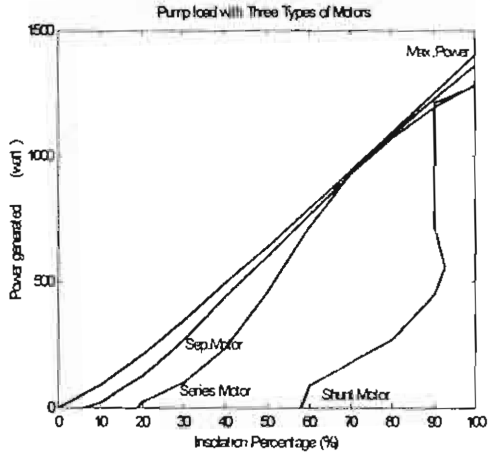


Fig. (17) Utilization curves for a centrifugal pump connected different motor types

4-4 Comparisons between Different Case Studies

The appropriate motor type connected to each load for optimum utilization of solar radiation can be obtained by comparing between the different case studies. Table 12 presents a comparison between start up insolation level for the different case studies. The lowest start up insolation level occurs for the centrifugal load connected to separately excited motors, whereas for shunt motors, the start up insolation level is beyond the maximum insolation level. Addition of a storage battery picks up the start insolation level for all case studies except the const load case.

Table 13 presents a comparison between "quality of load matching" for the different case studies. The best utilization of SCA energy occurs for the ventilator load connected to separately excited motors in presence of storage battery.

Table 12 Comparison between start up insolation levels for the different case studies

Motor Type	Constant load		Ventilator load		Centrifugal Pump
	Without Storage Battery	With Storage Battery	Without Storage Battery	With Storage Battery	
Series Motors	57.94 %	9.38%	19.9 %	9.38%	20%
Separately Excited Motors	49.68%	9.38%	9.6%	9.38%	6%
Shunt Motors	------	------	59.6%	9.38%	59%

Table 13 Comparison between "Quality of load matching" for the different case studies

Motor Type	Constant load		Ventilator load		Centrifugal Pump
	Without Storage Battery	With Storage Battery	Without Storage Battery	With Storage Battery	
Series Motors	62.73%	93.25%	83.54%	97.7%	81.73%
Separately Excited Motors	65.84%	94.65%	96.07%	98.65%	93.5%
Shunt Motors	—	—	32.25%	92.25%	29.66%

5- CONCLUSIONS:

- The performances of a combined PV-dc motor system have been analyzed.
- A graphical analysis technique has been applied to different load types (constant, ventilator, and centrifugal loads) connected to different motor types (series, separately excited and shunt motors) supplied by SCA generator
- A comparison between different case studies was introduced to indicate the appropriate motor type for each load.
- Out of this study it can be concluded that:

  For a constant load torque:
  - The separately excited motor is the appropriate type for a constant mechanical load. Its efficiency and matching quality are better than the series motor.
  - Connecting a storage battery to the studied system in this case improves the systems performance in case of separately excited and series motors. The start up isolation level is improved from 49.68% to 9.38 %, which improve the quality of matching from 65.84% to 94.65%, in case of separately excited motors. Whereas, the start up isolation level is improved from 57.94 % to 9.38 %, and the quality of matching is improved from 62.73% to 93.25%, in case of series motors
  - For a shunt motor the full insolation level cannot produce sufficient torque to start up the motor even in case of adding storage battery. It is not preferable to use shunt motors with constant mechanical loads.

  For a ventilator load torque:
  - Separately excited motor coupled to a ventilator load type is found to be the most suitable combination for SCA generator.
  - The separately excited motors are the best choice for the ventilator loads supplied by SCA generator; the utilization of SCA output energy is 96.07% of its maximum output power.
  - In contrast to the constant load torque the SCA generator can produce sufficient torque to start up the shunt motor to supply this load type (at 59.6% of insolation level). Although the shunt motor has the best efficiency, it has a poor quality of load matching, because of its high starting torque value
  - Connecting a storage battery to the system has a reasonable effect on the shunt motor system. It improves the quality of load matching from 32.25% to 92 25%. On the other hand the storage battery has a little effect on the separately excited motor system. It improves the quality of load matching from 96.07% to 98 65%

  For a centrifugal pump load:
  - Separately excited motors are more compatible to the centrifugal pump than series motor for different head levels
  - The importance use of the centrifugal pump regardless to the performance matching is the capability of storage water to use in need, so there is no need use storage battery.

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