PHOTOVOLTAIC PUMPING SYSTEM

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I. Introduction

A photovoltaic cell is a device which can generate electrical energy directly when sunlight strikes the surface. There are a number of semiconductor materials which are suitable for solar cell fabrication such as single crystal silicon, cadmiumsulfide/ayorous sulfide, gallium arsenide and some more materials $CuInSe_2$ and $In\text{-}SnO_2$. Among these single crystal materials silicon is the vast majority for cell production. However, two types of solar cells may be classified based on the material structures from which they are produced; single crystal silicon and polycrystalline crystal. The single crystal silicon solar cells have shown the efficiency of about 15 percent which is almost twice as high than the polycrystalline solar cells and the cost of production is also higher accordingly. However, the price of the solar cells is still considerably high even if it has fallen dramatically in recent years comparatively with the other conventional energy sources. It is expected that by introducing an advance technology for the solar cell prodution and development the price may be brought down further so that they will become more attractive for various applications.

The solar cell is also considered as a convenient device for generating electricity some problems may arise when used in a large scale system. These problems are mostly concerned with system installation, power quality, energy storage as well as controls and safety which may affect the working performance.

*1) The design of a photovoltaic system is generally addressed to the best matching between the energy supplied to the system by the sun, and the energy required by the load that is to be fed by the system.

The best matching can be searched in terms of minimum loss, less efficiency, reliability or a compromise between these contraints.

In any case the design of a photovoltaic system can be roughly divided into three main parts:

a. Load requirements

b. Choice of system configuration

c. Sizing of the different blocks of the system

1.1. Load characteristics

The design of a PV system must start from a careful analysis of the load. It should take into acount:

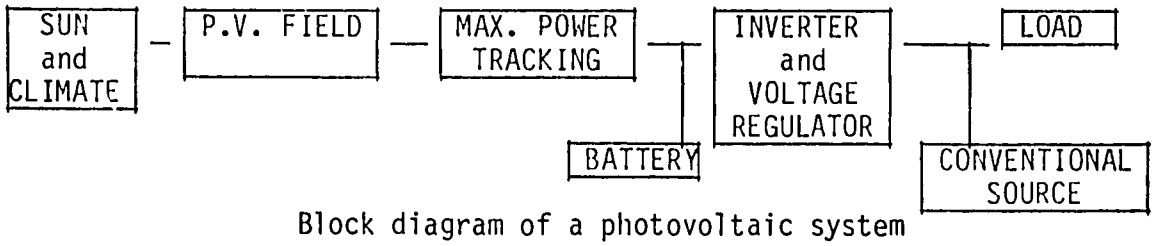
- the annual energy requirements
- the season and hourly energy diagrams
- the peak power requirements
- the type of supply (d.c. or a.c.)

Another relevant point in defining the load is:

- The possibility of making use of an auxiliary power generator, that can f. ex. a diesel-powered generator, covering the load demand in days of very low solar radiation. A photovoltaic plant which must work in a stand-alone mode without any auxiliary energy source, will have size and cost much larger than one that allows a little percentage of the load, say 10%, to be covered by the auxiliary generator. *(This is especially for loads with high power demands.)

1.2. Choice of system configuration

The actual system configuration depends mainly on the final use of the energy produced by the photovoltaic.



Block diagram of a photovoltaic system

The criteria that lead to the choice of a particular system according to the type of utility are in the following outline.

- Output block

The most part of electric equipment are designed to be supplied by the utility network. Therfore, the output block usually consists of an inverter in order to feed the load with a.c. voltage at 56 or 60 HZ, single phase or three phase. If the load requires d.c. power, so the inverter will be eliminated with advantage on the cost and efficiency of the system. This can be the case when the load is an electric motor; in this case we choose a d.c. motor instead of an a.c. motor. Thus eliminating the need for the inverter.

- Storage

Mostly the p.v. systems operate in the stand-alone mode, it is customary to have a battery that stores energy for utilization in those time intervals when it is not generated. Also in systems that include auxiliary power source, the battery is useful in utilizing the whole energy generated by the PV field, by accumulating the surplus energy on days of high solar radiation and giving it back on cloudy days and in the night. Thus the need of operting the auxiliary source is greatly reduced when the system is to be operated in parallel with the utility grid. The battery can be eliminated. In this case it is the grid itself that acts as a storage block with an infinite storage capacity. The main problems related to the utilization of batteries are:

- their high cost
- the need for maintenance at frequent times
- their low efficiency 70% expected
- self discharge rate, difficult to store long

New batteries that have not yet been developed on an industrial basis should overcome all these problems and will change drastically the criteria of battery utilization in PV systems.

- Input block

If the PV system contains some storage batteries it can be valuable to use a d.c. voltage regulator in order to regulate the voltage given by the photovoltaic field to the correct level for battery charging, in spite of fluctuations of solar radiation, ambient temperature etc. This block may also perform the function of tracking the maximum power point of the photovoltaic field in order to obtain the maximum efficiency of the cells. The cost now of this equipment is very high.

1.3 Sizing of the system blocks

a. A numerical or analytical model of each system block is to be developed

b. A model of the whole system is obtained by connecting together all the models of the single blocks.

The size of PV field is characterized by its area times efficiency product. That number represents also the peak power (KW) generated by the PV field, namely the maximum output power when the incident radiation intensity is of $1KW/m^2$. The solar cell efficiency varies with radiation intensity and temperature.

The size of the battery is defined in terms of nominal battery capacity C_{max}. The actual state of charge C_B, must exceed a minimum charge C_{min} in order to ensure a long battery life.

If the battery reaches its minimum allowed charge C_{min} the load will be fed by the conventional power source. At the same time the PV field is connected only to the battery and charging it until a given state of charge (typically 0.89 C_{max}) has been reached, then the load is connected again to the PV plant. If the battery reaches the maximum charge, C_{max}, and energy generated by the PV plant exceeds the load demand.

II. Theory

II.1 Solar cell

A solar cell is made of two very thin layers of semiconductor materials which is usually a silicon. These materials are doped with other materials in order to give a negative electrical bias (p-type semiconductor) and the other a positive bias (N-type semiconductor). The p- and n-type semiconductors are then brought into contact to create a p-n junction which is called a diode or a solar cell. In the region of the junction the electric field is created by the transfer of mobile carriers through the recombination process until reaching electrically equilibrium. This region with electric field may be called a depletion region a barrier. It is a region of empty charged carries. Whenever, the charged carrier enter in this region they will be depleted by the electric field. When the sunlight strikes the region of the junction electron-hole pairs will be created and flows through the external circuit which is attached to the front and the back of the solar cell through the load. This leads to a current flowing through the load to perform work. If the load is a motor as a d.c. electric motor it will be operated by the current as shown in a diagram.

The solar cells are then connected together both in a series and parallel in order to provide high power which is called a PV array.

II.2 Formula used in calculation

- Solar energy power input

$P_{sin} = E \times A$ (watt)

E = solar insolation (watt/m^2)

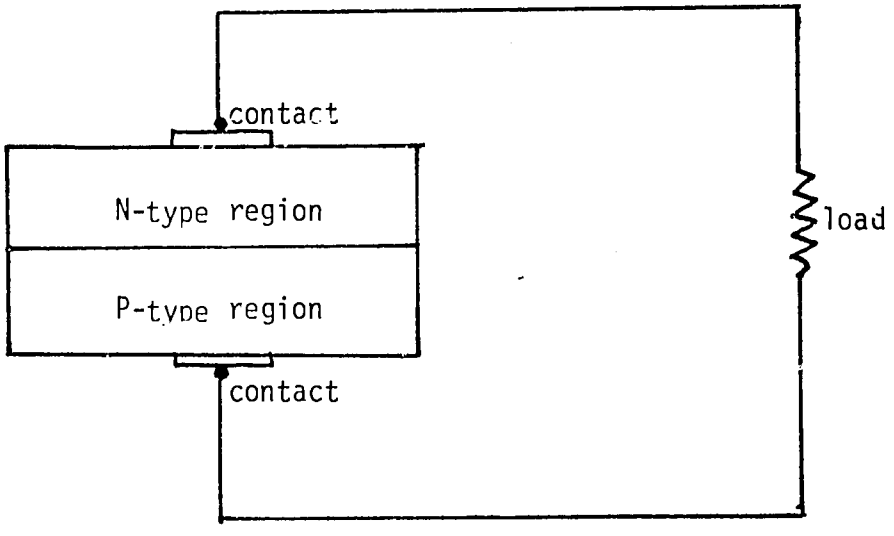
A = P.V. array surface (m^2)

- Power output from the PV array to the MPC

$P_o = VI$

V = voltage (volts)

I = current (ampere)


contact
N-type region
P-type region
contact
load

- Efficiency of the PV array with or without MPC

$$\eta_{PV} = \frac{P_0}{P_{sin}} \times 100 = \frac{VI}{EA} \times 100\%$$

- Power input, the pump

$$P_{inp} = P_0 = VI \text{ (watt)}$$

- M.P.C. efficiency

$$\eta_{npc} = \frac{V_2 I_2}{V_1 I_1} \times 100\%$$

V_2, I_2 voltage and current after MPC

V_2, T_2 voltageand current before MPC

- Power output, the pump

$$P_{op} = \delta QH = \delta gQH \text{ (watt)} = \rho g QH$$

$\delta = 9800 \text{ N/m}^3$

Q = discharge m^3/s

H = head m

- Pump efficiency

$$\eta_p = \frac{P_{op}}{P_{inp}} \times 100 = \frac{\delta QH}{VI} \times 100\% \text{ (watt)}$$

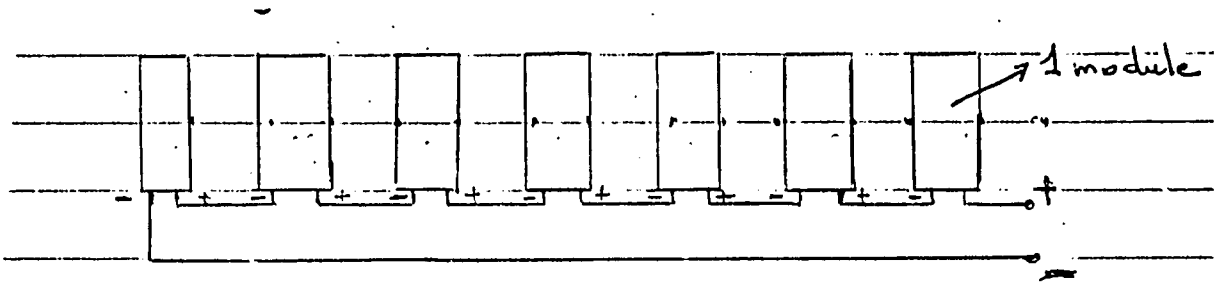
- PV system efficiency

$$\eta_{system} = \frac{P_{op}}{P_{sin}} \times 100 = \frac{\delta QH}{EA} \times 100\%$$

III. Description of the PV system

The PV system consists of: a PV array (semicrystalline silicone cells) of 7 modules that produce d.c. electricity, a Maximum Power controller which is a electronic service that controls the power and allows the pump to operate with a maximum power, and a pump for pumping water.

III.1 P.V. array



- 1 module: solarex

  type SX 110 serial n° L-07/9/50

  surface: 42 in x 17.5 in = 735 in^2 = 0.474 m^2

  voltage at peak power 17.25 volt

- the array

  - 7 modules in series

  - surface = 3.32 m^2

  - voltage at peak power: 120 volts

III.2 Maximum Power Controller (MPC)

An electronic device which controls the power to the pump and allowed to operate at maximum power.

III.3 The pump

Type SEI 250

d.c. motor

submersible, variable voltage and speed

nominal operation: 3000 RPM at 60 volts d.c.

III.4 Instruments of measure

- Voltmeter: type Simpson 0-150 volts d.c.

- Ampermeters: type Simpson 0-15 amperes

- Pyranometer: eppley radiometer mode 8-48 C = 89.286 w/m^2 mv

- Resistance: 0-200 Ω (variable)

- Millivoltmeter:

IV. Condition of experiment

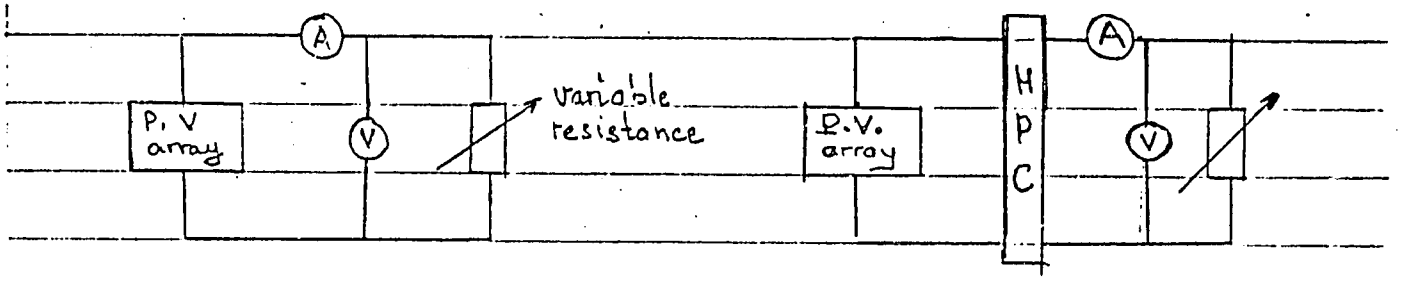
The PV system is located in TREEO center (Gainesville, Florida). All the data had been taken outside with solar radiation, between 10 a.m. and 4 p.m. Changing weather: sometimes clear sky, sometimes cloudy sky.

V. Experiment

V.1 P.V. array characheristics

a. without MPC

b. with MPC

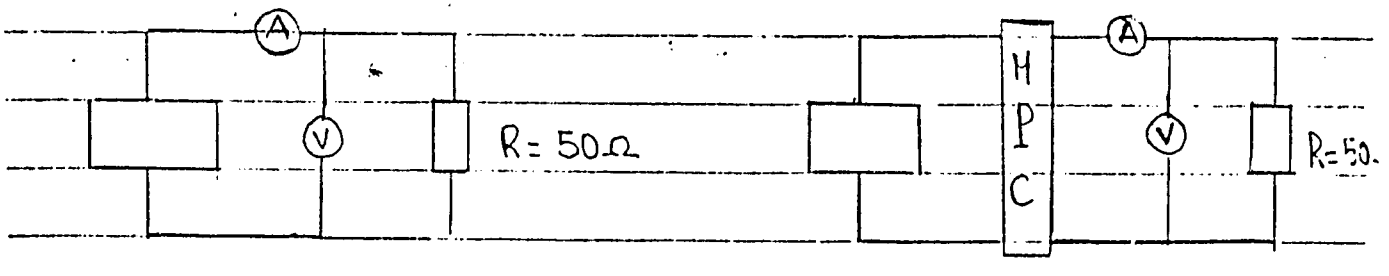


within a little interval of time (less than 1 min) in which the solar insolation is assumed constant, the load is adjusted from short circuit to open circuit. The voltage and current are recorded. The results of this experiment are tabulated.

V.2 P.V. system performance

a. without NPC

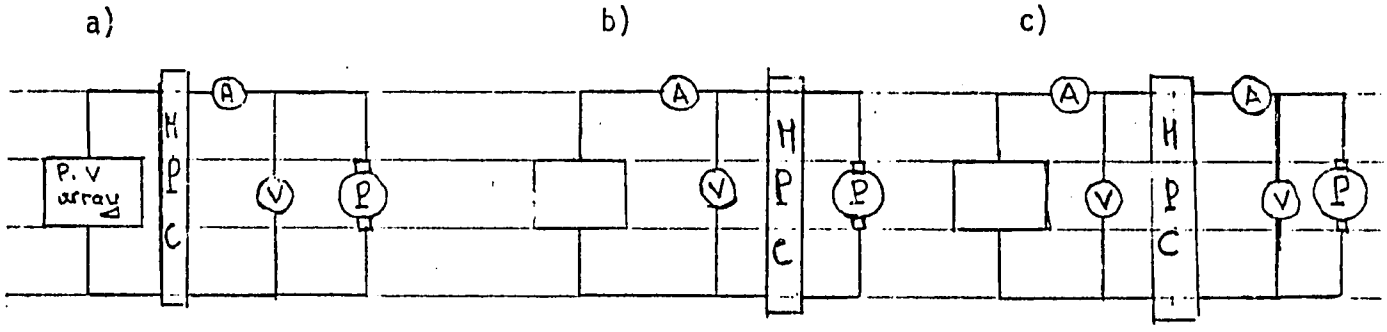
b. with NPC



Between 10 a.m. and 4 p.m., the PV array was exposed to variable sunlight. On constant resistance set 50Ω was used as a load. The insolation, voltage, and current are recorded.

Results of this experiment are tabulated

V.3 P.V. system with pump as load



The results of this experiment are tabulated

VI. P.V. array characteristic

VI.1 Operation without MPC

The P.V. array will be always characterized by its I-V curve where I and V are the output current and voltage of the array resp. This will be first examined without using a maximum power control (MPC), then with switching a MPC between the array and the load. This will also explain the function of the MPC in the system.

Table (1) shows the obtained measurement results without MPC. The load is an ohmic resistance which can be varried from 0 to 200 Ω with a rated power of 200 W. Fig. 6.1 represents the I-V curves of the array with the insolation as a parameter. From these graphs it is clear that the output current increases with growing insolation (E).

The graph for E = 891 W/m^2 point out through the whole load range the highest current values. This means that at a constant temperature of the array the array output power increases also with growing insolation. As the results which will be shown later, the increasing of the cells temperature has a negative effect on the array efficiency. Fig. (6.1) shows also that the load increasing causes voltage drop and current increasing respectively. From all three graphs it is also clear that the amount of the insolation has not a big influence on the open circuit voltage of the array but it has an influence on the short circuit current.

P.V. array characteristic (without MPC)

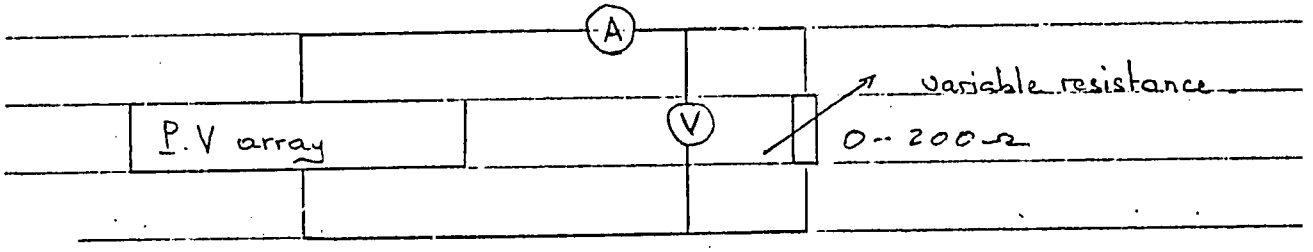


Table VI.1.

Insolation E = 891 w/m^2		E = 455 w/m^2		E = 300 w/m^2	
V_{Volt}	I_{Amp}	V	I	V	I
130	0.7			123	0.65
120	1.2			120	0.75
110	1.5	115	0.64	110	0.85
100	1.65	114	0.75	100	0.85
90	1.75	90	0.9	90	0.9
80	1.8	80	0.9	80	0.91
70	1.84	70	1	70	0.94
60	1.85	60	1	60	0.95
50	1.86	50	1	-	-
40	1.86	40	1	40	0.96
30	1.86	30	1	30	0.97
20	1.87	20	0.95	20	0.97
10	1.89	10	0.95	10	0.98
2	1.9	2	1	2	1

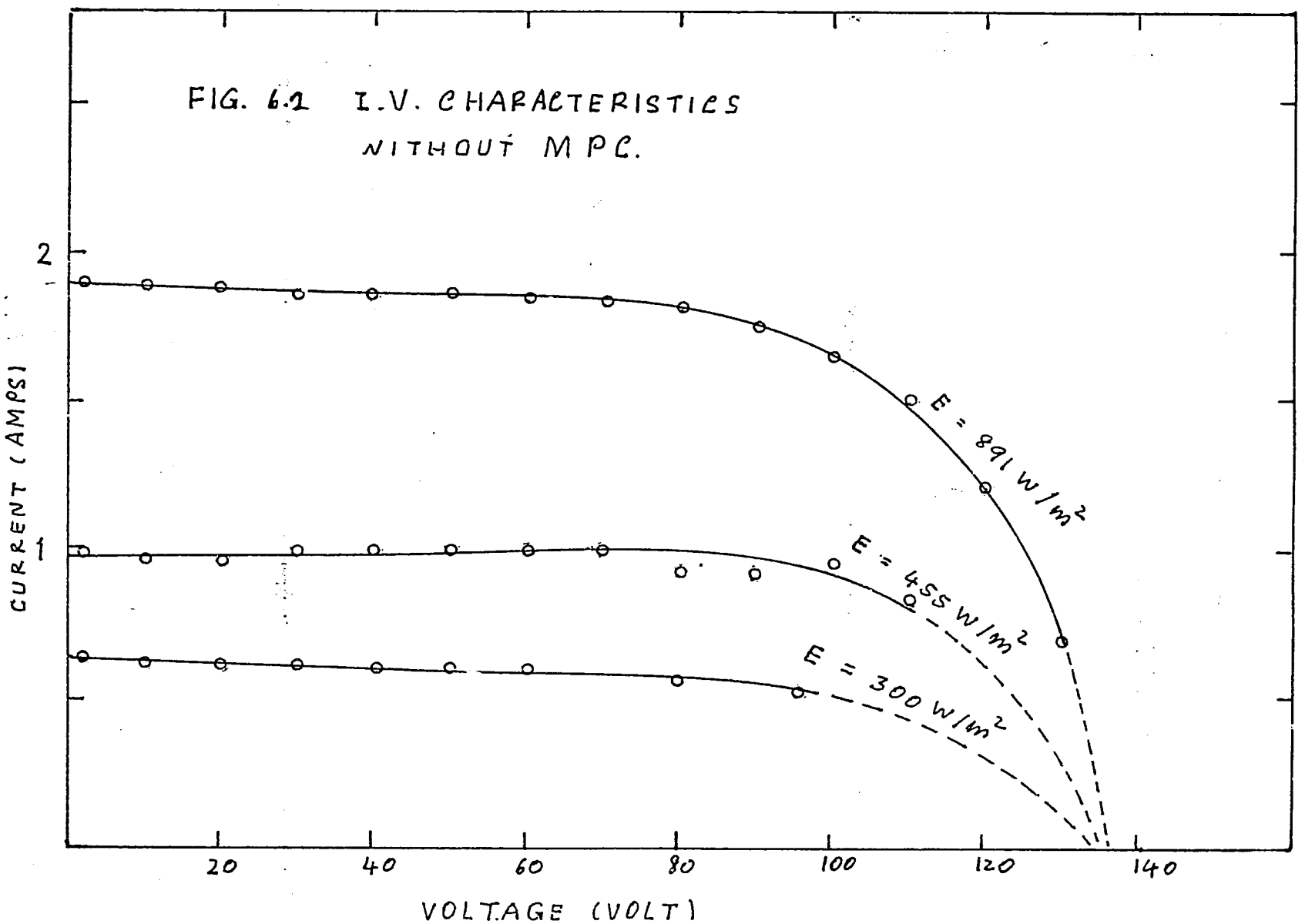


FIG. 6.1 I.V. CHARACTERISTICS
WITHOUT MPC.
CURRENT (AMPS)
2
1
E = 891 W/m²
E = 455 W/m²
E = 300 W/m²
20
40
60
80
100
120
140
VOLTAGE (VOLT)

VI.2 Operation with MPC

Table (6.2) shows the measurement results with the used electrical circuit above. Fig. (6.2) which concerns to Table (6.2) represents the relation between the voltage and the current of the PV array at different insolations. Also here the graph at the highest insolation point out through the whole load range the highest current values. Only at a very low load (I = 0.5A) the three graphs meet in one point and show the same current values. In respect to Fig. (6.7) (no MPC). Fig. (6.2) shows especially at high load that through the MPC the change of the voltage causes a higher change in the output current. This means that through the MPC the internal resistance of the system will be very small and the circuit (PV array + MPC) become the character of a current source.

Fig. 6.2b shows the effect of the MPC on the output variables. The relation between the output variables (I,V) of the system and the load variation with and without switching a MPC is presented in Fig. (6.3). Both experiments were done at about the same insolation (no MPC: $E = 891\ W/m^2$ and with MPC: $E = 889.7\ W/m^2$.

In load range I (low load $R_L = 200 - 48\ \Omega$) it is clear that the voltage current and the output power are higher when there is no MPC between the PV array and the load. This means that in this case the MPC will be superfluous.

In load range II (high load $R_L = 48 - 0\ \Omega$) the relation between the output variables and the load are inverted. The voltage and the current graphs by using MPC shows the higher values. This means that the output power is also higher and the switching of the MPC will be useful.

In this range it is also important to notice that the change of the load causes a high change in the current when there is a MPC in the circuit relative to it when there is no MPC.

Moreover, in the two cases both output voltage graphs show only little difference in variation. This means that through the MPC the internal

VI.3 P.V. array characteristic (with MPC)

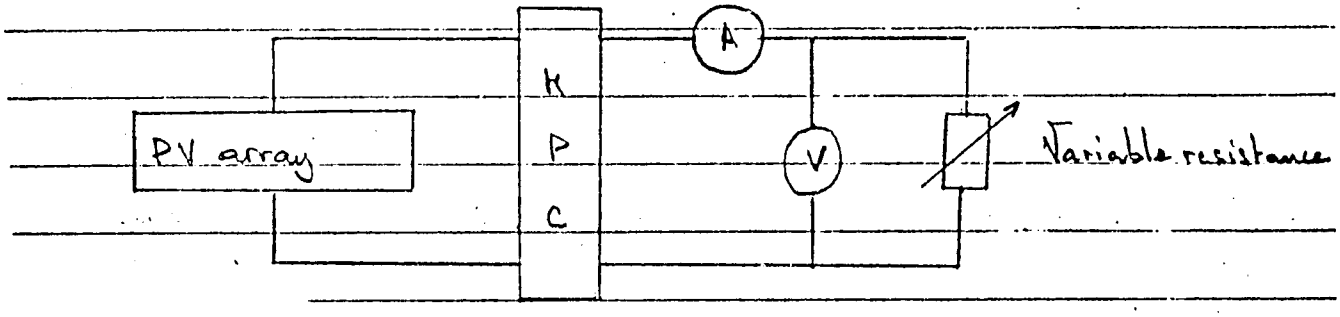


Table VI.2b

Insolation E = 267.8 W/m^2		E = 563.1 W/m^2		E = 889.7 W/m^2	
V_{Volt}	I_{Amp}	V	I	V	I
94	0.5	95	0.5	95	0.5
90	0.52	95	0.8	95	0.9
80	0.56	96	1	94	1.3
70	0.62	92	1.1	87	1.7
60	0.75	90	1.2	80	2.1
50	0.85	84	1.3	68	2.5
40	1	74	1.5	55	3.1
30	1.35	68	1.6	49	3.95
20	2.1	61	1.8	40	4
10	3.7	55	2	30	5
4	5	50	2.2		
		45	2.4		
		40	2.7		
		35	3		
		30	3.5		
		25	4		
		20	5		

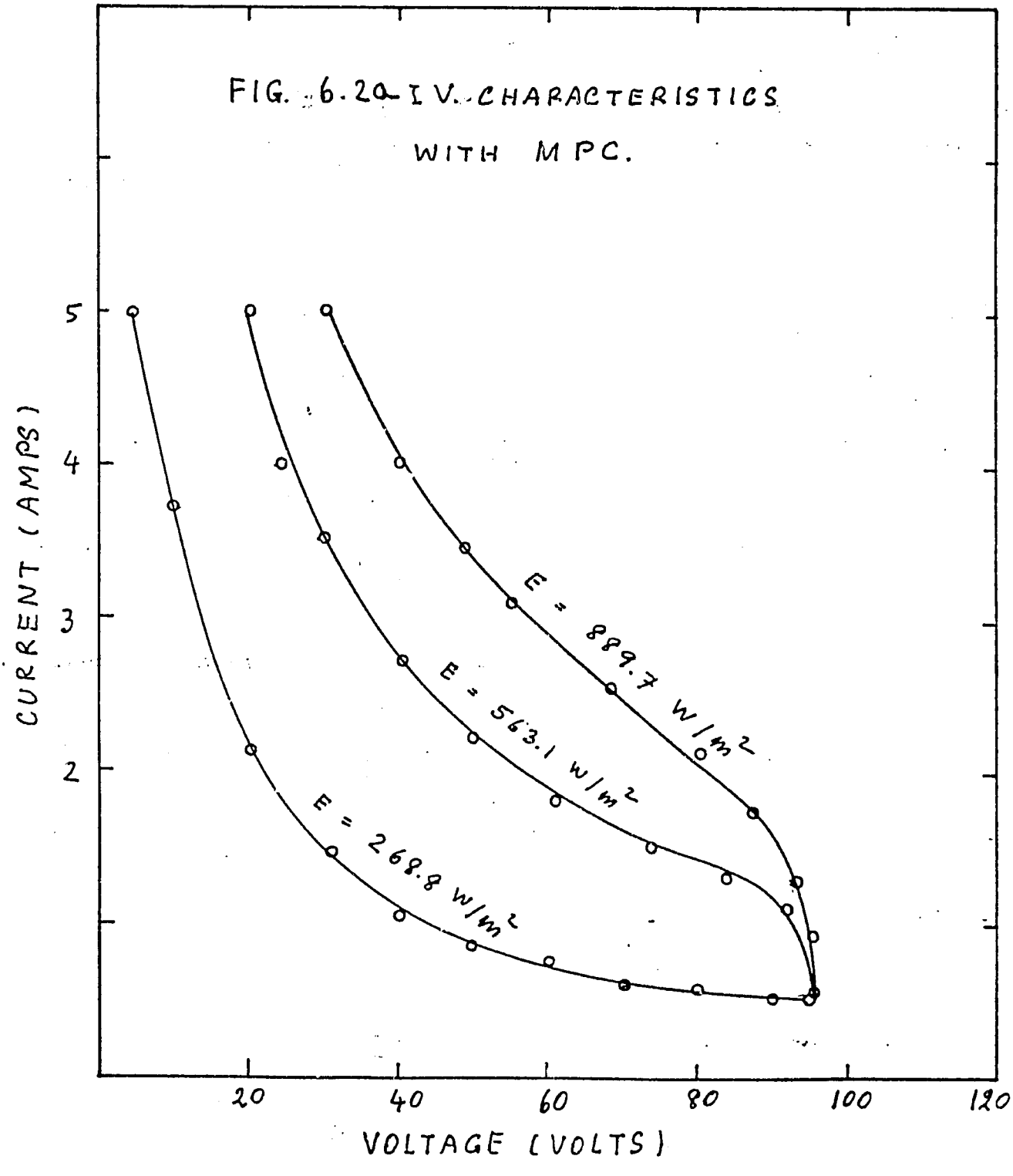


FIG. 6.2a I V. CHARACTERISTICS
WITH MPC.
CURRENT (AMPS)
5
4
3
2
E = 889.7 W/m²
E = 563.1 W/m²
E = 268.8 W/m²
20
40
60
80
100
120
VOLTAGE (VOLTS)

Figure: 2

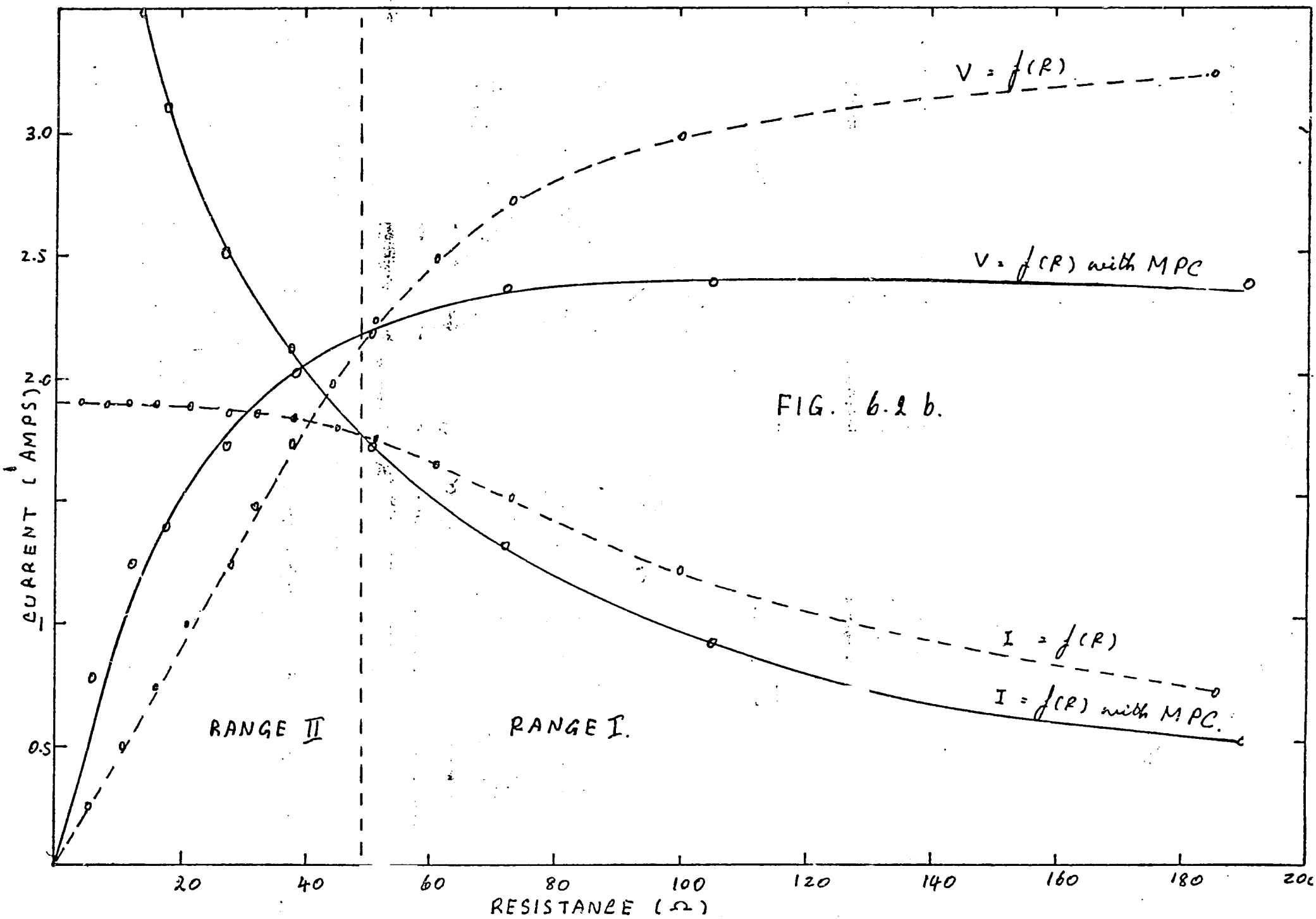

V = f(R)
V = f(R) with MPC
I = f(R)
I = f(R) with MPC.
RANGE II
RANGE I.
CURRENT (AMPS)
RESISTANCE (Ω)
3.0
2.5
2.0
1
0.5
20
40
60
80
100
120
140
160
180
200

FIG. 6.2 b.

resistance of the system becomes lower. Because of this, the short circuit current arises from 1.9 Amps to 6 Amps.

Finally, the above results show that the function of the MPC is the tracking of the I-V curve to deliver the load the maximum power from the PV array.

VI.3 The efficiency of the MPC

The MPC is a DC-DC electric converter which has a very high efficiency. The reason for this is that the electronic circuits of the MPC has a very low power consumption. For efficiency calculations of the MPC its output power and its input power were measured. The measurement results and the efficiency are shown in Table 3. From this it is clear that the input power has no influence on the efficiency which varies in the whole power range between 92-99%.

Table (6.3) shows moreover that the coil resistance of the pump is about 20 Ω. A comparison between the input and the output resistance of the MPC will show that the MPC works as a resistance transformer.

VI.4 PV system performance with MPC

In this part of the experiment with the set up shown in Table 6.4, current coming out of and voltage across the MPC is measured with a constant load (50 Ω). Then power output and efficiency are calculated. Power outputs calculated from measured values are plotted against power input in Fig. 6.4a. As can be seen from the graph, power output varies linearly up to an input power of 2667.9 W(803.6 W/m^2). After this point the output power starts to decrease which is probably due to the increase in temperature of the PV array.

In Fig. 6.4b the efficiency is plotted as a function of the power input to the system. Efficiency reaches its maximum value at 2.3 kW of input power and after that point starts to decrease probably due to the temperature increase of the PV array. When we compare this curve with Fig. 6.5b we see the effect of MPC.

P.V. system with pump as a load

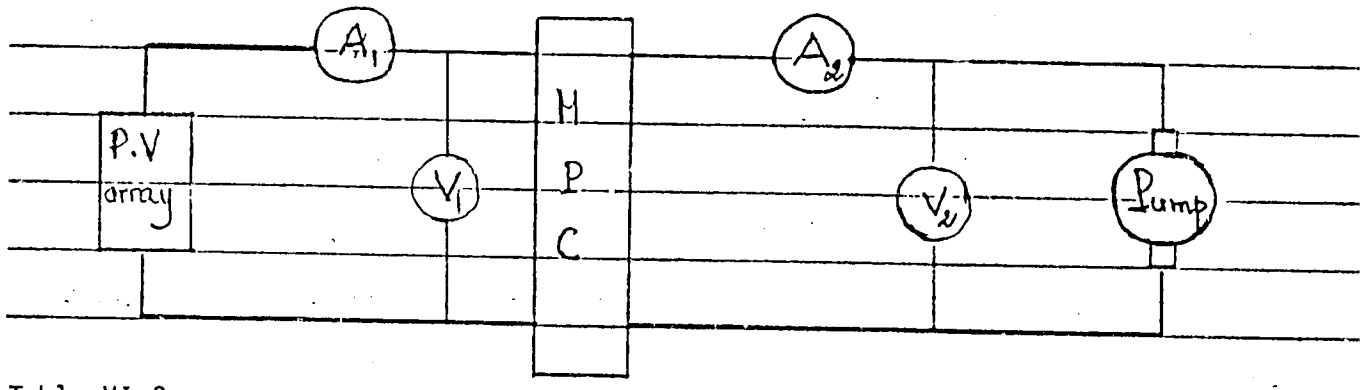


Table VI.3

Insolation W/m^2	Power Input P.V. W	I_1 Amp	V_1 Volt	P_1 Watt	I_2	V_2	P_2	$\eta_{NPC}=\frac{P_2}{P_1}$
314.3	1043.4	0.6	105	63	1.6	36	57.6	0.92
337.5	1120.5	0.6	105	63	1.65	37.5	61.88	0.98
500	1660	0.95	105	92.75	2.2	45.2	99.44	0.99
578.6	1220.9	1.15	105	120.75	2.4	48.4	116.16	0.96
654.8	2174	1.3	105	136.5	2.6	51.1	132.86	0.97
750.6	2492	1.5	101	151.5	2.8	54.1	151.48	0.99
788.8	2618.7	1.6	104	166.4	2.9	55.2	160.08	0.96
846.8	2811.3	1.75	100	175	2.95	56.6	166.97	0.95
890.7	2957.2	1.8	98	176.4	3	57.5	172.5	0.97

P.V. system performanced with MPI

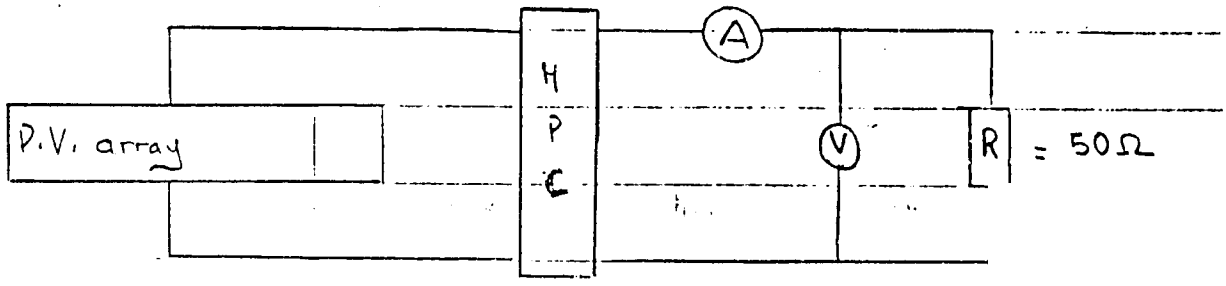


Table VI.4

Insolation ..... W/m^2	Power input PV W	V_{Volt}	I_{Amp}	Power output (V.I.) Watt	Efficiency N %
214.3	711.4	42	0.75	31.5	4.4
236.1	770.7	43.5	0.8	34.8	4.5
250	830	47	0.85	39.95	4.8
267.9	889.3	49	0.87	42.6	4.8
276.8	918.9	50	0.9	45	4.9
285.7	948.6	54	0.95	51.3	5.4
294.6	978.2	52	0.9	46.8	4.8
303.6	1007.9	56	1	56	5.6
410.7	1363.6	66	1.15	75.9	5.6
464.3	1541.4	80	1.4	112	7.3
678.6	2252.9	87	1.56	135.7	6
741.1	2460.4	92	1.65	151.8	6.2
803.6	2667.9	93	1.7	158.1	5.9
812.5	2697.5	94	1.7	159.8	5.9
830.4	2964.3	94	1.7	159.8	5.4
994.6	3302.2	92	1.65	151.8	4.6

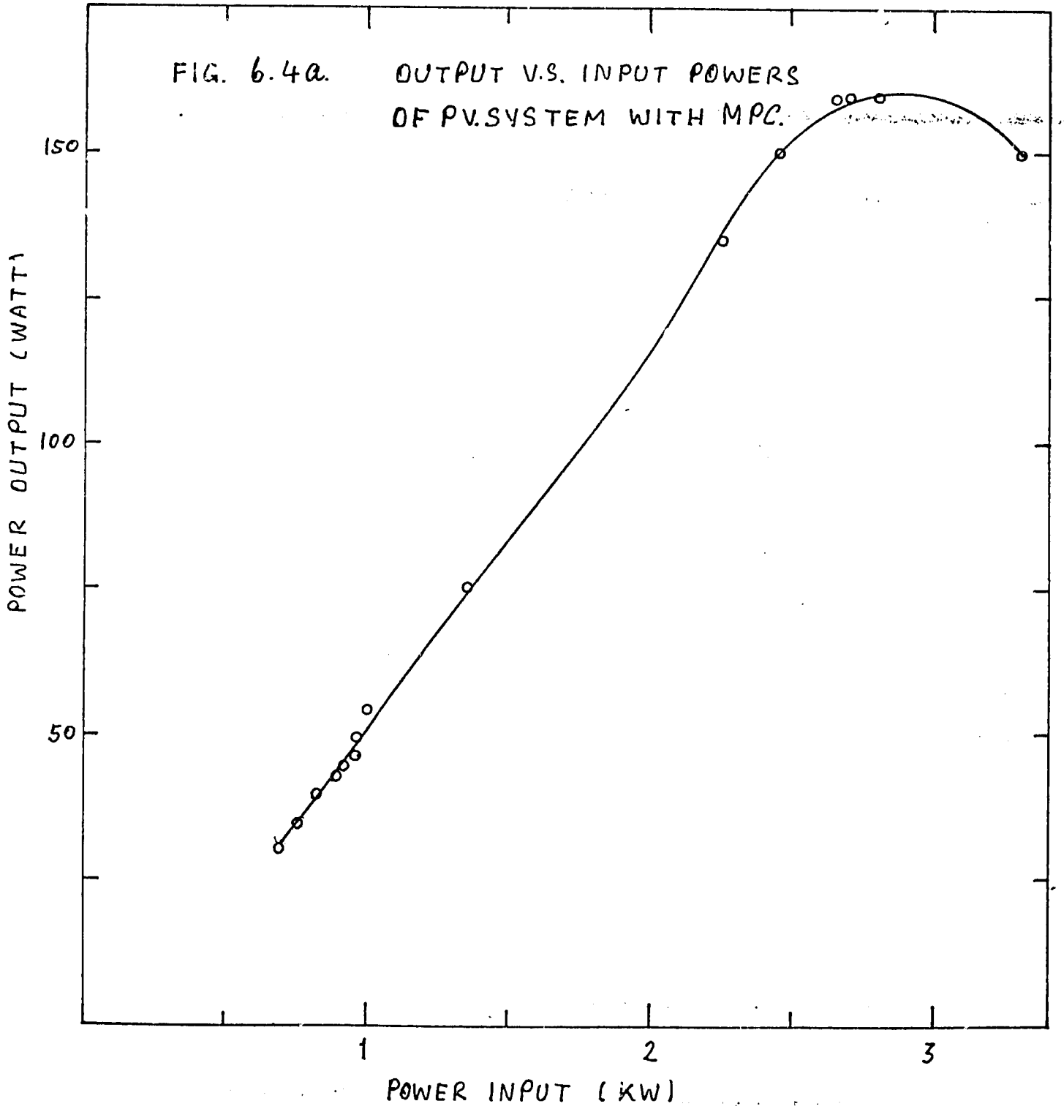


FIG. 6.4a. OUTPUT V.S. INPUT POWERS
OF PV.SYSTEM WITH MPC.
150
100
50
POWER OUTPUT (WATT)
1
2
3
POWER INPUT (KW)

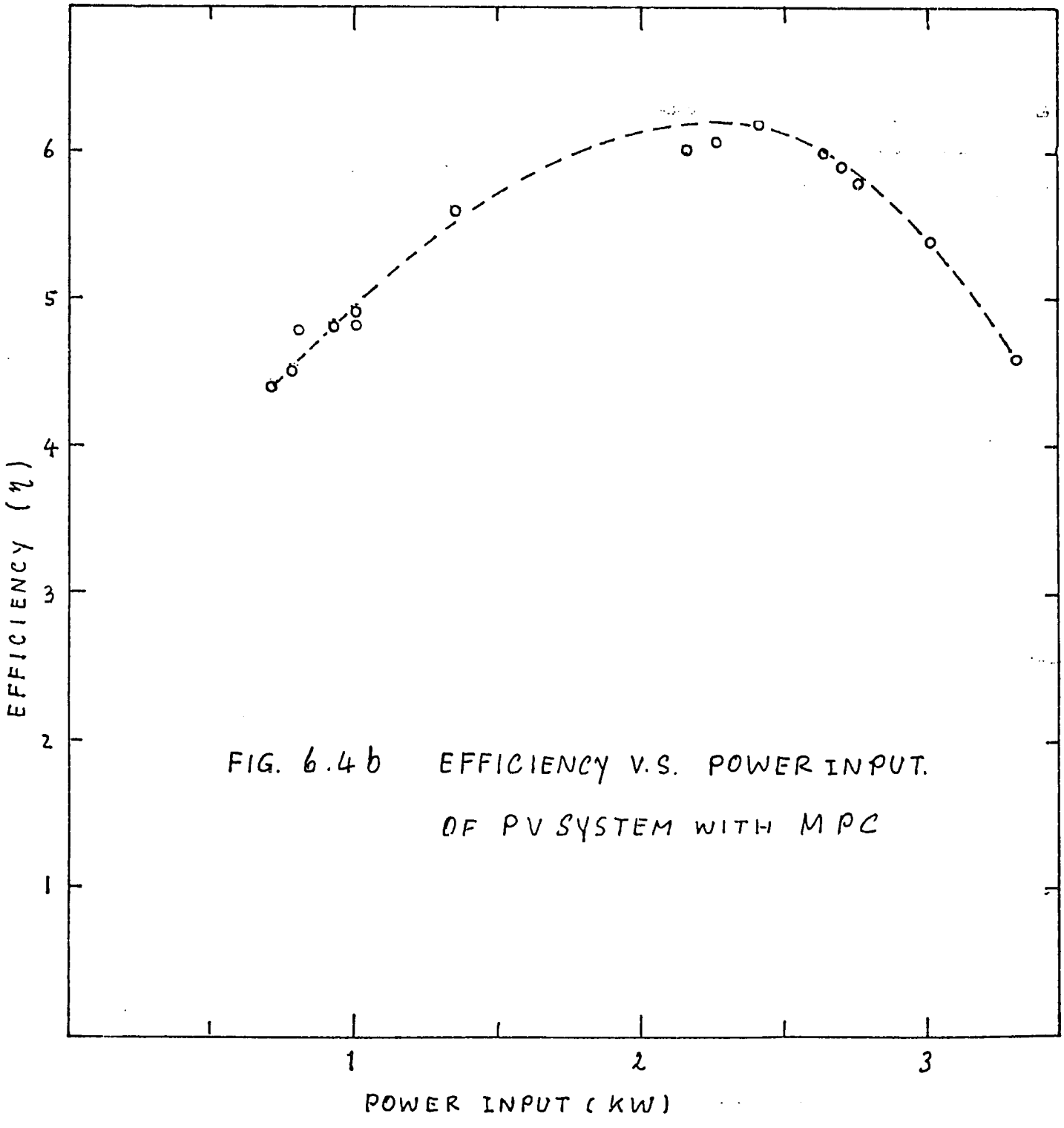


FIG. 6.4b EFFICIENCY V.S. POWER INPUT. OF PV SYSTEM WITH MPC

VI.5 P.V. systems performance without MPC

In this part of the experiment with the set up shown in Table 6.5 voltage across and current coming out of the PV array is measured power output and the efficiency of the PV array are calculated.

The relation between output power of the PV array and the input power is shown in Fig. 6.5a. This graph shows that the output power varies linearly with input power through the 1.5-3kw range.

Power input v.s. efficiency graph for the PV array is plotted in Fig. 6.5b. As it can be seen from the graph efficiency varies linearly w.r.t. power input up to 2.519 watts. Then it curves down also probably due to the temperature increase of the photovoltaic array.

VI.6. PV system performance with MPC and pump

In this part of the experiment, for each insolation, the voltage across and current flowing out of the PV array is measured and the power output of the PV array is calculated. Output power of the pump is determined by measuring the amount of the work done by the water pump for lifting a certain amount of water to a certain height under gravity conditions in a certain time interval. Then the efficiencies of the PV array and the system are calculated.

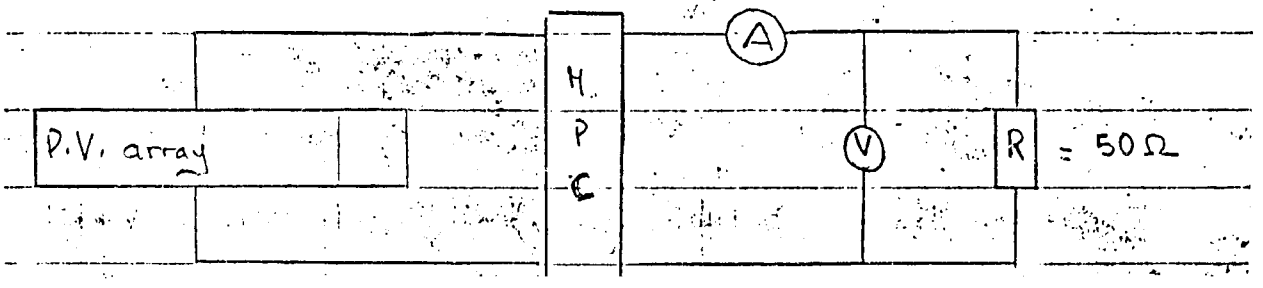
Output powers of PV array and water pump v.s. input power to the system (due to insolation) are plotted in Fig. 6.6a and 6.6b.

Output of the PV array varies linearly w.r.t. the insolation up to 2.667 kw, then it starts to decrease which is probably due to the increase in temeprature of the PV array (Fig. 6.6a).

On the other hand, output of the water pump increases linerly up to 1.5 kw of input power where it curves down but still continues to increase linearly. Efficiencies for different insolation of PV array and system are plotted in Fig. 6.6c and Fig. 6.6d respectively. Efficiency of the PV array which increases up to 2.15 kw of input power starts to decrease at this point probably due to the increase in temperature at higher insolations.

System efficiency which reaches its maximum value (1.8%) at 1.5 kw of input power starts to decrease at this point and for the maximum insolation (985.7 W/m^2) gets the value 1.4%.

VI.5 P.V. system performance without MPI



Insolation W/m^2	Power Input PV W	V_{Volt}	I_{Amp}	Power output (V.I.) Watt	Efficiency η %
157.1	521.7	20	0.34	6.8	1.3
205.4	681.8	25	0.45	11.25	1.7
223.2	741.7	25	0.45	11.25	1.5
241.1	800.4	30	0.5	15	1.9
276.8	918.9	34	0.6	20.4	2.2
383.9	1274.7	45	0.8	36	2.8
678.6	2253	84	1.5	126	5.6
714.3	2371.4	88	1.6	140.8	5.9
741.1	2460.4	90	1.62	145.8	5.9
758.9	2519.6	92	1.65	151.8	6
928.5	3082.9	105	1.9	199.5	6.5
991	3290.4	105	1.9	199.5	6.1

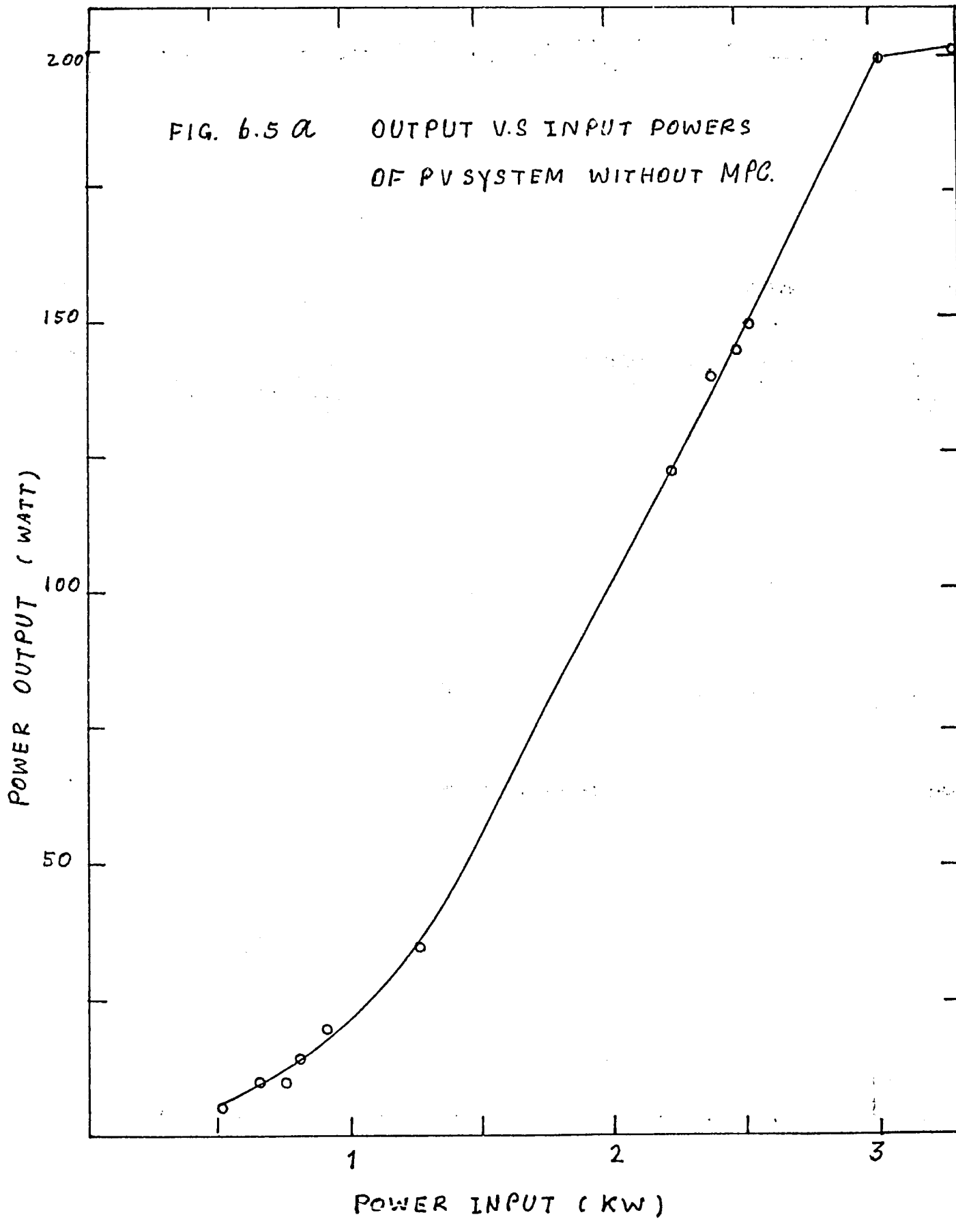


FIG. 6.5 a OUTPUT V.S INPUT POWERS OF PV SYSTEM WITHOUT MPC.

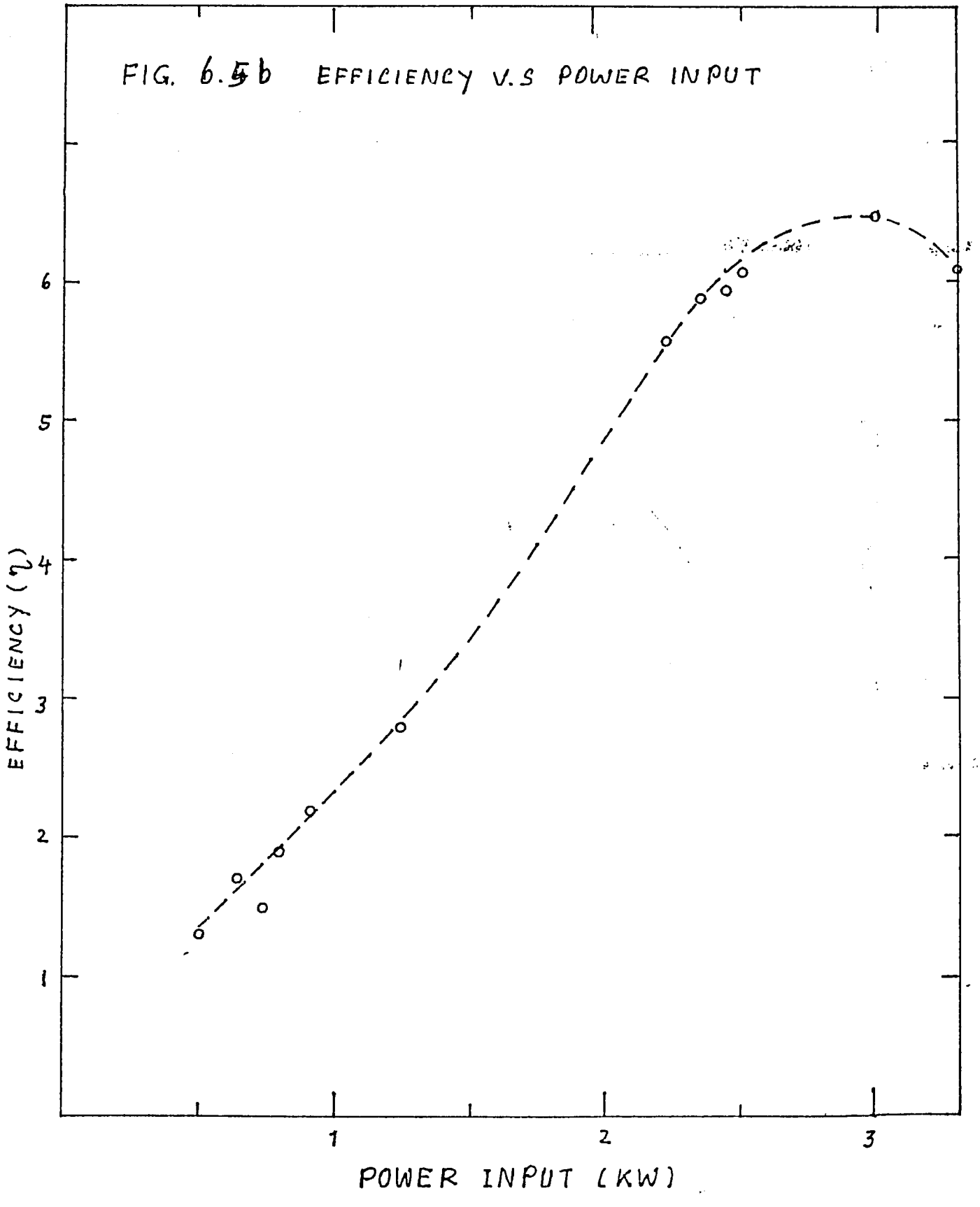


FIG. 6.5b EFFICIENCY V.S POWER INPUT
EFFICIENCY (η)
6
5
4
3
2
1
1
2
3
POWER INPUT (KW)

P.V. system performance

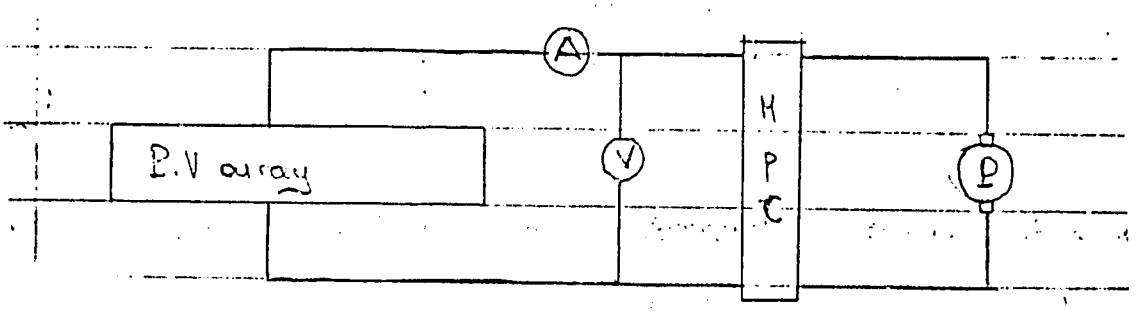


Table VI.6

W/m^2	W	V_{Volt}	I_{Amp}	Power input PV VI Watt	Pump power output Watt	Efficiency % η_{PV} Array	Efficiency % η_{system}
258.9	859.6	88	0.5	44	5.24	5.1	0.6
267.86	889.3	95	0.5	47.5	5.39	5.3	0.6
401.8	1333.9	110	0.7	77	20.94	5.8	1.6
410.7	1363.6	110	0.8	88	23.56	6.5	1.7
446.4	1482.2	110	0.7	77	26.93	5.2	1.8
482.1	1600.7	110	0.9	99	26.93	6.2	1.7
544.6	1808.2	110	1	110	31.41	6.1	1.7
732.1	2430.1	110	1.5	165	37.7	6.8	1.6
758.9	2519.6	107	1.5	160.5	37.7	6.4	1.5
803.6	2667.9	105	1.6	168	39.68	6.3	1.5
985.7	3272.5	105	1.4	147	47.12	4.5	1.4

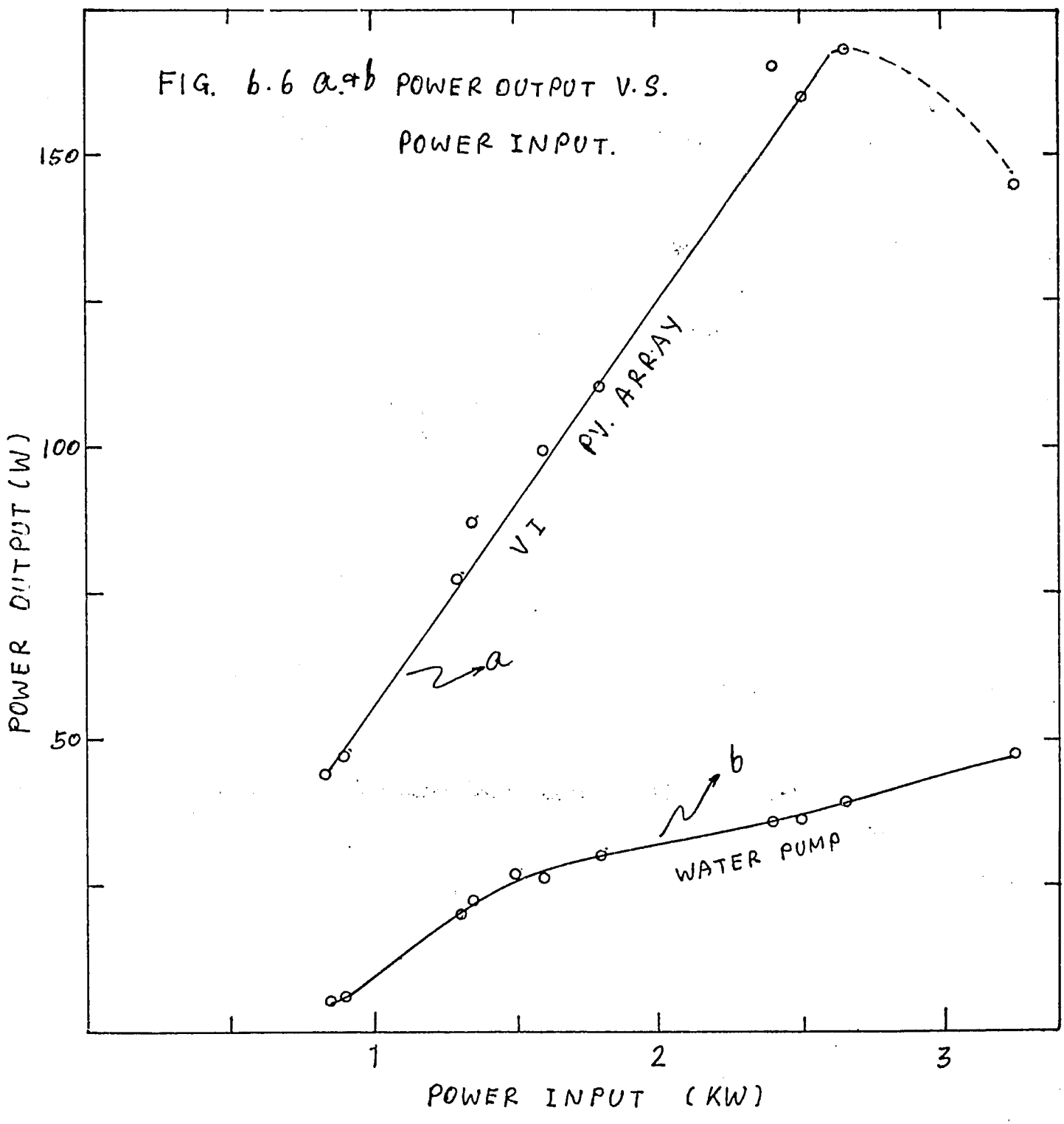


FIG. 6.6 a&b POWER OUTPUT V.S. POWER INPUT.
150
100
50
POWER OUTPUT (W)
VI
PV. ARRAY
a
b
WATER PUMP
1
2
3
POWER INPUT (KW)

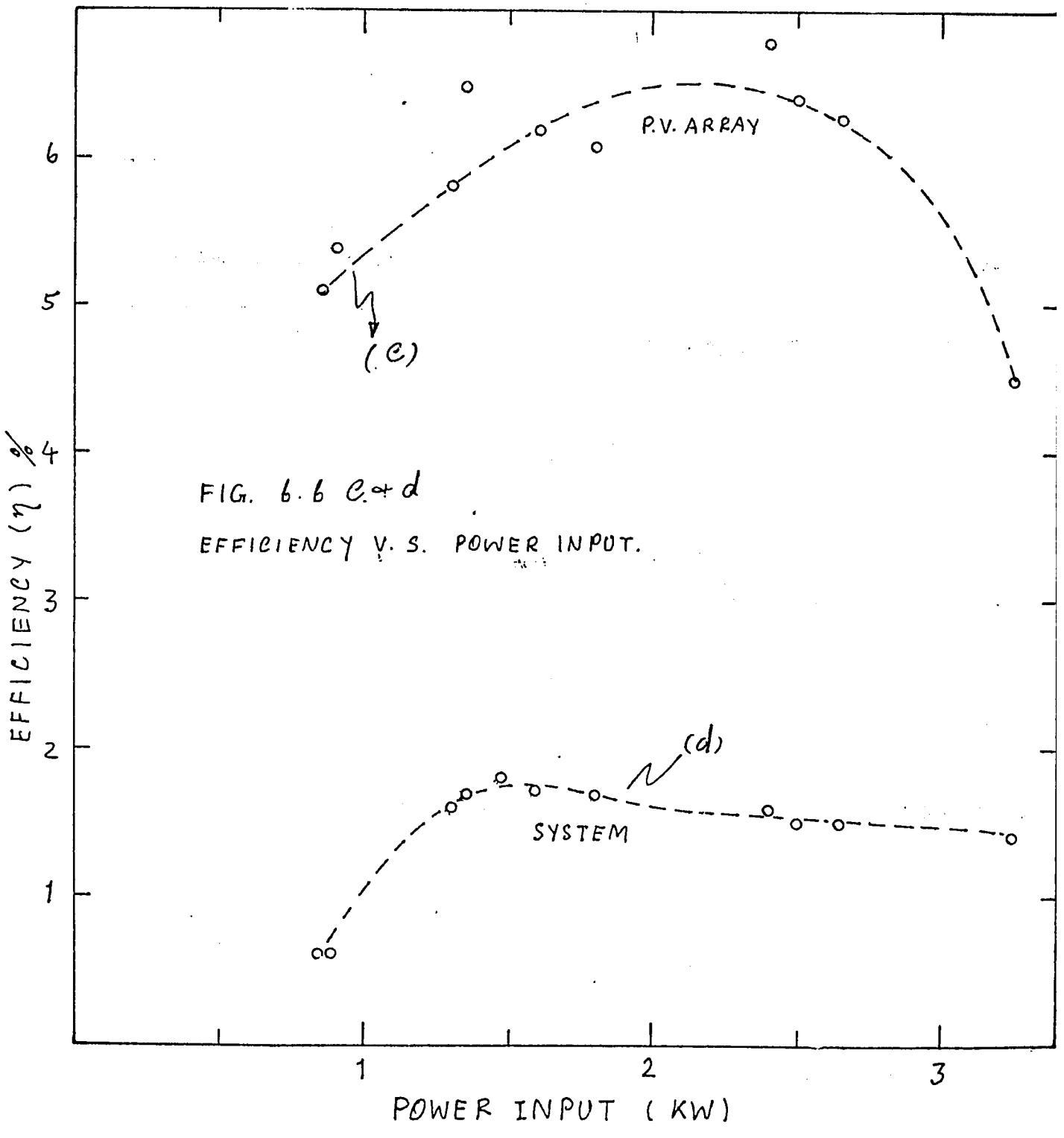


FIG. 6.6 c & d

EFFICIENCY V.S. POWER INPUT.

VI.7 PV performance with pump as a load

To see the effect of the MPC we measured the current coming out of and voltage across the MPC. Then we calculated power delivered by the MPC to the pump. We also calculated the power output of the pump with the same method used in section 6.6. Using the data obtained we calculated the efficiencies of i) the photovoltaic array with MPC, ii) the pump and iii) the system.

When we compare Fig. 6.6a with Fig. 6.7a we see that power output of PV array is not affected by the MPC.

As we expected it to be so the power output of the water pump is not affected by the presence of MPC (Fig. 6.6b is the same as Fig. 6.7b).

Efficiency of the pump v.s. the power input is plotted in Fig. 6.7c which reaches its maximum (30.75%) at 1.5 kw input power. Efficiency of the PV array with MPC is plotted in Fig. 6.7d. When we compare this graph Fig. 6.6c which gives the efficiency of PV array alone we see that for higher insolations we can improve the efficiency by using MPC.

Fig. 6.7e is a plot of the system efficiency v.s. input power to the system which has the same curve as Fig. 6.6d.

VIII. Economic Analysis

Cost of the PV system

Photovoltaic panel (7)	$2,100.00
MPC	550.00
D.C. submersible pump	980.00
	$3,630.00

At the present stage of the PV technologies, the equipment is still very expensive but we hope, that in the next few years, the cost will be decreased.

PV performance with pump as a load

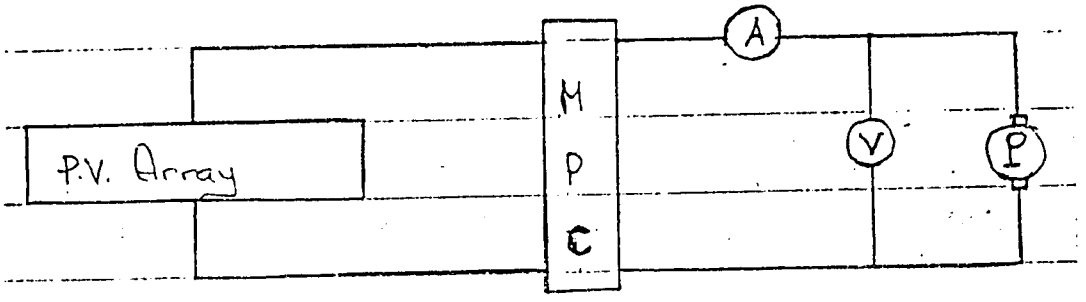


Table VI.7

Insol-ation w/m^2	Power input PV w	V volt	I amp	Power out-put MPC (VI) watt	Q m^3/s	Power out-put pump watt	Effi-ciency η_{PV} with MPC	% η_{pump}	% η_{pump}
241.1	800.4	34	1.1	37.4	0.177	3.28	4.7	8.77	0.41
282.2	936.7	36	1.3	46.8	0.52	9.64	5	20.6	1.03
312.5	1037.5	38	1.4	53.2	0.696	12.89	5.1	24.2	1.24
357.1	1185.7	40	1.55	62	0.88	16.31	5.2	26.3	1.38
383.9	1274.6	40	1.7	68	1.19	22.05	5.3	32.4	1.73
392.8	1304.3	42	2.2	92.4	1.56	28.9	7.1	31.27	2.2
410.7	1363.6	44	1.9	79.2	1.44	26.69	5.8	33.7	1.96
463.6	1539	48	2.3	110.4	1.69	31.32	7.2	28.30	2
512.5	1701.5	54	2.2	118.8	1.64	30.39	7.0	27.6	1.79
533	2104.6	52	2.4	124.8	1.94	35.95	5.9	28.8	1.71
642.9	2134.3	53	2.45	129.85	2.05	37.99	6.1	29.26	1.78
669.6	2223.2	54	2.5	135	2.24	41.51	6.1	30.75	1.87
750	2490	60	2.9	174	2.32	43	7	24.7	1.73
803.6	2668	60	2.9	174	2.37	43.92	6.5	25.24	1.64
883.9	2934.6	62	3	186	2.65	49.11	6.3	26.4	1.67

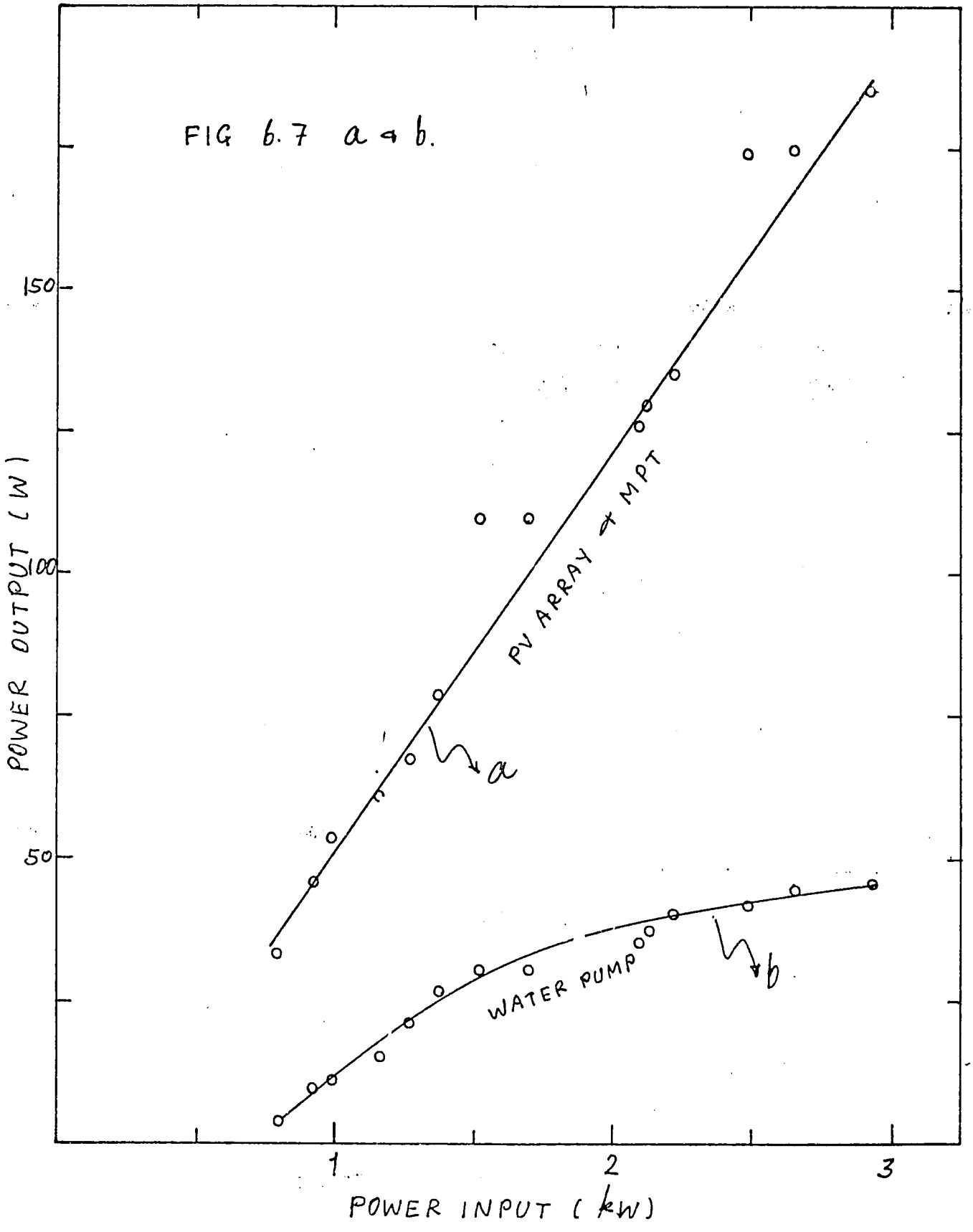
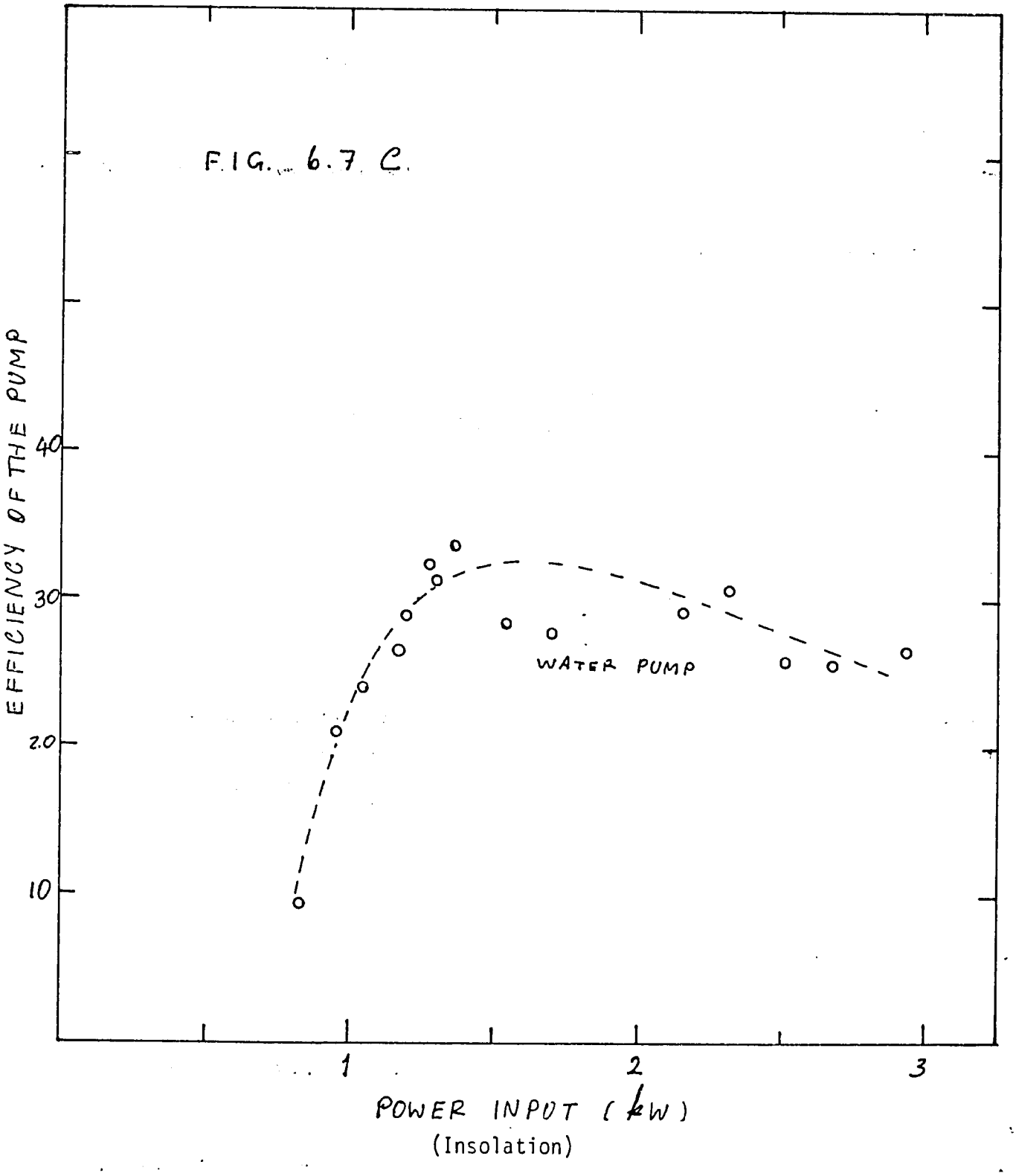


FIG 6.7 a & b.
150
100
50
POWER OUTPUT (W)
PV ARRAY & MPT
a
WATER PUMP
b
1
2
3
POWER INPUT (kW)


F.IG. 6.7 C.
EFFICIENCY OF THE PUMP
40
30
2.0
10
WATER PUMP
1
2
3
POWER INPUT (kW)
(Insolation)

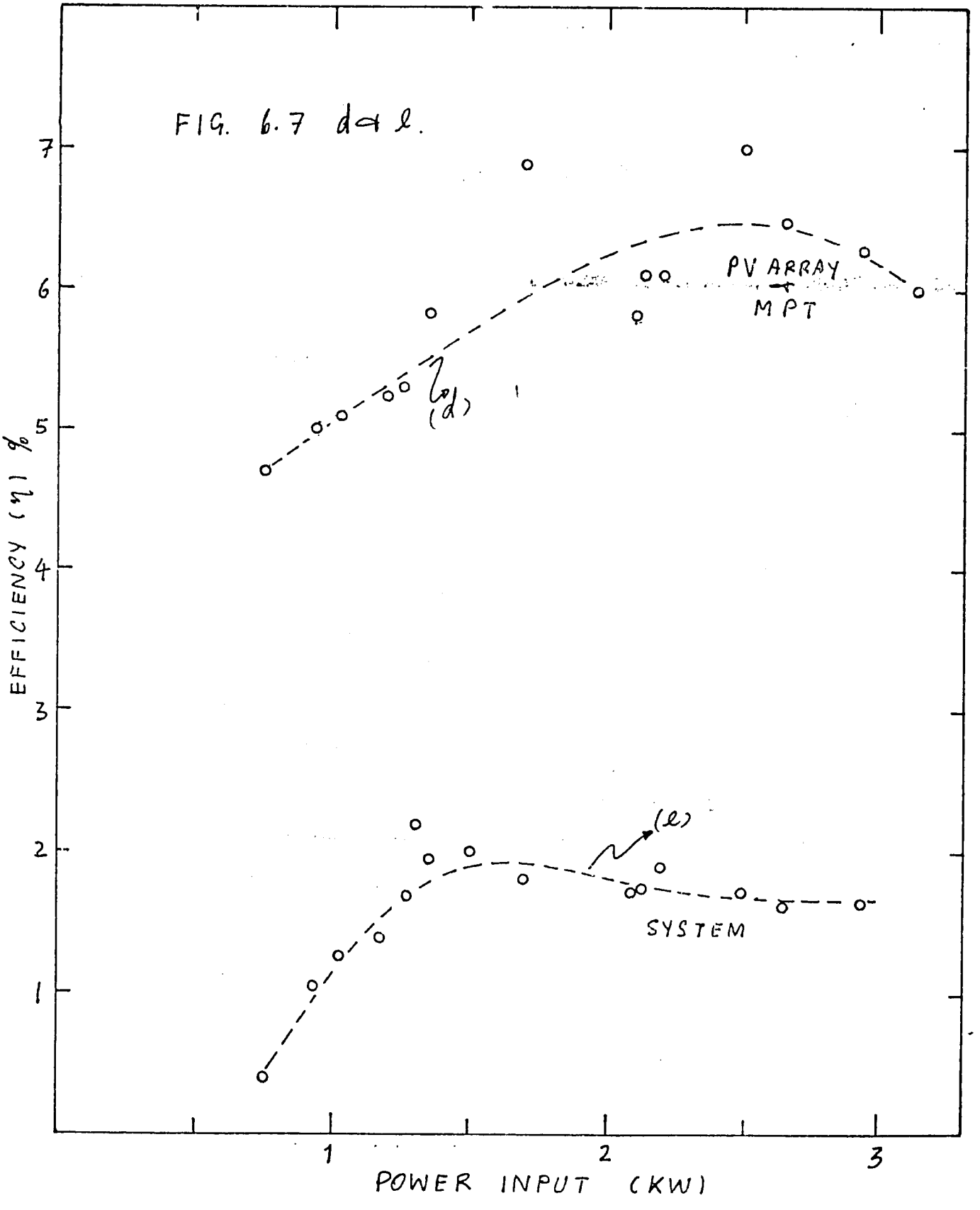
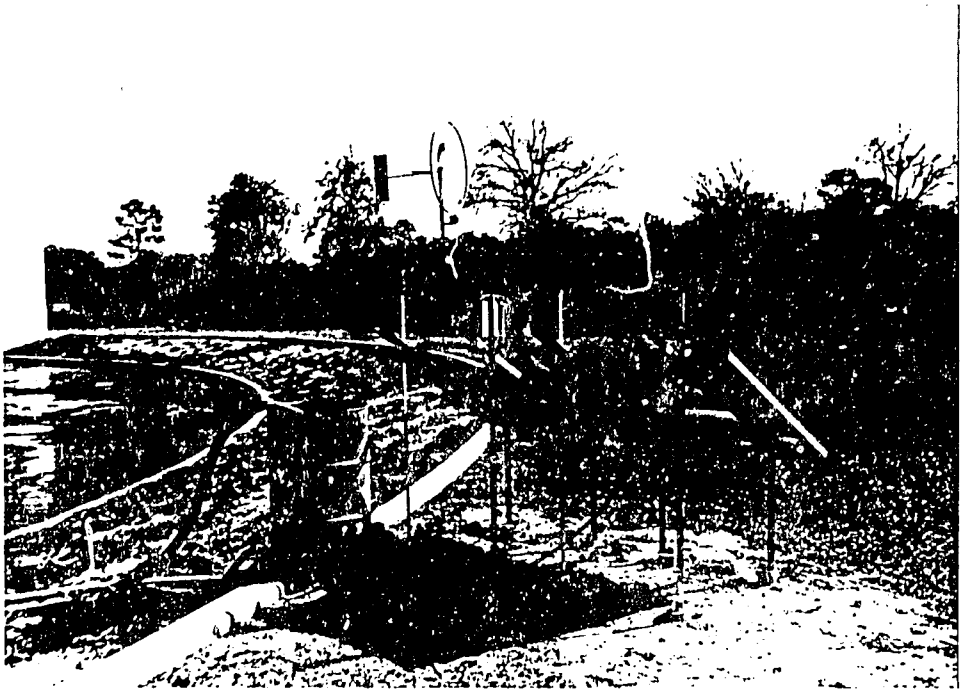
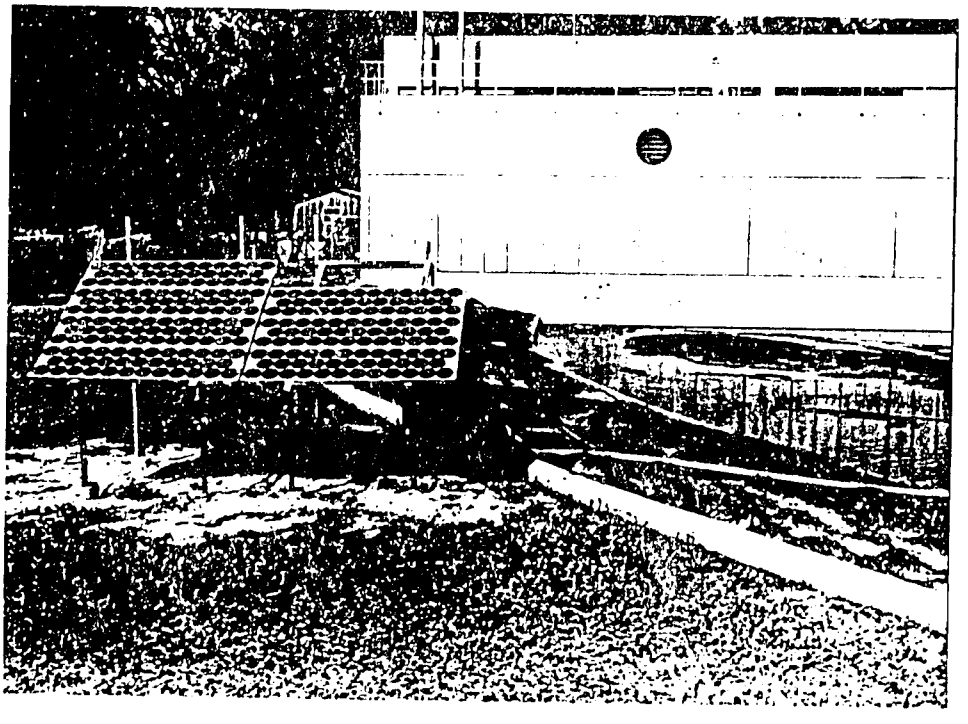


FIG. 6.7 d & e.
PV ARRAY + MPT
(d)
(e)
SYSTEM
EFFICIENCY (η) %
POWER INPUT (KW)
1
2
3
4
5
6
7