Adaptation of a Positive-Displacement Pump Directly Connected to a Photovoltaic Generator

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ABSTRACT

The direct connection between a photovoltaic generator and a positive-displacement pump of local manufacture was studied. This led to the development of an adaptator of impedance with an efficiency of 85%. The basic principle and technical details are presented in this paper. Experimental analysis reveals that a satisfactory adaptation was achieved, technically simplifying the system. The advantage of such a simple device is twofold: decreasing system cost by avoiding the need for battery storage and improving the efficiency of the system.

INTRODUCTION

The electrical power supplied by a photovoltaic generator depends on solar radiation intensity, ambient temperature and load requirement. In order to maximize the transfer of electrical power, the electrical load must be such that its current-voltage (I-V) characteristic curve intercepts that of the photovoltaic (PV) generator as close to the maximum power point as possible. Depending on their nature, some loads are more adapted to the PV generator than others; this is the case for centrifugal pumping system or battery. Some others (such as the surveyed positive-displacement pump, which is typically a current receiver), cannot be operated without an additional matching device, called an adaptor of impedance or DC-DC converter. This device has two functions, the tracking of the maximum power point and the transfer of power to the load. These two functions were realized using a pulse-width-modulated series-switch step-down regulator. An experimental efficiency of 85% was achieved using locally available technology. This device was tested on a locally made positive-displacement pump, providing satisfactory results.

SYSTEM CHARACTERIZATION

The system comprises a PV array of eight modules (Type BPX 47C) in two parallel arrangements of four modules in series. It is capable of supplying a maximum current (I_{max}) of 3.5A at an insolation level of 1 kW/m^2 and an open circuit voltage of nearly 70V. The surveyed pump is a locally-made piston pump coupled to a permanent magnet motor (nominal characteristics: 51V, 1500 rpm, R_i = 1Ω, L = 40 mH, I_{max} = 10A). A flywheel is coupled to the motor shaft to keep the cyclic torque virtually constant. In such a motor-pump device, the torque (and consequently the motor current) is virtually independent of the speed (and consequently the motor voltage) for a given head under nominal operating conditions.

In order to simulate varying discharge heads of up to 50 m, a hydropneumatic tank was installed at the outlet of the pump (Fig. 1). The characteristics of the motor-pump set were recorded using an external power supply and are presented in Fig. 2. The load characteristic curves (Figs. 2-3) and related efficiencies (Table 1) show that this motor-pump combination is suitable for a minimum manometric head of 20 m requiring a motor current close to 3.9A (Table 1). The comparison between the PV generator and the load $I = f(V)$ (Fig. 2) characteristics at different heads shows that the load cannot be connected directly to the PV array for total manometric heads higher than 15-20 meters. Moreover, the higher the head, the higher will be the efficiency of the pump if the PV array is capable of supplying the required input power.

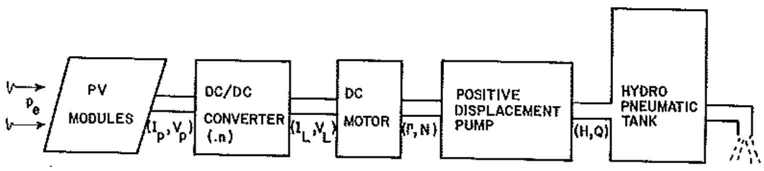


Fig. 1 Schematic diagram.

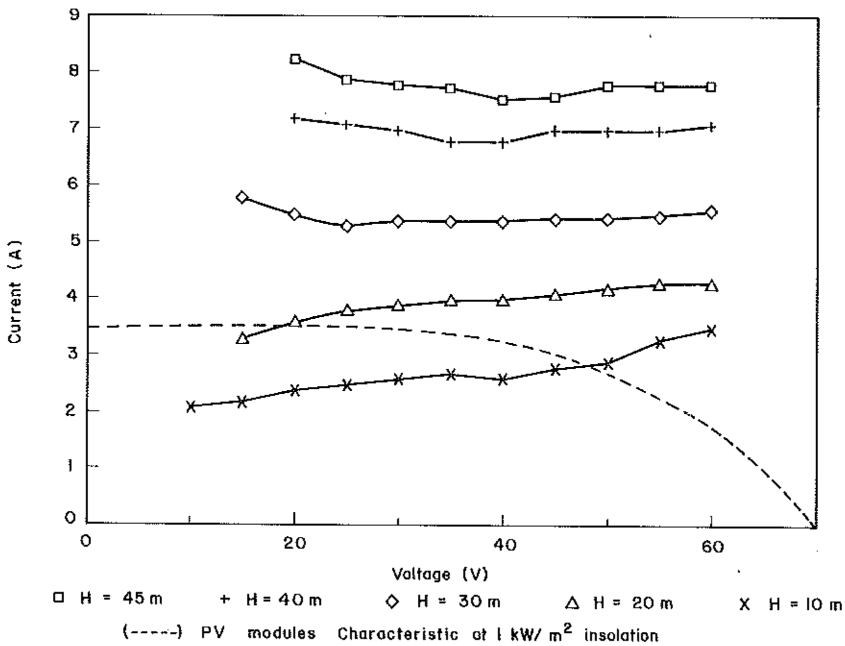


Fig. 2 Positive displacement pump, I = f (V).

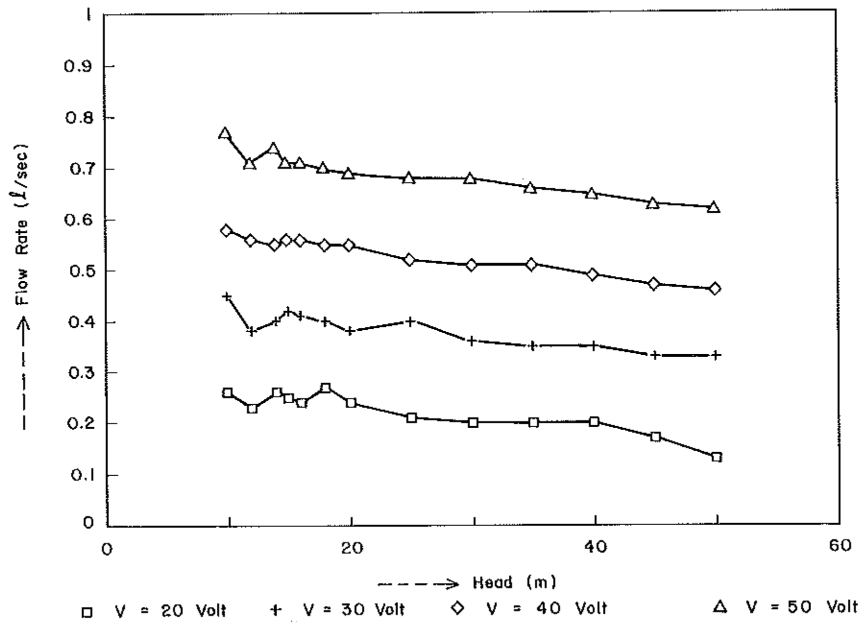


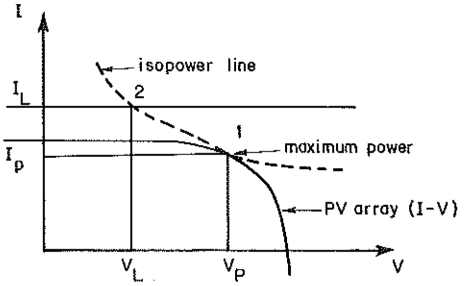
Fig. 3 Positive displacement pump, Q = f (H).

Table 1
Motor-pump efficiency
(for various heads and speeds (voltage))

Head (m)	Voltage (V)				
	20	30	40	50	60
10	.52	.56	.55	.52	.47
15	.62	.65	.62	.58	.57
20	.65	.64	.67	.64	.63
25	.55	.73	.69	.69	.70
30	.54	.65	.69	.73	.71
35	.55	.65	.71	.74	.79
40	.55	.65	.71	.73	.72
45	.46	.62	.69	.71	.73

Given the respective characteristics of the PV array and the load, an adaptor of impedance was designed and tested in order to allow a direct connection between the modules and the motor-pump system in order to maximize the energy transfer between the PV array and the motor-pump.

The basic concept of this device is to determine the maximum power point of the PV generator by following the isopower graph until it intersects the load characteristic. As illustrated in Fig. 4, the power consumed by the load is equal to the area ($I_L * V_L$). The maximum power produced by the PV generator is represented by the area ($I_P * V_P$). The operating points at different loads are such that the consumed power equals the maximum power produced by the PV generator (i.e., area $I_L * V_L$ equals area $I_P * V_P$ in Fig. 4).



$$P_m = \Gamma . N$$
$$P_h = \sigma . g . H . Q$$
$$P_L = I_L . V_L$$
$$P_P = I_P . V_P$$
$$P_L = \eta . P_P$$
$$V_L = V_P . \frac{T_c}{T}$$
$$I_L = I_P . \frac{T_c}{T} . \eta$$

Fig. 4 Basic concept of adaptor of impedance.

For this prototype, the maximum power was tracked assuming that the maximum power occurs at a fixed reference voltage (Vref) independent of the insolation level. The lack of accuracy an subsequent decrease in efficiency are considered small in relation to the achieved simplicity and high degree of reliability of the device. Since the nominal voltage of the motor is 51 V, the DC-DC converter is a voltage reducer and current booster using a pulse-width-modulated series-switch step-down regulator.

PULSE-WIDTH-MODULATED SERIES-SWITCH STEP-DOWN REGULATOR

An efficient way to obtain a lower voltage from a higher level source is shown in Fig. 5. Instead of absorbing the difference between the input and required output with a power-dissipating element, a low-impedance transistor switch is made to open and close periodically between input and output. The variation of energy during the two operating modes of the switch is absorbed by a large capacitor (C_1).

If the switch (S_1) has zero voltage drop in its closed position, the output (as shown in Fig. 5) varies periodically between zero volt and the input voltage. The average value of this waveform is $V_L = V_p * T_c/T$, where T_c is the switch closed time and T is the switching period. This is the voltage that would be read with a DC voltmeter at the output terminals. The ripple component has a peak-to-peak value of V_p volts and would not be observed by a DC voltmeter. By adding the L_1 C_1 filter shown in Fig. 5, the ripple component of the input voltage is reduced to a value acceptable to the motor. In particular, V_p can be chosen to correspond to the maximum power of the PV modules, and regulated by the duty cycle of the switch (the ratio of the opening time over the total time of one cycle, T_c/T).

During the time (T_c) the switch is closed, the load current (I_L) is supplied both by the PV modules and the capacitor C_1. When the switch is opened no current is supplied to the load. This means the current taken from the input source is a series of pulses of amplitude I_L lasting for a

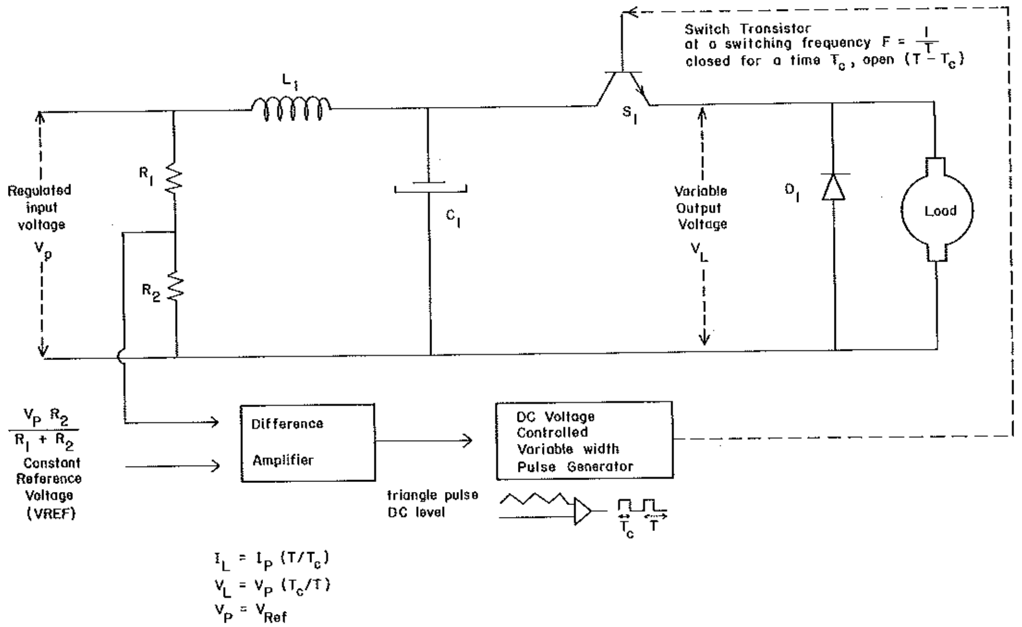


Fig. 5 Adaptator of impedance-conceptual design, DC-DC converter.

time T_c out of every T units of time. The average value of the input current is $I_L * (T_c/T)$.

If the commutation losses in the switch are neglected, input power must equal output power. The circuit thus acts like a step down transformer – it takes from the input source voltage (V_p) a current (I_p) of average magnitude $I_L * (T_c/T)$. It transforms this at the output to a lower voltage $V_L = V_P * (T_c/T)$ at a stepped-up average output current $I_L = I_P * (T/T_c)$. I_L is nearly constant at a given manometric head for the surveyed positive-displacement pump.

The duty cycle (T_c/T) of the DC-DC converter is regulated in such a way that (I_p, V_p) corresponds to the maximum power points of the PV array. As a consequence, V_L at nominal operating conditions varies corresponding to the current (I_p) of the panels which is proportional to the insolation.

The voltage stepdown is achieved at a high efficiency, since the only losses in such a step-down DC-DC converter are those in the switch S_1 when it is closed. Using a transistor switch, the voltage drop within the switch in the closed position can be as low as 1 V. During the time it is open, the full input voltage exists across the switch. Since no current flows in it, there is no power dissipation. During the transition between open-switch and closed-switch times or vice versa, there is a momentary overlap of high voltage and current, resulting in some losses.

EXPERIMENTAL RESULTS

The DC-DC converter was designed for a current load close to 3.9 A (or in other words, for a total manometric head of 20 m). In this case the value of the capacitor is 1200 μF and the operating frequency 1800 Hz. At the beginning the capacitor charges and as soon as the PV array and the load are matched the voltage of the capacitor fluctuates around 60 V, which corresponds to the maximum power extracted from the panels. It can be seen in Fig. 6 that during this operating mode the load voltage follows the trends of the panel current itself, i.e., proportional to the insolation, the load current being constant for a constant head.

Table 2 presents results at 20 m head. These data yielded an experimental efficiency of 85% averaged over a wide range of output voltages.

Table 2
Operation of the positive-displacement pump using a DC-DC converter

Hour	I_p	V_p	I_L	V_L	P_p	P_m	Eff.
9:15	2.40	51.2	3.90	28.0	123	109	.89
9:22	2.55	50.8	3.90	28.0	130	109	.84
9:25	2.68	52.2	3.97	30.4	140	121	.86
9:35	2.79	55.4	3.90	34.0	155	133	.85
9:45	2.85	56.7	3.90	35.0	162	137	.84
9:55	2.85	57.5	3.90	36.2	164	141	.86
10:05	2.95	58.7	3.92	37.5	173	147	.85
10:15	3.00	59.6	3.95	38.5	179	152	.85
10:25	3.02	60.5	3.85	40.5	183	156	.85
10:35	3.17	61.6	3.87	43.5	195	169	.86
10:51	3.24	63.3	3.84	46.2	205	177	.86
11:00	3.02	62.2	3.82	43.4	188	166	.86
11:10	3.15	63.1	3.74	45.8	199	171	.88
11:20	3.15	62.4	3.84	44.0	197	169	.86
11:30	3.10	63.0	3.77	44.8	195	169	.86
11:40	3.12	62.9	3.77	44.8	197	169	.86
11:50	3.12	62.6	3.82	44.0	196	168	.86
12:00	3.19	62.8	3.90	44.5	200	174	.86
12:10	3.15	62.8	3.87	44.2	198	171	.86
12:20	3.12	62.3	3.87	43.4	195	168	.86
12:30	3.12	62.1	3.88	42.5	194	165	.85
12:40	3.15	62.5	3.90	43.4	197	169	.86
12:50	3.12	62.0	3.88	42.5	193	165	.85
13:00	3.11	61.6	3.92	41.8	192	164	.85
13:10	3.08	61.2	3.89	41.4	188	161	.85
13:20	3.04	61.2	3.87	41.2	186	160	.86
13:30	3.00	60.6	3.85	40.0	182	154	.85
13:40	3.01	60.4	3.88	39.5	182	153	.84
13:50	3.00	60.0	3.95	39.0	180	154	.86
14:00	3.05	60.5	3.98	39.5	185	157	.85
14:10	2.94	59.4	3.95	37.5	175	148	.85
14:20	2.83	58.6	3.88	36.4	166	141	.85
14:30	2.75	57.6	3.96	34.0	158	135	.85
14:40	2.62	56.9	3.89	32.0	149	124	.84
14:50	2.56	56.4	3.89	31.0	144	120	.84
15:00	2.47	55.5	3.82	30.0	137	115	.84

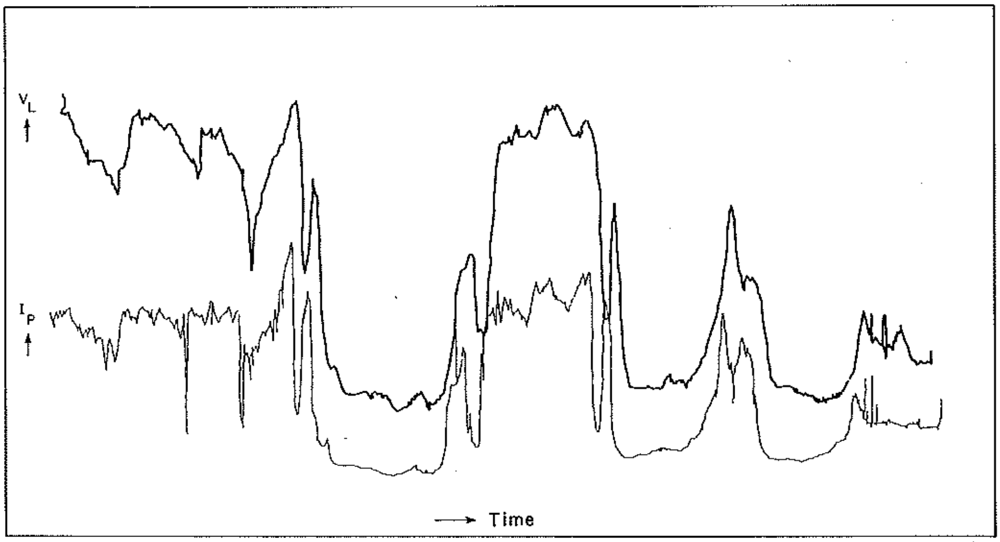


Fig. 6 Motor voltage V_L as a function of time and panel current I_P as a function of time.

CONCLUSION

A DC-DC converter with 85% efficiency has been developed and tested with a locally-made positive displacement pump. The minimum head required for this pump was 20 m, with a corresponding load current of 3.9 A. If the average module efficiency is about 10%, and at 20 m the motor-pump efficiency is about 65%, the overall efficiency of the system can be expected to be in the order of 6%.

The DC-DC converter efficiency also depends on the technology used in its design. The system can be improved by using more sophisticated maximum power point tracking. Investigations will be pursued in order to assess the performance of the pump and the degree of reliability of the DC-DC converter over a period of at least one year.

NOMENCLATURE

P_e : Solar radiation intensity (W)
P_m : Motor power (W)
P_h : Hydraulic power (W)
V_p : Module voltage (V)
I_p : Module current (A)
V_L : Load voltage (V)
I_L : Load current (A)
R_I : Motor armature resistance (Ω)

L	:	Motor inductance (H)
Γ	:	Torque (N.m)
N	:	Speed (Rd/s)
H	:	Total manometric head (m)
Q	:	Flow-rate (m^3/s)
η	:	DC-DC converter efficiency (%)
T	:	Pulse period (s)
T_c	:	Time switch closed (s)
σ	:	Volumetric mass (kg/m^3)
g	:	Acceleration of gravity (m/s^2)
Eff	:	Efficiency (%)

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