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A DIRECT COUPLED PHOTOVOLTAIC WATER PUMPING SYSTEM WITH IMPROVED PERFORMANCE

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ABSTRACT

This paper presents a new approach to the control of Direct - Coupled, Photovoltaic (PV) Water Pumping Systems. The PV generator is connected in series and parallel combinations to a permanent magnet dc motor (PMDC) which acts as a prime mover for a rotary displacement pump. The switch over is achieved by using a simple - low cost - electronically controlled relay. It is shown that with one configuration, output current is doubled at the expense of reduced voltage. This mode is suitable for operation during early morning hours, late in the evening or during cloudy days. The second mode performs very well at higher insolation levels because voltage close to the rated voltage of the motor is attained. With the proposed switch-over mechanism, the system provides improved performance in remote areas where less attention and minimum operating costs are the prime goals. This approach differs from previous attempts in that losses are minimal and no grounding problems are experienced.

INTRODUCTION

Background

The use of photovoltaic (PV) water pumping system has recently received increasing attention especially in areas where solar energy is abundant and in remote areas where grid power is non-existent. The major problem hindering its wide spread is the cost of the solar panels which account for a large portion of the cost of the complete system. Researchers the world over have centred their work on: increasing the conversion efficiency [1,2,3], reducing the manufacturing cost [4], reducing the cost of materials [2,5] and increasing the utilization of available insolation [2,3,4,5,6]. Increasing the conversion efficiency and maximum utilization of available insolation will reduce the size and hence the cost of the solar generator. PV systems for water pumping, for example will economically compare well with other conventional means if the price of the solar panel drops to about US $ 4 per peak Watt [7].

There are several techniques that have been employed to improve the system performance. These include: optimal matching of direct coupled systems [1,7,8], solid state controller [9,10], single and two-axis trackers [2,5,6] and maximum power trackers [3,4]. This paper presents an alternative, low cost approach to direct coupled PV - Systems.

System configuration

The block diagram of the system under consideration is shown in Figure 1. A direct coupled system has several advantages over PV systems with battery-back up system, or utility grid connected system. A direct coupled system also offers enhanced simplicity, reliability and low cost. However, a direct coupled system performs poorly during periods of insufficient irradiation, e.g. early in the morning or during cloudy days. During these periods the solar arrays do not give out enough current to drive the load. Several works in the past [7,11,12] have suggested the use of direct coupled system for non - continuous operating systems, like water pumping.

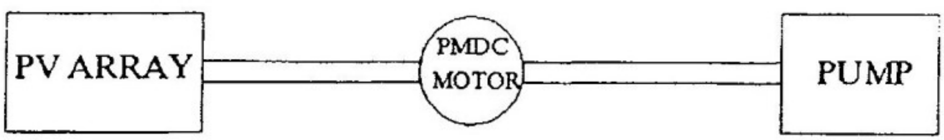

Figure 1: A direct coupled PMDC motor drive

In this paper, a 0.5 kW solar generator is configured in two different configurations, one for starting and another for running. In the first configuration, the solar panel is connected to give a short circuit current of 10 A and an open circuit voltage of 50 V. This configuration is suitable for starting conditions because even at low insolation levels, enough current can be generated to start the motor. During high insolation periods, the panel is configured to give a short circuit current of 5 A and an open circuit voltage of 100 V. In this mode less current is required to keep the motor in the running condition at the higher voltage, resulting in a better performance of the system. Since most of the solar generators are located in remote areas, a mechanism to operate the array in these configurations automatically have to be provided. In order to accomplish this, a simple electronic relay is proposed. The results show that the PV array could operate satisfactory at almost all times of the day even when the insolation goes as low as 250 W/m2. At higher insolation levels, the flow rate greatly improves by configuring the panel in the high voltage low current mode (HVLC).

Figure 2 is the power circuit of a 0.5 kW solar panel which consists of 8 modules (numbered 1 up to 8). These modules can be connected in two different series/parallel configurations through the operations of switches SW1, SW2 and SW3. SW1 is a normally closed switch while SW2 and SW3 are normally open switches. These switches are operated through the electronic control circuit shown in Figure 5.

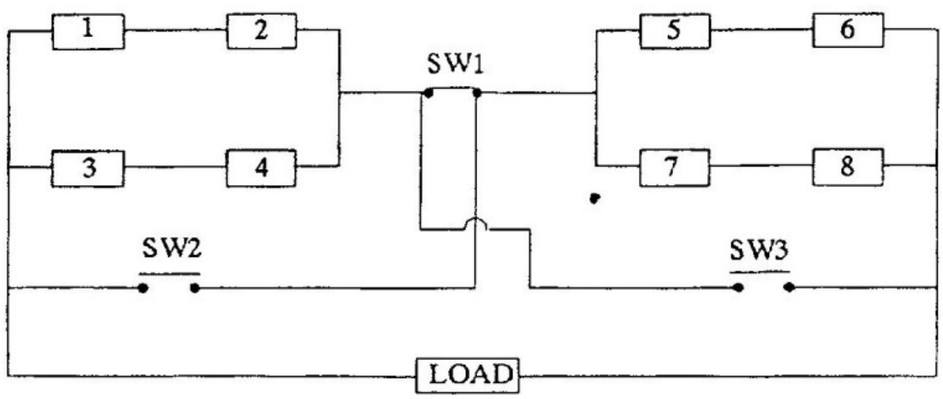

Figure 2: The power circuit of a 0.5 kW solar panel

In the previous attempts [9,10], though the authors had successfully designed circuits to operate the system in two-stage and three stage array configurations, the controllers used were characterized by high switching and conduction losses observed from the switching technique that was employed. Moreover, with increased number of modules, more power supplies, gate driver circuits and opto-couplers would be needed to provide the floating grounds, making the complete circuitry complex and expensive. When an electronically controlled relay is used, the losses are minimal.

REVIEW OF THEORY

PV Array

The I-V characteristic of the solar array shown in Figure 3, is determined by using the method developed elsewhere [13], using the equivalent circuit diagram shown in Figure 4.

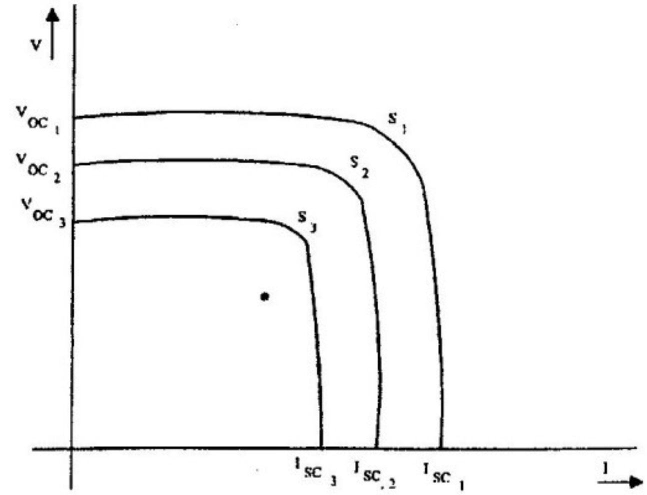

Figure 3:I - V Characteristics of the solar array

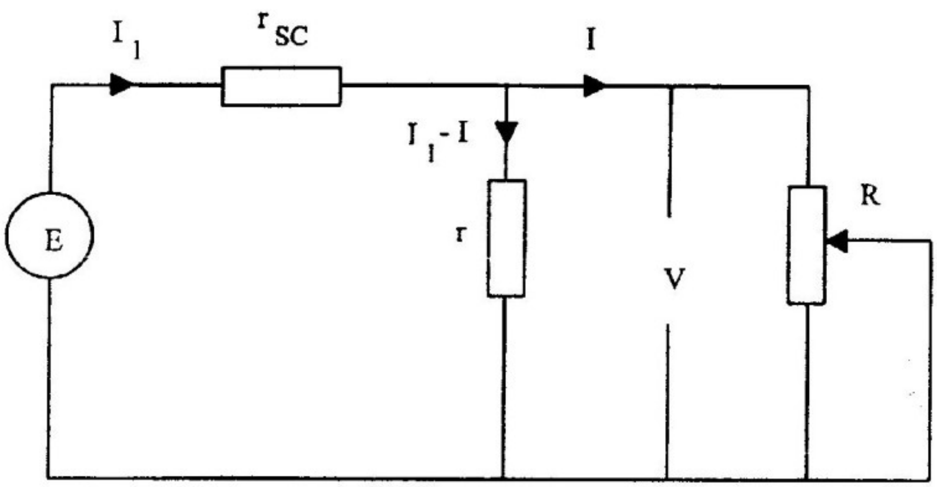

Figure 4: An equivalent diagram of a solar generator

The solar generator is represented by an e.m.f., E, two resistances, r_{SC} and r determined from open and short circuit tests.

The e.m.f., E is given by

$$E = \frac{S}{I_{SC}} \tag{1}$$

where S = Insolation

I_{SC} = short circuit current

E is constant for any given irradiation

The short circuit resistance,

$$r_{SC} = \frac{E}{I_{SC}} \tag{2}$$

This resistance is constant for a given irradiation.

The resistance r is constant for a given irradiation and changes with a varying load. This resistance varies between the open circuit resistance r_{OC} under open circuit condition and infinity under short circuit condition.

The resistance r is given by:

$$r = \frac{V \cdot r_{SC}}{E - V - I \cdot r_{SC}} \tag{3}$$

at open circuit, the resistance r is given by:

$$r_{OC} = \frac{V_{OC}}{I_{OC}} \tag{4}$$

where $$I_{OC} = \frac{E - V_{OC}}{r_{OC}} \tag{5}$$

where V_{OC}= open circuit voltage, I_{OC}= open circuit current
V= terminal voltage and I = output current

The empirical expression for determining the value of r is given by [13]

$$r = r_{OC}\left(1 + \frac{r_{OC}}{R} + \left(\frac{r_{OC}}{R}\right)^{n}\right) \tag{6}$$

The I-V characteristic of the solar generator is determined by using equations (3) and (6) by varying R from 0 to

The efficiency of the array η_a is evaluated from

$$\eta_a = \frac{I \times V}{S_a \times A} \tag{7}$$

where I = array output current (I)
V = array terminal voltage (V)
S_a = Insolation (W/m^2)
A = area of the solar panel (m^2)

Permanent magnet dc motor

The equations that govern the operation of a permanent magnet dc motor are given here below:
The power output of a permanent magnet dc motor is given by:

$$P_m = 2 \; n_m T_m \tag{8}$$

where n_m= speed of the motor and T_m= load torque
The load torque is determined from

$$T_m = K_t I_a - T_{fr} \tag{9}$$

where $$K_t = \frac{T_{st} . R_a}{V_{st}} = \text{torque constant} \tag{10}$$

I_a = I = load current

$$T_{fr} = \frac{V_{oc} I_{oc} - I_{oc}^2 R_a}{\omega_{oc}} = \text{friction torque} \tag{11}$$

where V_{OC}= no load voltage, I_{OC}= no load current and
ω_{OC}= no load speed
The efficiency of the motor, η_m is obtained from

$$\eta_m = \frac{P_m}{I \times V} \tag{12}$$

The Pump

The power output of the pump is given by:

$$P_P = Q \times h \times g \times \rho \tag{13}$$

where Q = flow rate (m^3/sec)
h = head (m)
g = acceleration due to gravity (m/sec^2)
ρ = density of water (kg/m^3)
Neglecting motor-pump coupling efficiency and internal losses of the pump
Power input of the pump = P_m
and the efficiency of the pump is given by

$$\eta_P = P_P / P_m \tag{14}$$

The efficiency of the system, η will be given by;

$$\eta = \eta_a . \eta_m . \eta_p \quad (15)$$

CIRCUIT DESCRIPTION AND OPERATION

The control circuit of the proposed relay is shown in Figure 5. It consists of a photoelectric transducer, the amplifying circuit, the comparator and the coil of the relay. The photovoltaic transducer is essentially a dc amplifier forming a potential divider network. The resistance presented by the photoresistor (LDR in Figure 5) is inversely proportional to the insolation level. When the insolation is low the photoresistor presents a high resistance, raising the base voltage of transistor Q1 (BC 084). This allows a high collector current to flow through Q1 which consequently creates a big voltage drop across the collector resistor, R_C. In contrast, a high collector voltage is obtained when the irradiation is high, because the resistance of the photoresistor is low and consequently the base voltage is decreased resulting in low collector current.

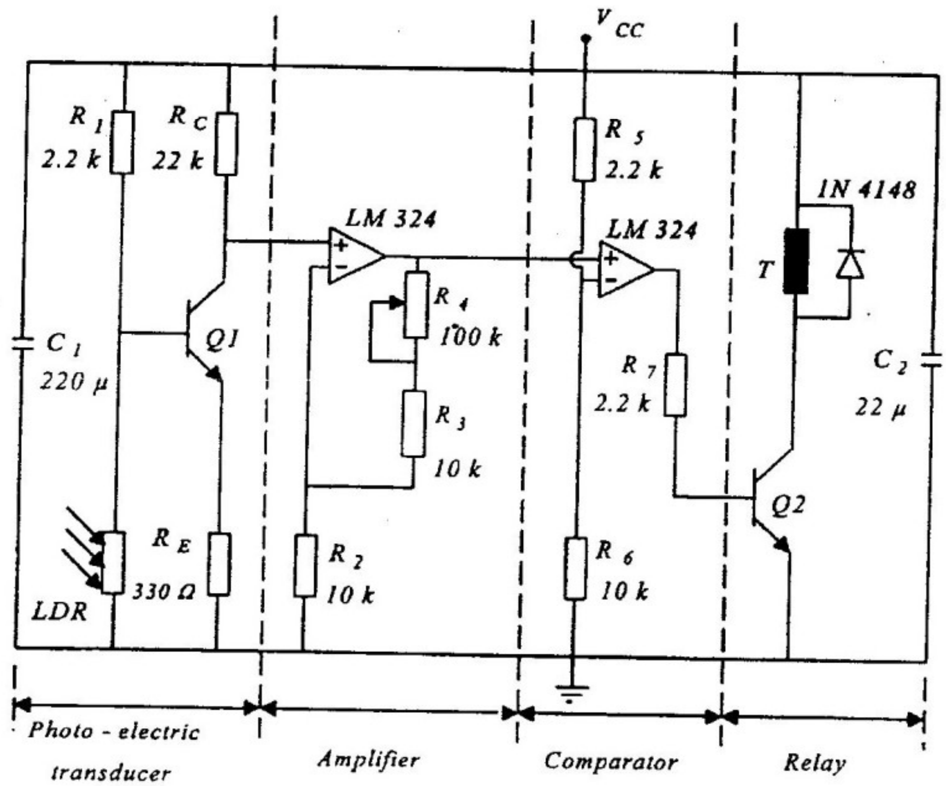

Figure 5: Control circuit for the power circuit

The above explanation clearly indicates that the photo-electric transducer produces an output voltage proportional to the insolation level. The output of the photo-electric transducer is applied to the OPAMP which has a variable gain for determining the insolation level at which the relay should be operated. This output is compared with a reference voltage provided by the potential divider circuit to give an output voltage of +Vcc or 0 V.

A fast switching transistor Q2 (2N 3904) is included in the circuit to amplify the current passing through resistor R_7 to be able to activate the coil of the relay T. This coil is normally wound on a ferromagnetic core. When the current passes through this coil, a magnetic field is created to attract a soft iron armature whose movement results in the opening or closing of the relay contacts used to operate the switches. When the current is removed, the magnetic field dies out, the soft iron is demagnetized and the operated switch contacts return to their normal position. Diode D is a freewheeling diode to protect transistor Q2 from getting damaged during turn-off due to high di/dt. Capacitors C_1 and C_2 are smoothing capacitors.

Under low irradiation level, the coil of the relay is activated to open SW1 and close SW2 and SW3.The base voltage of transistor Q1 is raised to allow high collector current to flow through Q1, the amplified signal from the OPAMP is compared with the reference voltage provided by the potential divider network formed by resistors R_5 and R_6. In this case the input signal is greater than reference voltage and the comparator gives an output voltage of V_{CC}. The output current through R_7 amplified by transistor Q2 is used to activate the relay. The current passes through the coil of a three terminal electromechanical relay and a magnetic field is created to attract a soft iron arm whose movement changes the states of the switches. This operation activates SW1 to open while SW2 and SW3 close . Under this condition the generator is configured to give a high-current, low voltage mode. From Figure 2, assuming that each unit provides current I and voltage V, then the current to the motor will be 4I and the voltage 2V. This configuration is suitable for starting. At higher insolation. SW1 will be closed while switches SW2 and SW3 will open. This will give a high voltage, low current configuration and the output will be 2I and 4V. This configuration is suitable for the running condition.

EXPERIMENTAL SET-UP

A typical PV pumping system consists of a PV array, an electrical interface, a motor, a pump, water storage tank and piping. The system that has been installed consists of a 0.5 kW, 3.2m^2 PV array, a permanent magnet dc motor rated 0.5 hp, 90 V, 4.8 A, 1750 rpm, electrically connected to the PV array. A monosolar lift pump (S2M) suitable for heads up to 150m and capable of delivering 2000 *l*/h with a minimum starting torque requirement of 3 Nm and maximum speed of 1200 rev/min was used. The pump is driven by the motor through pulleys of ratio 2:1.

The laboratory arrangement used to simulate the water circuit consisted of a 1.4m deep water reservoir, a 2m long steel pipe connected to the pump and mounted vertically, a manually operated diaphragm valve for simulating a wide range of static heads by adjusting the pressure setting of the valve, a control instrument pressure gauge capable of measuring up to 600 kPa and a plastic flow meter covering a range of 60 - 1000 *l*/h. The pump was immersed in the water reservoir and the complete system (excluding the PV array) is firmly mounted on the reservoir. The insolation is measured by using an LI-2005 A pyranometer sensor with sensitivity of 80 μA per 1000 W/m^2.

EXPERIMENTAL RESULTS

In order to compare the performance of the high current low voltage mode (HCLV) and the high voltage low current mode (HVLC), several parameters on the two set-up were measured. The minimum insolation at which each mode can operate was determined and found to be 250 W/m^2 for the HCLV mode and about 530 W/m^2 for the HVLC mode. The efficiency of each mode at a constant head of 20m was determined by measuring the output and input current of the array, no load and load characteristics of the permanent magnet dc motor, the flow rate and the insolation.

Figures 6(a) and 6(b) show the flow rate of the two configurations against the solar insolation at a constant head of 20m. The HVLC mode shows the capability of giving about 800 *l*/hr at an insolation of about 1300 W/m^2. The HCLV mode, purposely for starting and operating on cloudy days was able to pump at a maximum flow rate of 160 *l*/hr.

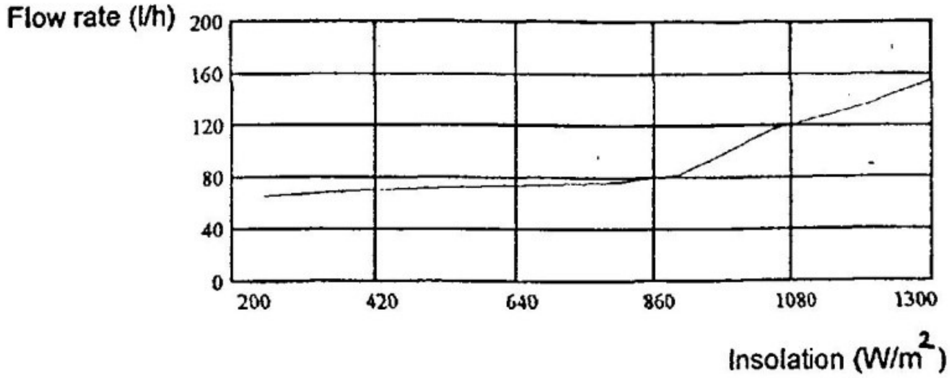

Figure 6(a): Flow Rate (l/h) against Insolation (W/m2) for HCLV

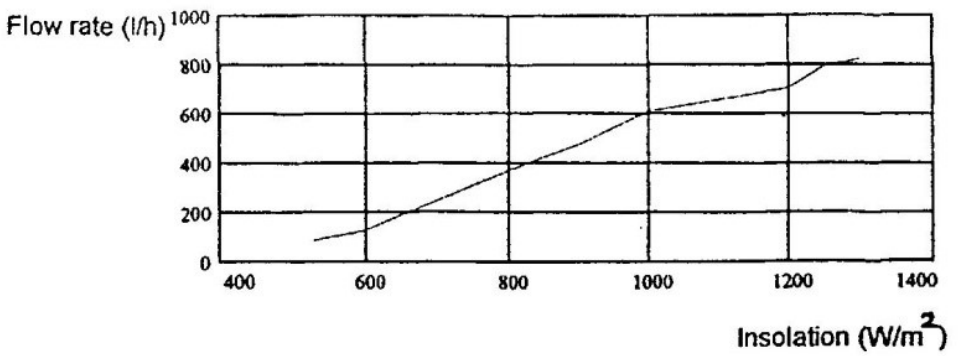

Figure 6(b): Flow Rate (l/h) against Insolation (W/m2) for HVLC

Figures 7(a), 7(b), and 7(c) show the efficiencies of the various components used in the system. The overall efficiency is shown in Figure 7(d). When the relay is introduced the efficiencies of PV array, motor and pump are higher than in the direct coupled system.

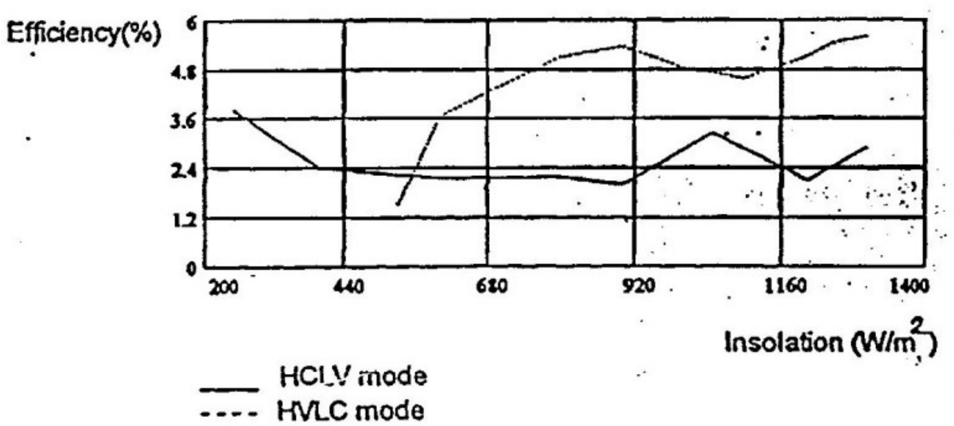

Figure 7(a): Efficiency (in %) of the PV array against Insolation (W/m2)

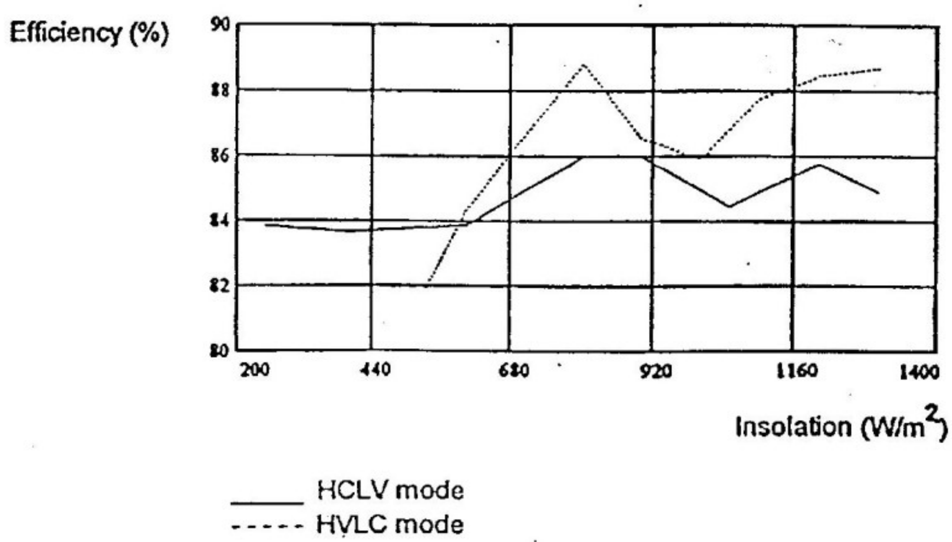

Figure 7(b): Efficiency (in %) of the motor against Insolation (W/m2)

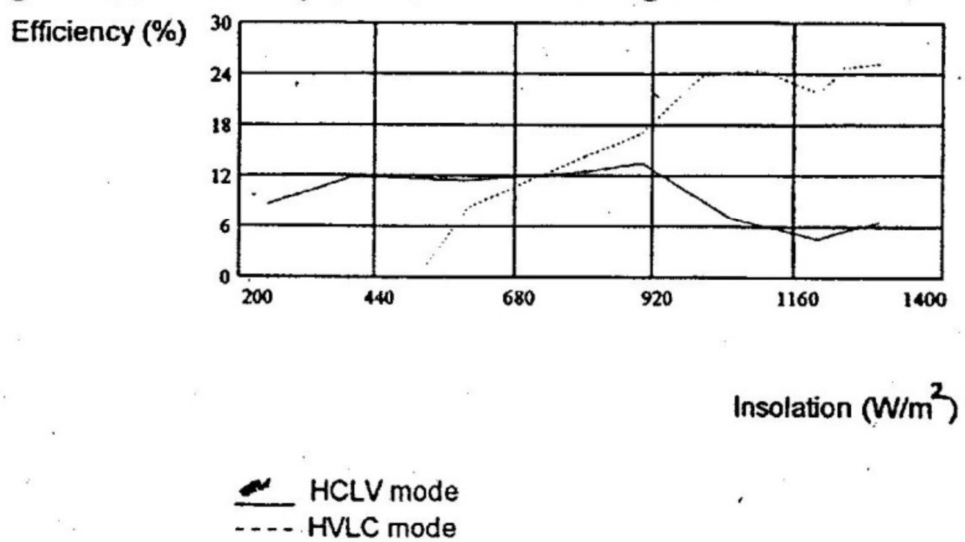

Figure 7(c): Efficiency (in %) of the pump against Insolation (w/m2)

DISCUSSION OF RESULTS

The above graphs show that the High Current - Low Voltage (HCLV) mode gives better efficiency and flow rates at low value of insolation when compared to the HVLC mode. This makes it suitable for early morning hours as well as during periods of heavy overcast. The HVLC mode is more suitable for insolation value above 530 W/m2. An interesting observation from Figures 6(b) and 7(c) is that the flow rate follow the pump efficiency, implying that it is less influenced by the individual efficiencies of the motor and solar generator, particularly in the HVLC mode. It is also observed from Figure 7(d) that the overall efficiency increases with the insolation in the HVLC mode, this is because the motor and the pump are operating close to their rated speed.

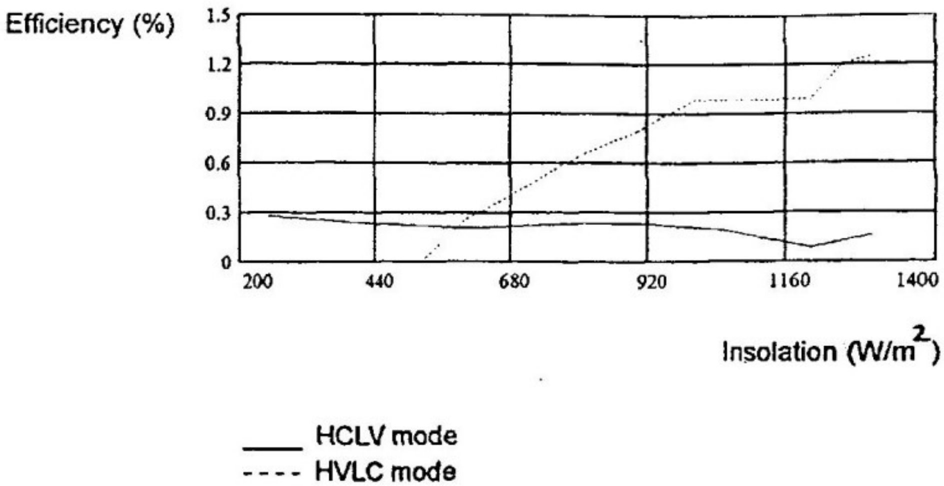

Figure 7(d): Overall efficiency (in %) against Insolation (W/m2)

The observed fluctuations in the solar array efficiency shown in Figure 7(a) are due to changes in the operating point during the course of the experiment. In the absence of a maximum power tracker, such fluctuations are inevitable. For maximum efficiency of the solar generator, a maximum power tracker is therefore necessary.

CONCLUSION

This paper presents a new approach to the control of Direct-Coupled, Photovoltaic Water Pumping Systems with improved performance. The system provides improved performance in remote rural applications where less attention and minimum operating costs are the prime goals. The improvement is achieved through the use of a simple low-cost electronically-controlled relay to match the PV array configuration to the insolation level. The PV generator is connected in series and parallel combinations to a permanent magnet dc motor (PMDC) which acts as a prime mover for a rotary displacement pump. A prototype system has been designed and tested.

It is shown that with this approach, two modes of operation, namely, High Current, Low Voltage (HCLV) and High Voltage, Low Current (HVLC) are possible, thereby allowing the system to operate at both low and high levels of insolation with improved efficiency. Compared to previous attempts, the new approach does not exhibit grounding problems and has lower losses. It is proposed that the inclusion of a maximum power tracker would result in even higher efficiency.

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