# PHOTOVOLTAIC WATER PUMPING FROM DEEP WELLS

E. Vazeos*, J.N. Avaritsiotis** and C.D. Rakopoulos***

*Solar Dept., BP Greece, Athens 152 32, Greece
**Electr. Engng. Dept., Nat. Techn. Univ., Athens 106 82, Greece
***Mech. Engng. Dept., Nat. Techn. Univ., Athens 106 82, Greece

## ABSTRACT

Today there is a growing interest for photovoltaic water pumping from deep wells. For such photovoltaic systems battery storage could be added, but the alternative choice of using multistage centrifugal submersible pumps with 3-phase motors presents more advantages. However, for this latter configuration it is necessary to include a DC/AC inverter which not only incorporates a Maximum Power Point Tracker (MPPT) but it is also capable of regulating the motor speed in proportion to the intensity of the in-plane radiation. In the present work the simulated performance of the 10 $KW_p$ EEC demonstration project for water pumping at Karpathos island in the Aegean Sea in Greece has been studied on an hourly basis, taking into consideration meteorological data, technical characteristics of the components of the system, and the characteristics of the well. The results of the simulation analysis are compared with some of the up to now recorded data of the Karpathos island with encouraging success.

## KEYWORDS

Photovoltaic panel; DC/AC Inverter; Three-phase motor; Water pumping; Deep well.

## INTRODUCTION

The application of photovoltaic (PV) electrical supplies to water pumping has received increasing attention, especially during the recent time, because of the expected reduction of cost production of photovoltaic solar panels (Hsiao and Blevins, 1984). There are two basic design approaches for photovoltaic water-pumping systems. The first one is to use a backup battery with the pumping system and the second one is to power the pump from the photovoltaic system without a battery. With the second approach, the pump can be driven either by a DC motor powered by directly coupling the PV array and motor (with the possible use of a peak power tracker as an interface between the motor and the PV array), or by an AC motor through a DC to AC inverter having the ability to regulate the speed of the motor in proportion to the incident solar radiation. The inverter is usually equipped with a peak power tracker.

The second solution presents the advantage of being possible to use submersible centrifugal pumps coupled to 3-phase induction motors in one piece. This motor-pump combination is commercially available in a wide range of volume-head characteristics, while inverters with motor speed variation and peak power tracking are easily available in the market. These systems are relatively efficient and reliable. Concerning the submersible pumps it can be said that they show a high efficiency at installation depths of 20 meters and deeper.

In a recent publication by the present research group (Vazeos, Rakopoulos and Kosmopoulos, 1986), a theoretical analysis was presented for the performance prediction of a PV pumping system with AC induction motors, centrifugal pumps and variable speed DC to AC inverters, covering a seemed gap in the open literature. In the present paper a brief outline of this theoretical model is given, while attention is focussed on the application for the related water pumping project at Karpathos island (36° latitude) in the Aegean Sea/Greece for irrigation, comparing theoretical and (up to now recorded) experimental results.

## OUTLINE OF THEORETICAL ANALYSIS

The arrangement of the PV system to be analyzed is shown on Fig.1.

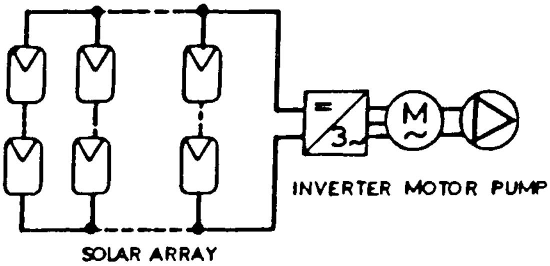

Fig. 1. General configuration of a photovoltaic pump with tree-phase motor.

The mean power output P (in Watts) of the PV system for each hour of a typical day can be expressed according to Siegel, Klein and Beckman (1981) as

$$P = A_c \bar{\tau} \bar{I}_t \bar{\eta} \eta_c / 3600 \qquad (1)$$

where $A_c$ = array surface ($m^2$)
$\bar{\tau}$ = average transmissivity of array cover
$\bar{I}_t$ = hourly average irradiation per unit area ($J/m^2$)
$\bar{\eta}$ = monthly average array efficiency
$\eta_c$ = inverter efficiency given by the manufacturer,

which can generally be considered constant and equal, for the present project, to 0.90 when the inverter power is higher than 1/3 of the nominal power of the inverter, while dropping (for example linearly to zero, at zero power) when the inverter power becomes less than 1/3 of its nominal power.

The inverter is equiped with a maximum power point tracker (MPPT).

For the calculation in eq.(1), the following PV array characteristics are needed (Duffie and Beckman, 1980), which are provided by the manufacturer of the PV modules:

$T_R$ = reference cell temperature
$\eta_R$ = reference array efficiency at temperature $T_R$
$\beta$ = cell temperature coefficient of efficiency
$U_c$ = overall loss coefficient of the array
$(\overline{\tau\alpha})$= monthly average transmissivity-absorptivity product.

An AC 3-phase squirel cage motor is used directly coupled to a multistage centrifugal pump. The efficiency of the motor is generally considered to be constant at various operation conditions with a negligible error. The characteristic curves of the centrifugal pumps for the nominal speed are given by the manufacturer. These plot the total head, H, and the pump efficiency, $\eta_p$, against the volumetric capacity Q.

The operating points of the whole system are found from the intersection of the H-Q characteristics of the pump with the pipeline (external) characteristic. This latter one is given (for turbulent flow) by an equation of the type (Stepanoff, 1957),

$$H = h_s + \zeta Q^2 \qquad (2)$$

where $h_s$ = static head and
$\zeta$ = characteristic number of the pipeline including pipe length, diameter, friction coefficient and individual head losses (in valves and fittings).

For each operation point the power P (in Watts) required to feed the motor-pump system can be expressed by the equation,

$$P = \rho g Q H / \eta_m \eta_p \, 3600 \qquad (3)$$

where $\rho$ = fluid density (kg/$m^3$), H in m, and Q in $m^3$/h,
g = gravitational constant (= 9.81 m/$s^2$)
$\eta_m$ = efficiency of the motor (assumed constant)
$\eta_p$ = " " " pump, so that one can now plot a curve showing the relation between the water capacity of the system and the motor feeding power.

## TECHNICAL CHARACTERISTICS OF KARPATHOS/GREECE PROJECT

The level of the water in the well varies with the pumping rate, from 8.1 m down to 69.5 m (depth of the well). As an example, after 8 hours of pumping at a rate of 8 $m^3$/h, the level of the water in the well drops to 32.4 m from the opening of the borehole. Therefore the water level can be expressed by: L = 8.1+3.04 Q.

The water is pumped either to a tank positioned 12 m below and 1550 m far from the well opening or to a second one positioned 27 m above and 264 m far from the same point. The changeover from one tank to the other is done automatically according to the incident solar radiation, i.e. if the intensity of solar radiation on PV modules plane exceeds 400 W/$m^2$ the water is pumped to the upper tank. Concerning the piping system, the following characteristics apply: Diameter 0.063 m. Pipe loss coefficient 0.016. Individual head losses for upper tank 2.94 and for lower tank 8.5 .

Pump data at 2900 RPM:

| $Q(m^3/h)$ | 6 | 10 | 14 | 18 | 22 |
|---|---|---|---|---|---|
| $H(m)$ | 88 | 86 | 76 | 62 | 44 |
| $\eta_p$ | 0.45 | 0.59 | 0.68 | 0.62 | 0.48 |

Motor efficiency $\eta_m = 0.82$.

The photovoltaic solar array feeding the pump (8850 $W_p$) is tilted at 35° towards South, and has the following characteristics: $A_c = 133\ m^2$, $\eta_R = 0.066$ at $T_R = 28\ {}^oC$, $\beta = 0.004\ K^{-1}$, $U_c = 28.2\ W/m^2\ {}^oC$, $(\overline{\tau\alpha}) = 0.95$, $\bar{\tau} = 1$.

The monitored parameters are: insolation, ambient temperature, wind velocity, cell working temperature, power output from the PV array and the inverter, water flow and level in the well. The data recording frequency is 3 min with integration during an hour. The data logging system is a personal computer (fully IBM PC compatible) and signal conditioning cards. The data are recorded on floppy disks (360 KB DS/DD) which are sent to Athens University every fortnight.

## THEORETICAL AND EXPERIMENTAL RESULTS-DISCUSSION

A computer program was developed for the simulation of the system on an hourly basis (Vazeos, Rakopoulos and Kosmopoulos, 1986). The mean hourly values for the various days, as they were monitored, were inputed into the program. The characteristics of the pump for the nominal speed, given by the manufacturer, were inserted into the computer program as second order equations of (H/n) against Q. The characteristics at other rotational speeds were found by the affinity representation (Stepanoff, 1957). The operation points of the system are the intercepts of pump and pipeline characteristics, i.e. equation (2). For each operation point the required electrical power P is found according to equation (3), and the Q-P curve of the system is plotted. For computer convenience purposes this curve was expressed as a second order equation of Q against P. For each hour of the actual day the useful photovoltaic energy is found by applying equation (1). The volume of the water pumped every hour is then found from the Q-P equation.

Figures 2 and 3 show two typical diagrams (one for a partly cloudy day and one for a shinny one, respectively) of hourly pumped water volume variation during a day. As can be observed the theoretical and experimental curves (Karpathos island photovoltaic project) coincide very well, prooving the validity of the analysis. For other days tested (not presented here) the coincidence of experimental and theoretical results is of equal success. This kind of comparison is continuing during the first year of monitoring of the present system.

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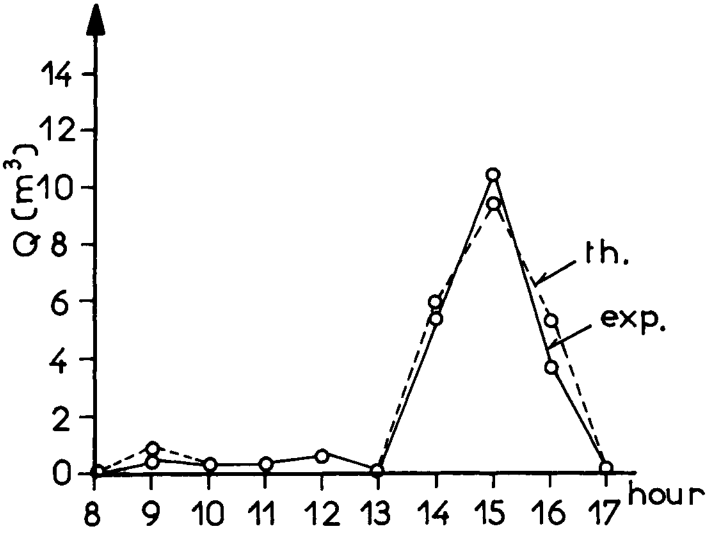

Fig. 2. Hourly pumped water volume for 21-11-86.

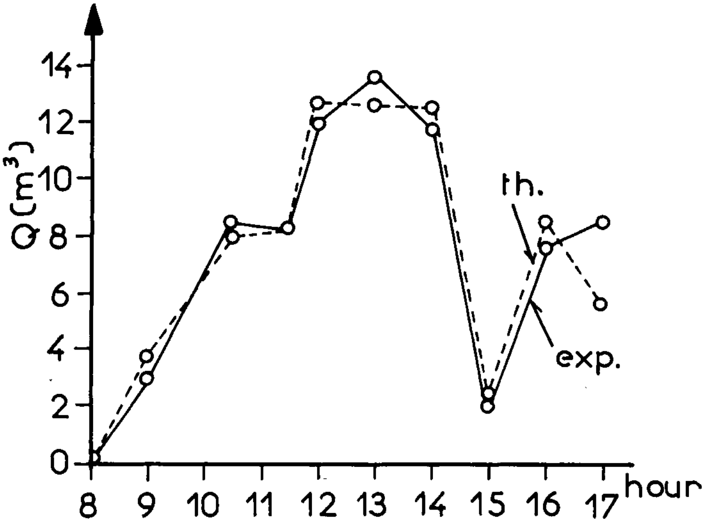

Fig. 3. Hourly pumped water volume for 12-4-87.