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Performance Evaluation of PV Pumping Systems

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ABSTRACT

Photovoltaic pumping systems (AC motor-submersible multistage pump set) capable of lifting water from total heads of 20 m and 50 m have been commissioned at selected sites. Overall system efficiencies measured at each site indicated the sub-optimal performance of these systems. An analysis based on the performance of individual system components, viz; array, inverter and motor/pump unit at a chosen site has been carried out. Installation at off-design pumping head was indicated to be a major reason for sub-optimal system performance. Measurements taken at simulated head equal to the designed one showed a significant improvement in overall system performance.

ABOUT THE STUDY

Seven solar photovoltaic water pumping systems were installed at selected sites and their performance studied under different field conditions. The sites were selected on the basis of the end-use requirement and technical compatibility with the system.

The systems manufactured in France, were donated to India by the French author Mr. Dominique Lappiere under the ASVIN (Application Solaires dans les Villages de l'Inde et du Nepal) programme executed by the CNRS (Centre National de la Recherche Scientifique), France.

The PV array of each system having an installed capacity of 1.28 kWp, is comprised of multicrystalline silicon modules. Other components included a high efficiency DC-to-AC inverter and a submersible three phase AC motor multistage centrifugal pump unit. One of the systems is designed to pump water against a total head of 50 m, while the rest are designed for a head of 20 m only. These systems are used only for rural water supply applications such as the provision of drinking water and other domestic purposes. Irrigation could not be considered as one of the end-uses because of the limited capacity of the system and the consequent difficulty of sharing water for irrigation purposes.

One of the systems, designed to pump water from a total pumping head of 20 m, has been commissioned at the Tata Energy Research Institute's (TERI's) campus (site A). Experiments have been conducted on this system to study the performance of individual sub-systems, and the system as a whole. This system has been in operation for more than 3 years. The highest output obtained so far is 53 m^3 in the month of April 1989. During the following two consecutive years, the system performed best in the same month in terms of average daily water output. The cumulative output for the year 1989 was 15,263 m^3, this was found to have been reduced to 13,973 m^3 in the year 1990. As the solar radiation and other weather parameters could not be monitored at the site, it is difficult to comment upon the exact nature of various factors responsible for the reduction in performance.

PV PUMPING CHARACTERISTICS

The PV pumping system is a dynamic system consisting of more than one sub-system, the characteristics of which change continuously throughout the day depending on variations in climatic and hydrological parameters. The output from the array varies as the irradiance on the array plane changes. The performance of the motor/pump unit is affected by the electric current and the voltage from the array as well as the depth of the water table, and is reflected in the water output pattern.

Essentially, the PV pumping system consists of four sub-systems, viz.:

- PV array;
- control equipment;
- motor-pump assembly; and
- water storage and distribution system.

The input solar energy to the array undergoes several conversions before it is made available as mechanical energy for pumping water. Each conversion is associated with a certain amount of energy loss which ultimately influences the cost of pumping water. The efficiencies of energy conversion in each of these stages are, therefore, of critical importance.

To start operation, the motor/pump unit requires a certain amount of power to overcome the starting torque. A centrifugal pump has a relatively low starting torque and will readily start to rotate slowly even if the solar irradiance is low. There will not be any water output, however, until the irradiance increases to a level where array power is sufficient to develop the rotational speed required for pumping water through the required height.

Typically, a PV pumping system starts pumping water when the irradiance rises above this threshold level. The water output rate continues to increase with the irradiance. As the motor/pump unit reaches its optimal operation point, the overall system efficiency improves. In the afternoon, when the ambient temperature increases and hence the solar cell operating temperature also, the efficiency of PV conversion decreases. Although, the cells cool down later in the afternoon, the water output continues to decrease on account of low irradiance and finally, stops when the array is unable to generate enough electrical power.

The overall efficiency of the system obtained in the field depends critically on the matching of operating parameters to the design ones. The significance of this matching has been a major highlight of this study.

Cell operating temperature and module front surface soiling were observed to be two critical aspects related to PV array performance. As per the following relation:

$$T_c\,(^\circ\mathrm{C}) = T_a\,(^\circ\mathrm{C}) = 0.3 \text{ x intensity} \quad (\mathrm{mW/cm^2}) \qquad \text{[A]}$$

the cell operating temperature (T_c) would be a few tens of degree higher than the ambient temperature (T_a) under typical field conditions [1]. The instantaneous array efficiency or array power, being a linear function of cell temperature would be [2]:

$$\eta_c = \eta_R \; [\, 1 - \beta (T_c - T_a) \,] \qquad \text{[B]}$$

The reference array efficiency η_R is the product of the module fill factor and the cell reference efficiency determined at a reference cell temperature T_R. β is the temperature coefficient of efficiency which is relatively constant over a range of temperatures encountered in terrestrial flat plate arrays. The typical value of β is between 0.35% and 0.4% per °C.

Dirt accumulation on the PV module surface can also have an appreciable effect on its output power. In dense urban areas, the high carbon content of urban pollution is considered the major cause of soiling. In rural agricultural areas, pollen dust is the chief cause. In arid regions, data during five years revealed a 30 per cent reduction in current output due to dirt having settled on modules [3]. Typically, the soiling factor, which measures the power generated despite soiling, could be anywhere between 0.97 to 0.92 after a six months exposure [4]. Site A is an open agricultural area having frequent dust-storms. Although the modules are regularly cleaned with a dry cloth, the possibility of significant reduction in their electrical output due to dust accumulation cannot be overlooked.

The high efficiency inverter, as per the manufacturer, is designed to 'follow-the-sun'. DC-to-AC inverters are commonly equipped with fixed voltage inputs or maximum power point trackers to provide impedance matching. In most practical situations, the frequency of the generated waveform in saturable-core oscillator type inverters – the modern technology devices commonly used today – is directly proportional to the DC supply voltage. This property is utilized in the operation of pumping systems at lower irradiance levels. As the array voltage rises initially, the frequency of AC power also increases, thus increasing the rpm of the motor, enabling the system to pump water even at a low irradiance level.

At any fixed speed, the pump will operate at a combination of head (H) and capacity or flow rate (Q) given by its characteristic curve. The efficiency will be considerably less both at an excessively high head and an excessively low head. This aspect was reflected in overall system efficiency values obtained in the field.

OVERALL SYSTEM AND SUB-SYSTEM EFFICIENCIES

Tables 1 and 2 present the system efficiencies for six different installations and sub-system efficiencies at installation site A. The efficiencies were calculated by monitoring the following parameters manually for a fixed duration:

1. Solar irradiation received on the array plane and ambient temperature;
2. Array electrical energy output;
3. Inverter energy output; and
4. Volume of water pumped.

Table 1. Overall system efficiencies.

Site	Total Pumping Head (m)		Overall System Efficiency (per cent)
	Design	Actual	
A	20	9	1.11
B	20	6	0.82
C	20	7	0.81
D	20	12	1.36
E	20	12	1.30
F	50	20	1.06

Table 2. Sub-system efficiencies at site A.

Sub-system	Efficiency (%)
PV array (η_{PV})	6.02
Inverter (η_{inv})	90.00
Motor/pump unit ($\eta_{m/p}$)	21.10
Overall ($\eta_s = \eta_{PV}\,\eta_{inv}\,\eta_{m/p}$)	1.14
Field Conditions at Site A	
Ambient temperature	29°C
Average solar irradiance on the plane of the array during the experiment	833 W/m^2
Total pumping head	9 m
Average flow rate	6 m^3/h

Sub-system efficiencies of individual system components at site A were calculated from measurements at 833 W/m^2 average solar irradiance on the plane of the array and 29°C ambient temperature, chosen at random from a set of similar measurements taken under different field conditions.

The tables clearly indicate that the systems are performing sub-optimally as they are commissioned at off-design pumping heads. The overall system efficiencies improve as the actual pumping heads get closer to the designed ones. The array and motor/pump unit efficiencies obtained at site A are lower than the optimum achievable values.

Array

From the typical data (at 1000 W/m^2, AM 1.5 insolation) supplied by the manufacturer on PV modules used in the system, the temperature coefficient β has a value of 0.38% per degree rise in temperature. Considering a soiling factor of 0.95, the array efficiency under 833 W/m^2 on its plane and 29°C ambient temperature was calculated to be 7%. The PV array which is rated for 1.28 kW$_p$ at 1000 W/m^2, AM 1.5 insolation and 25°C cell operating temperature, would thus produce a total amount of power equal to 900 Wp, as calculated using expressions [A] and [B].

There are several other considerations that can further limit the power output of an array in the field, some of these are electrical degradation, loss in wiring and diodes, mismatch between modules in a string and variance from the array's maximum power point. The rate at which the performance of a module decreases is difficult to predict. The quality of module design, components other than solar cells used in a module, the temperature extremes that a module is exposed to and the effect of solar spectrum on the cover glass and solar cells are factors that cause modules to degrade. It is estimated that PV energy output will decrease at a rate of about 1% to 2% a year due to all such factors [4].

These factors could account for low conversion efficiency of the PV array at site A as most of the measurements were carried out one year after the system was commissioned.

Inverter

The load which is powered by the PV array may cause the array to operate at a point different from its maximum power point. In the studied system, although the total pumping head is different from the design head, the inverter functions as the maximum power point tracker, as per the manufacturer's claim. In the absence of any technical specifications available from the manufacturer on the inverter characteristics, it is difficult to compare the design efficiency with the one obtained in the field. However, the 90 per cent efficiency obtained in the field is comparable to expected efficiency of modern technology inverters[1].

Motor Pump Unit

The combined efficiency of the motor pump unit as measured in the field is 21.1 per cent. The highest efficiency of the pump is 55% obtainable at a flow rate between 3.3 and 4.2 m^3/h according to the pump characteristics supplied by the manufacturer. The flow rate corresponds to a total pumping head of 20 to 25 m. The induction motor used in the system usually has an efficiency in the range of 75-80 per cent. The combined highest efficiency of the unit (assuming 80% efficiency of the motor and 55% efficiency of the pump at design head) is expected to be 44%.

The measured efficiency of motor/pump unit (21.1%) indicates the importance of maintaining the operating head as close as possible to the design head. The unit is designed for 20 m head while it is actually working at a total head of 9 m which has not changed much since the system was commissioned in October 1988 (8.7-9.4 m). Total head of 9 m corresponds to a flow rate higher than 6 m^3/h according to the pump characteristic curve, which also agrees with the measured value at which the pump efficiency falls below 30%. Although the motor efficiency could not be measured independently, it was estimated to be 70% from the combined unit efficiency of 21.1% and pump efficiency of 30% at actual pumping head of 9 m.

From the characteristic curve of the pump, it is clear that the pump can operate at an optimum efficiency within a very small range of flow rate. It, therefore, becomes important that the desired flow rate be maintained to achieve the optimum performance of the entire motor/pump unit.

EXPECTED EFFICIENCIES AND PERFORMANCE AT SIMULATED PUMPING HEAD

Measurements were conducted by artificially altering the total operating head of the pumping system with the help of a pressure gauge and a gate valve on the delivery pipe line. The efficiency values obtained thereafter (presented in Table 3) show that the pump would work at its maximum design efficiency of 55% only when it operates at a total head of 20 m. The highest system efficiency is also achieved in this case.

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[1] Commercially available inverters from Photoelectric Inc. San Diego, U.S.A. and Heart Interface, Washington, rated at 3000 W and 1800 W respectively suitable for connecting a PV array to a 120/240-V, 60 Hz system, offer efficiencies in the range of 92 to 95 per cent. The high efficiency DC/AC inverter used in Grundfos pumping systems claims an efficiency of 95%. It is a variable frequency inverter incorporating constant voltage tracking.

Table 3. Performance at simulated pumping heads.

Total Simulated Pumping Head (m)	Flow Rate (m^3/h)	Corresponding Pump Efficiency (%)	System Efficiency (%)
12	5.20	45	1.6
14	5.95	30	1.6
16	5.62	40	1.7
18	5.14	47	1.7
20	3.76	55	2.0

The overall expected system efficiency under studied field conditions (833 W/m^2 irradiance and 29°C ambient temperature) at design head of 20 m would be 2.8% as calculated from the product of the maximum achievable sub-system efficiencies, viz.: $\eta_{PV} = 7\%$, $\eta_{inv} = 90\%$, $\eta_{motor} = 80\%$, $\eta_{pump} = 55\%$.

However, the actual sub-system efficiencies obtained at a simulated pumping head equal to 20 m; $\eta_{PV} = 6.02\%$, $\eta_{inv} = 90\%$, $\eta_{motor} = 70\%$ and $\eta_{pump} = 55\%$ give an overall efficiency value of 2.1%, which is indicated in Table 3.

The result suggests that in such an installation where the water table is shallower than the one for which the pumping system is designed, it would be beneficial to create extra required head in order to enhance the overall efficiency of the system. Constructing an overhead storage tank is one possible way to increase the total pumping head. Another aspect worth considering in such situations is whether efficiency is the prime factor of importance in most applications or the volume of water pumped. While it may be advantageous to pump water into overhead tanks in some applications, in others it may be more appropriate to suffer the lower efficiency but to pump more water to a lower head.

SUMMARY

Although this study conducted at a preliminary level could not correctly predict the degree of sub-optimal performance of all the sub-systems due to limitations of data acquisition methods, it significantly highlights the critical need to operate the PV system at its design parameters. Other than physically creating the extra head, reducing the total array power utilized for pumping appears another plausible solution for improving the overall system efficiency. The excess power could be diverted to some other operation. However, for any such design change, a few aspects need careful consideration. The PV systems are designed taking into account the seasonal, daily and often the hourly variations in solar related parameters. The pumping system is designed such that water is available for maximum hours of sunshine during the day. It is possible that excess power is available during certain hours of the day or some days in a year and the reduced array power may not always be adequate to pump water at times when the irradiance level is low. In addition, the given system is designed to match parameters of various sub-systems. The altered array voltage and current to the inverter after diverting a part of the array power to some additional load, may not achieve a perfect matching of the array with the given inverter. In particular, the array voltage which directly affects the inverter frequency will alter the rpm of motor and pump. The characteristics of the pump given at a certain rpm would no longer be valid. Detailed and long duration experiments are essential to optimize the performance of any given system installed at off-design pumping head.

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