Photovoltaic Pumping Systems
A Comparison of Two Concepts

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Abstract

At the University of Oldenburg two different concepts of photovoltaic pumping subsystems available on the market were investigated: an asynchronous AC motor driving a multistage centrifugal pump and a brushless DC motor driving an eccentric screw pump. The characteristic data of the single components were measured, suitable physical models chosen and parameters for the models determined. Both systems were operated and monitored under field conditions at our test site. Computer simulations based on the models were performed and validated against the field data.

Using hourly radiation and temperature data from Northeast Brazil the annual energy flow diagrams for two hypothetical PV pumping systems composed of the above named subsystems were calculated in order to analyse and identify efficiency and loss mechanisms at component level.

This paper describes the modelling of the two different systems and discusses the energy flow diagrams.

1 Introduction

Photovoltaic pumping (PVP) has established itself as a water lifting technique for remote areas in sun-belt countries. Depending on the distance to existing electricity grids and the power requirements, photovoltaic pumping systems are considered technically and economically a favourable solution.

The state of the art of PVP systems consists of a photovoltaic generator, a subsystem (power conditioning unit, electrical motor, pump) and a hydraulic system (piping, water storage, water distribution). The subsystems differ with respect to the type of motor (AC motor / BDC motor) and the type of pump (centrifugal pump / displacement pump). The subsystem costs make up for a small part of the total PVP costs but its influence on the overall efficiency is considerable. For this reason intensive investigations of different system concepts are still an important issue.

Based on detailed measurements, physical models of the main components (PV generator, power conditioning unit, motor and pump) for two different system concepts available on the market have been derived.

Both systems were operated and monitored under field conditions at the pumping test facility of the University of Oldenburg. Computer simulations based on the models were validated against the field data.

Using hourly radiation and temperature data from Northeast Brazil energy flow diagrams for two hypothetical systems were calculated in order to analyse and identify long term efficiency and loss mechanisms at the component level.

2 Description of the systems

In the following the two systems under investigation will be named System A and System B. Both systems are powered by a standard PV generator. The technical data of the components of System A and System B are comprised in table 1. System A is a common system while System B has recently been developed.

	SYSTEM A	SYSTEM B
PV generator:		
	monocrystalline cells	monocrystalline cells
generator area:	15.36 m^2	3.41 m^2
P$_{nominal}$:	1.91 kW$_p$	0.43 kW$_p$
Power conditioning:		
	PWM three phase	MPP tracker comprise
	voltage source inverter	in motor electronic
P$_{DC,max}$:	4.8 kW	0.8 kW
P$_{AC,max}$:	3.5 kVA	
frequency:	0 ... 100 Hz	
Motor pump unit:		
	submersible	submersible
motor:	three phase asynchronous	brushless DC
P$_{nominal}$:	1100 W	600 W
pump:	three stage centrifugal	eccentric screw
head:	18 m (nominal)	25 - 90 m (range)
flow rate:	7 m^3/h (nominal)	2.5 m^3/h (max.)
Hydraulic system:		
geodetic head:	15 m	30 m

Table 1: Characteristics of the systems under investigation

3 Description of the models

The characteristic data of the single components were measured, suitable physical models chosen and the parameters for the models determined.

The PV generator was modelled by the two diode model [3] for solar cells. The total head of the hydraulic system is composed of constant geodetic head and dynamic head which is proportional to the second power of the flow rate.

SYSTEM A

The inverter is described by the efficiency characteristic, the voltage tracking of the PV generator and the AC voltage as a function of the output frequency.

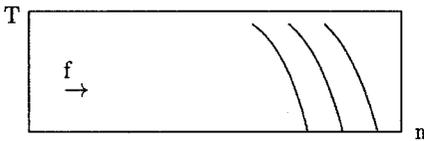The AC motor equations were derived from the T-equivalent-circuit of the asynchronous motor. (Fig. 1)

The centrifugal pump models (throttle curve and torque) are based on the "Euler Turbine Equation". (Fig. 2 and 3)
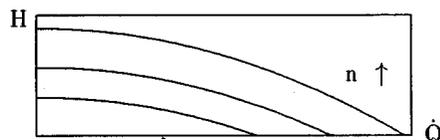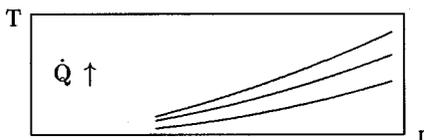These models are described in [1] and [2].

Fig.1: T(n)-characteristic of an AC motor

Fig. 2: T(n)-characteristic of a centrifugal pump　*Fig. 3: H(Q)-characteristic of a centrifugal pump*

SYSTEM B

A brushless DC motor is a self-synchronous machine with an electronic commutator in which the gap flux density distribution and back emf waveform are approximately trapezoidal, as in a conventional DC motor. The electrical power demand can be described as:

$$P_{DC} = 2\pi \cdot n \cdot T + \frac{R}{c_1^2} \cdot T^2 + c_2 \cdot n^2 + c_3$$

This equation describes the motor inherent copper, core and friction losses and the constant losses due to the electronic commutator.

The eccentric screw pump is a positive displacement pump. The design of the rotor and stator causes progression of cavities from the inlet to the outlet of the pump by rotation. The pump torque composes as follows:

$$T_{pump} = \frac{1}{2\pi} \cdot V_o \cdot g \cdot \rho \cdot H + c_4 + c_5 \cdot n^2$$

The three terms in this equation stand for the net hydraulic equivalent of the torque, the constant friction torque between stator and rotor and the losses due to turbulent flow in the cavities of the pump. (Fig. 4)
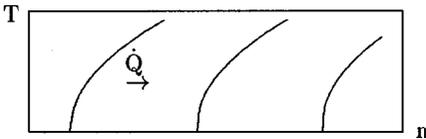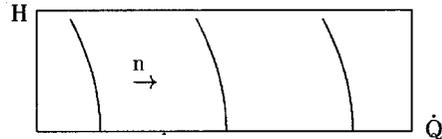

Fig. 4: T(n)-characteristic of an eccentric screw pump

Fig. 5: H(Q)-characteristic of an eccentric screw pump

The H($\dot{Q}$) characteristic can be obtained as:

$$\dot{Q} = V_o \cdot n - c_6 \cdot H^2$$

The first term represents the flow rate generated theoretically by the progression of cavities along the pump and the second term the volumetric losses between rotor and stator. (Fig. 5)

4 Measurement and simulation results

Extensive measurements of the performance of both systems have been carried out during several months under field conditions at a PV pumping test facility installed at the University of Oldenburg. The data obtained serves as a basis for the modelling of the system's behaviour and also for the validation of the models developed.

Time step simulation for the two systems were performed by implementing the individual component models in a simulation algorithm utilising the block oriented simulation system INSEL (INtegrated Simulation and Environment Language).

In order to compare measured and calculated data, the systems were first simulated in time steps of one minute, which is the time resolution of the measurement. In figure 6 and 7 some of the relevant results of the simulation are compared to the measured values.

Figure 6 shows the measured and the simulated water flow rates during one specific day for System A and System B.

In figure 7 the simulated and measured flow rate at constant geodetic head is plotted as a function of the DC power for both systems. This characteristic describes the subsystem performance and it is usually provided in data sheets of solar pump manufacturers.

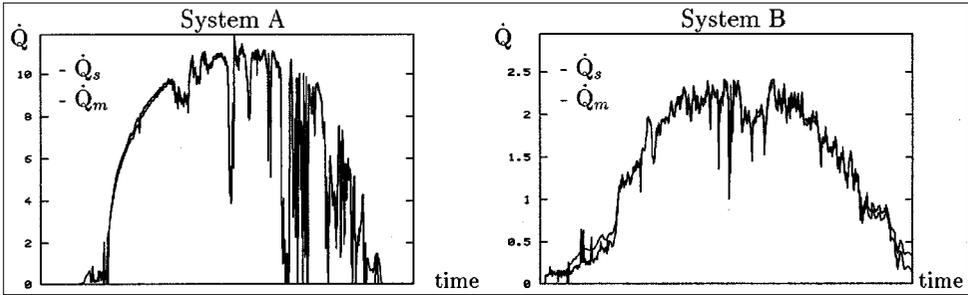A good agreement between simulation and measurement has been achieved.
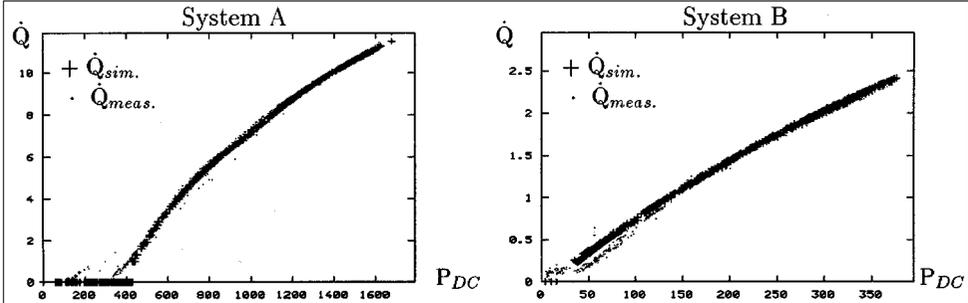
Fig. 6: $\dot{Q}$ [m³/h] during one day

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Fig. 7: $\dot{Q}$ [m³/h] versus P_{DC} [W]

5 Energetic analysis of the annual performance

In order to analyse the annual performance of the two systems simulations under meteorological conditions of Northeast Brazil (hourly data of irradiation and temperature of Lagoa das Pedras) were carried out. The mean irradiation was 5.3 kWhm^{-2}d^{-1}, the mean ambient temperature was 27 °C. Both hydraulic systems were designed to match the nominal operation of the subsystems.
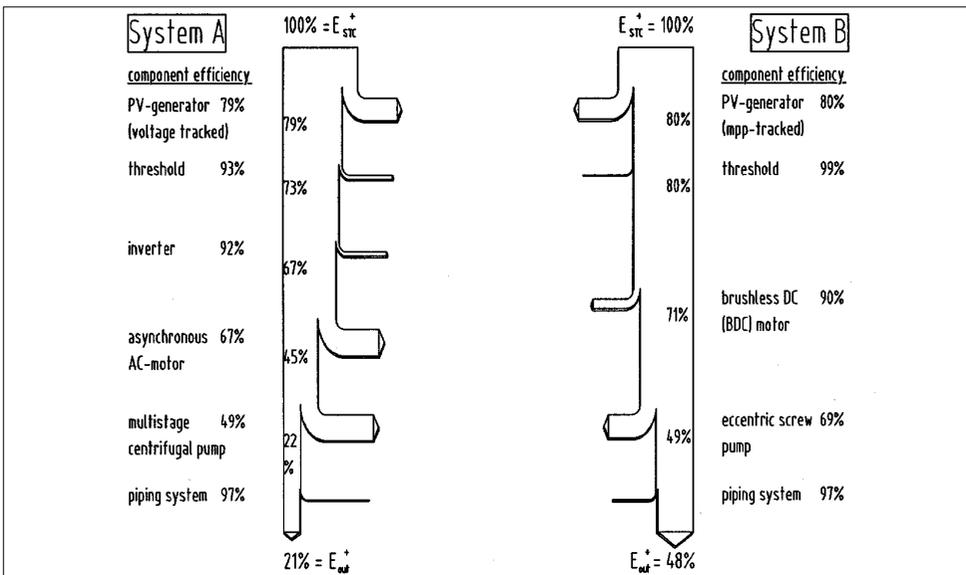

Fig. 8: Energy flow diagram

To compare the two systems the results of the simulations are presented as energy flow diagrams in figure 8. The performance ratio (PR) serves as a measure of system performance. It is defined as the net energy to overcome the geodetic head divided by the energy expected from the PV generator, when performing at STC efficiency. (Standard Test Conditions: 1000 W/m² , 25 °C, AM 1.5). The performance ratio of System A is 21 %, that of System B is 48 %.

The analysis of the losses at component level shows:

At optimised voltage setting a voltage tracked (VT) PV generator performs almost as good as a maximum power point tracked (MPPT) PV generator (80 % of E_{STC} for MPPT and 79 % of E_{STC} for VT). The losses when operating at conditions different from STC are 13 % for temperature and irradiation effects. 7 % are due to spectral, reflection and mismatch losses.

In centrifugal pumps a minimum rotational speed of the inipeller is required to generate head. This implies that 7 % of the DC power cannot be transformed into hydraulic power (threshold). An eccentric screw pump needs a high starting torque which may be overcome by the motor with the help of modern electronic power conditioning units at a very low electric input power. Therefore the threshold in System B results in losses of only 1 %.

The inverter losses in System A are in the range of 8 % of the inverter input. The power conditioning of System B is included in the motor.

The main motor losses (core and copper) act in the asynchronous motor in both rotor and stator while they occur in BDC motors in the stator only. System A motor losses amount to 33 %, in system B they are only 10 %.

Hydrodynamic losses are the main losses in the centrifugal pump and they increase with the second power of velocity. The main losses of an eccentric screw pump are due to friction between rotor and stator. These losses are almost linear to the rotational speed of the rotor. Therefore the pump of System B has an annual efficiency of 69 %, that of System A reaches 49 % when pumping.

Both piping systems were designed to have the same efficiency of 97 %.

6 Conclusion and outlook

From the energetic point of view PVP systems consisting of BDC motor and eccentric screw pump are superior to conventional asynchronous motor and multistage centrifugal pump systems.

For a final decision of the favourable system an economical evaluation has to be carried out. Because submersible motor pump systems are exposed to extreme wear conditions, the performance of both types of systems needs to be examined during a long period of operation in order to investigate the long term stability of the components. Detoriation will influence the efficiency of the components and hence the water output.

Nomenclature

A	PV generator area	c_i	empirical constants
E_G	irradiated solar energy	E_{out}	net energy to overcome geodetic head ($Q \cdot p \cdot g \cdot H_{geod}$)
E_{STC}	electric energy output when performing PV-generator at STC-efficiency ($E_G \cdot A \cdot h_{STC}$)		
f	frequency of inverter	g	gravitational constant (9.81 m/s²)
H	total head	H_{geod}	geodetic head
n	rotational speed	P_{DC}	power of the PV generator
Q	water volume	$\dot{Q}$	flow rate
R	ohmic resistance	ρ	density of fluid
T	torque	V_o	cavity

References

[1] H. Bloos, H. Gabler, R. Moraes, W. Wordtrnann, Das Photovoltaische Pumpsystem der Universiät Oldenburg, Proc. 9. Int. Sonnenforurn, 596 - 603, Stuttgart, 1994.
[2] H. Bloos, H. Gabler, A. Janssen, R. Moraes, Analytical and experimental investigation of the performance of PVP systems, ISES Solar World Congress, Harare 1995.
[3] A. L. Fahrenbruch, R. H. Bube, Fundamentals of Solar Cells, New York, 1983.

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