PUMP BEHAVIOUR MODELLING
FOR USE IN A GENERAL PV SIMULATION SOFTWARE

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ABSTRACT: The aim of this study is to implement a pumping system module in a general software for the study, sizing and simulation of PV systems (namely the software PVsyst). To be used in the simulation process, the pump model should describe the dynamic evolution of the output variable – usually the flowrate – in terms of pertinent input variables (head, voltage, power). The model should cover all types of pumps available on the market, suited for use in PV systems. The parameters necessary to the characterization of the model should be easily available from the manufacturer data sheet, or from detailed measurements when available. The computer model has been developed and tested using the measured data of CIEMAT on several pump models and types.

Keywords: PV Pumping, Modelling, Characterization, Simulation, Software

1. INTRODUCTION

With the increasing acuity of water supply problems, especially in developing countries, solar pumping systems are taking a great importance. However, Solar pumping system sizing and optimization is a rather complex task, involving a lot of variables, which mix together in a way that is not intuitive. Most pump manufacturers do indeed propose their own "standard" system configurations, valid for given conditions (usually based on one standard clear day). Their specifications or sizing tools don't allow to estimate the net water yield during a specified meteo time serie.

To our knowledge, there is no general tool available on the market, able to size and simulate such systems with sufficient generality and accuracy, in order to allow to compare the performance of different system configurations in a given situation.

The aim of this study is to implement pumping system sizing and simulation in PVsyst, a widely used general software for the study of other PV systems (Grid-connected, stand-alone or hybrid).

Some pump modelling attempts are reported in the Solar PV literature. Valuable work has been done about centrifugal pumps ([1],[4]). But other are often valid for reproducing accurately the results of one or two well-measured pumps; the model parameters are usually basic physical parameters of the motor or pump components, most of the time obtained by adjustment on the measured data.

2. REQUIREMENTS FOR A USEABLE MODEL

To be implemented in a general purpose simulation software, the pump model should match the following characteristics:

2.1. Input/Output variables

The model should describe the dynamic evolution of the output variable – usually the **flowrate** – as a function of the pertinent input variables, which are basically the **head** and **voltage** input, for any conditions within the admitted operating values. Indeed, when a given voltage is applied to the pump, this will run at an operating point characterised by a flowrate yield, as well as by a **current** drawn from the source. Therefore current is also a function of the Voltage and Head inputs.

The general model will give all the relationships between these 4 variables. Therefore it will include the determination of the Current/Voltage characteristic of the pump, which is necessary to the calculation of the operating point when coupling the pump directly to the PV array.

But in many cases the motor is specified for use at a nominal voltage, and detailed I/V behaviour is not available. The Flowrate is then given as a function of Head and input electrical **Power**. These only 3 variables are in principle sufficient for characterizing the operating point, when the power input is fed through some power-conditioning unit, which will provide an adequate voltage.

Besides these 4 operating variables, some pump types also require special starting conditions (starting peak current due to friction forces).

2.2 Applicability to any technology

The model should cover any motor-pump's technology, available on the market for use in PV systems: centrifugal pumps, positive displacement pumps (including piston, membrane or diaphragm, progressive cavity, rotating displacer, etc.). These pumps can be driven by diverse AC or DC motor technologies.

The model will also apply to other standard pumps (not specifically designed for solar applications), with AC induction motors, driven by frequency converters.

2.3. Parameter Availability

Ideally, the parameters necessary for achieving the modelling should be available from the manufacturer data sheets, in order that any user of the program can input its own pump model characteristics. In practice, manufacturers usually give performances for only a limited set of actual operating conditions. Details about the motor or pump technology and related fundamental parameter are usually not available.

Therefore, the model should apply to the motor-pump group as a whole, without reference to intermediate values like torque or speed, which are highly technology-dependent and rely to unavailable specific technical parameters.

3. DESCRIPTION OF THE MODEL

3.1. Model Structure

Let us define the following variables:

- Up, Ip = Voltage and current applied the pump.
- Pp = Up * Ip = Input power of the pump
- Uc, Ic, Pc = Voltage, Current and Power applied to the input of the power converter, if any.
- FR = Flowrate produced by the pump
- HT = Total Head, sum of the Static Head (related to the difference between input and output water levels), and Dynamic Head, due to friction losses in the pipes and system. Dynamic head is dependent on the flowrate, and will be computed by the system simulation process.

The pump characteristics may be considered as a set of operating points represented as a surface in the 4-variable space, i.e. corresponding to the equation:

$$\Phi\ (Up, Ip, HT, FR) = 0.$$

This function will be defined on an operating domain, which is bounded by some limits (usually specified by the manufacturer):

- Maximum voltage applied to the motor-pump,
- Maximum electrical power,
- Maximum current
- Maximum Head (implies maximum current),

and toward the low values:

- Power threshold for starting operating (i.e. not null flowrate), which is a function of the Head.

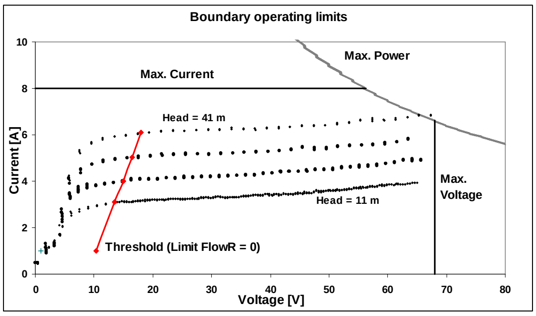

Fig 1. Boundary limits of the operating domain and I/V measurements for pump Watermax BU (CIEMAT measurements, [3])

The equation Φ=0 implies that only 3 of the 4 variables are independent. Therefore the model will provide relations allowing to calculate any one of the above variables, as functions of two others. The basic relations are:

- Ip = f (Up, HT), the fundamental relationship which will be used for determining the operating point when directly coupled to a PV array.
- FR = f (Pp, HT), completing the preceding relation for determining the corresponding flowrate.
- Pp = f (FR, HT) will be used for example for sizing the PV array power, or for determining the efficiency.

The other relations may be obtained by numerically inverting these 3 fundamental ones.

As a complement, the model also provides functions for determining the Power, Voltage or Current threshold (i.e. the boundary where the flowrate drops to zero) as function of the Head.

3.2. The Phenomenological Model

The problem is now to determine this function Φ. As previously stated, we would like to avoid references to technology-specific parameters, that is to physical models describing the motor or pump. Therefore our model is mainly based on the known performances, i.e. the operating points either specified by the manufacturer, or measured by other sources.

If these points are sufficiently well distributed over the operating domain of fig 1, they will completely define the pump behaviour. The informatic model has to interpolate between the given points; in practice, it will perform cubic interpolations between points, and linearly extrapolate the data up to the boundaries. Therefore this model is just a phenomenological one, without any physical contents.

Physical assumptions will be necessary only if the data set is not sufficiently well distributed for allowing extrapolations within the entire operating domain. These very general assumptions will be established according to general behaviours observed when measuring a great number of pump technologies. These are not yet quite fixed in the model, and will probably be refined during our future works. Of course this lack of primary information in the basic data will result in lower accuracies of the model's predictions.

In practice the manufacturers use to specify the performances of their products by giving different kinds of data sets. We identified 4 of them, and each one has to be treated specifically in the model; that is, the algorithms of the basic functions mentioned above will be different for each kind.

3.3. Given Ip and FR as f(Head) for fixed Voltage

This is the common data usually specified for positive displacement pumps. Complete characterisation of the model requires such data sets for several operating voltages. For one voltage, a set of data will specify some points (HT, Ip, FR) distributed along a vertical line on the fig 1.

It is unfortunately a common practice to specify such a data set for only one "nominal" voltage. This is of course not suitable for computing direct-coupled configurations. The extension to other voltages requires a strong hypothesis, which is (in this first status of the model) that the Pump Efficiency is constant when varying the voltage. Fig 2 shows an example of measured efficiency profile. We can observe that within the reasonable operating range 30-64V, the variations are of the order of 15%

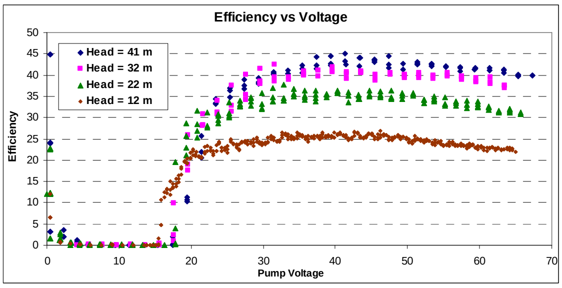

Fig 2. Efficiency vs voltage for Watermax BU [3]

If we avail of 2 voltage curves the efficiency figure is a linear interpolation, which improves the model's accuracy.

3.4. Given Pp and FR as f(Head) for fixed Voltage

This is equivalent to the preceding scheme, as for each data point the current may be easily determined from power, using the fixed voltage parameter of the curve.

3.5. Given FR as f(Pp) for fixed Heads

Grids of FR (Pp) curves for different Heads is the usual way of specifying the solar centrifugal pumps. These allow to get a very good determination of the Hydraulic/Power behaviour, but don't hold any information about the Voltage/Current characteristics. Such data are suited only when the pump is coupled to the PV system through a power converter (see below).

If needed, the basic function Ip (Up, HT) requires additional informations. These could be provided either by a set of Ip/Vp points for at least two head values (on which we can adjust curves), or by several parameters: Nominal voltage and Current at a given reference Head, $\Delta V/\Delta I$ at fixed Head (i.e. dynamic resistance) and $\Delta I/\Delta H$ at fixed voltage.

When specifying parameters instead of curves, we assume linear behaviours, which will of course penalise the accuracy.

3.6. Given HT and Pp as f(FR), fixed voltage or speed

Standard centrifugal pumps designed for grid applications are specified by one **Head vs Flowrate** curve, for nominal grid conditions (fixed voltage, 50 Hz). To be fully determined, the model will also need a **power or efficiency curve as function of the Head**. This is not always provided by the manufacturers, as the power consumption is not a key parameter when using grid-powered pumps.

Using this only information at nominal speed, centrifugal pump behaviour at other speeds may be very well described by the so-called "affinity laws" [1][4]. These relations state that for two operating points at different speeds along an iso-efficiency line, one has:

$$FL_1/FL_0 = \omega_1/\omega_0,\ \ H_1/H_0 = (\omega_1/\omega_0)^2,\ \ P_1/P_0 = (\omega_1/\omega_0)^3$$

Solving these equations allows to determine any operating point from two given variables. Buts this calculation doesn’t take the motor efficiency change with speed into account.

Such pumps are most of the time driven by AC synchronous motors, and may be powered using a cheap standard Frequency Converter (FC) [1][2]. When using a DC motor, the Ip/Vp characteristics is strongly dependent on the motor technology, and seldom known.

3.7. Power Converters

Most of systems are equipped with some electronic device for matching the PV-array power to the pump power requirements. DC-DC converters are used for providing the high current at low voltage required by the pump at low power levels. DC-AC inverters produce the suitable voltage for AC motors; with synchronous motors, they may also modulate the frequency for matching the pump speed to the best operating conditions. These converters may also provide the Maximum Power Point Tracking (MPPT) functionality to get the best from the PV array.

Usually (as in the software PVsyst, [6]), the Power Converter is treated independently in the system simulation process. But when the pump model input specifies power input only, without information about the I/V characteristics, then the Converter Model should be coupled to the pump model. In this case the Pump should be supposed to run at its nominal voltage (or optimal frequency), for which the given Power/Flow characteristics is valid. That is, the converter is supposed to provide the suitable electric characteristics. And no information about the real intermediate Voltage or Frequency will be available in the model.

Most of the time the power converter is proposed by the pump manufacturer, and one can admit that his pump characteristics are given in relation with the use of this converter/pump association.

In this case the simulation process has to consider this converter/pump set as a whole. The input electrical characteristics will be that of the Converter (DC fixed or MPPT input), and the output hydraulic variables will be the flowrate and head. This "black box" model will of course take the Converter efficiency (as function of the power) into account.

4. MODEL ACCURACY

The performances of the model were checked using the very good laboratory data of CIEMAT [3], for several pumps. The measurement sets are recorded under several fixed heads, with or without power converter, by slowly varying the input current. Each measurement point includes input voltage and current (therefore power), flowrate and head. Data with converter include of course both input and output Voltage and Current, and eventually frequency.

4.1. Check of the basic model

We first used data of a diaphragm positive displacement pump, driven with a DC motor (Model Watermax BU from All Power), for which we avail of data sets at Heads = 11, 21, 31 and 41m.

As a complete set of parameters for defining the model, we can choose 4 operating points at each Head among these data, for respectively 36V, 48V, 53V, and 63V. This sample of 16 points may be the basis for constructing and testing any of the "phenomenological" models described above. As the model represents a surface that passes through these fixed points, the errors at these points are null.

The errors introduced by the model are the uncertainties of the interpolation function between the given points, and the extrapolations until the operating boundaries (which are often worse determined, because of the linear approximation, and the lack of "extremity" fixing point).

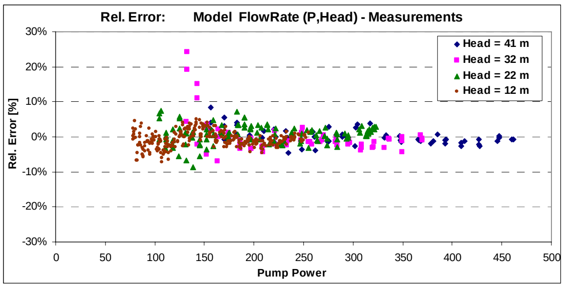

Fig 3. Errors Model – Measurements for Flowrate.

As an example, fig 3 shows the errors on calculated Flowrate (using the model *Ip and FR vs Heads*, for fixed Voltages) by respect to measured values. The scattering also reflects unavoidable measurements uncertainties. Nevertheless we can observe that most of the points lie within a +/- 5% range.

Each model, and each basic function of each model, may be analysed in this way, and give similar results.

4.2. Check of the model based on one only curve

The next figure shows the result degradation when the model is only based on the **4 points** for 4 heads at one given voltage (i.e. 48V). This set corresponds to the data set (at "nominal" voltage) usually available from most manufacturers.

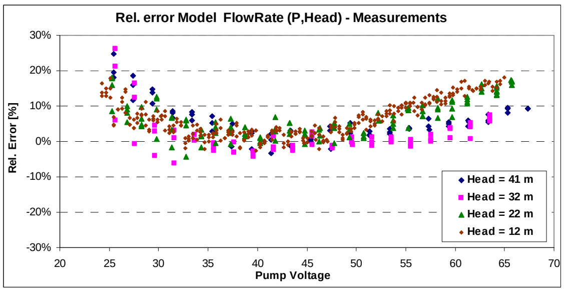

Fig 3. Error with model based on only 4 points at 48V.

Here we draw the results as function of the voltage, in order to illustrate the deviations by respect to the basic given data at 48V. We remind that the main additional hypothesis is here that the pump efficiency is constant according to the voltage. It can be seen that the results remain acceptable in the medium voltages.

4.3. Check of the model based on "Similarity Laws"

Finally, we used data from a centrifugal pump (Solarjack SCS 14-160) for analysing the model based on the Similarity Laws.

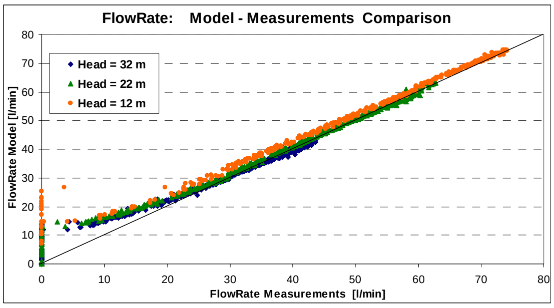

Fig 4. Flowrate Simulation-Measurements comparison with "Similarity Laws" model.

The model is based here on only 3 operating points (Pp, HT, FR). The accuracy is excellent for high flowrates; but the model tends to overestimates the data under 20 l/min (probably due to the motor efficiency), and doesn't reproduce well the threshold conditions (it still indicates significant flowrates when the measurements are under the threshold). We have still to perform some work for well understanding and reproduce these marginal conditions.

4.4. Model based on Manufacturer data

Do not confuse Model accuracy
with Parameter accuracy !

When using the basic model for the Watermax BU pump, with the 16 basic points analogous to the mentioned ones, but given by the manufacturer, the results errors are split between 0 and +20% (according to voltage). This does not reflect the model accuracy, but the knowing of the parameters. This indicates that the performances given by the manufacturer overestimate the real performance of this particular pump by about 10% on an average.

In practice any model will never be able to give better results than the input parameter accuracy !

IMPLEMENTATION IN THE SOFTWARE PVSYST

For being effectively useable in a general-purpose PV software, this should offer a comfortable interface, which allows to easily define the model parameters from manufacturer datasheet. In PVsyst, the user can choose the working units, and avails of graphical representations when entering the data.

As the pump behaviour is not intuitive the program will perform coherence and plausibility checks, and show an extensive set of "pedagogic" graphs.

CONCLUSIONS

We have developed a phenomenological pump model, based on performance data sets directly available from the usual manufacturer datasheets or from measurements. The model accepts a great variety of kinds of data sets. When the original data set is limited, extension to unusual operating conditions are calculated using general behaviours established with measurements on pumps of similar technology. Of course, the model accuracy will increase if a more extended set of performance values is available.

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REFERENCES

[1] M. Alonso-Abella, E. Lorenzo, F. Chenlo: PV Water Pumping Systems based on Standard Frequency Converters. Progress in Photovoltaic Research and Applications 2003, **11**:1-13.

[2] M. Alonso-Abella, F. Chenlo, J. Blanco, D. Manso: Use of Standard Frequency Converters in PV pumping systems. 2nd World Conf. and Exhibition on PVSEC, Vienna, 1998.

[3] M. Alonso-Abella, CIEMAT, private communication.

[4] H. Suehrcke, J. Appelbaum, B. Reshef: Modelling a Permanent Magnete DC Motor/Centrifugal Pump Assembly in a PV system. Solar Energy 59, nos 1-3, 1997.

[5] André Mermoud: Pumping System Sizing and Modelling Tool. 19th European PVSEC, Paris, France, June 7-11, 2004.

[6] PVsyst software. CUEPE, University of Geneva. www.pvsyst.com