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1 Introduction

1.1 Overview of the State-of-the-Art of Photovoltaic Pumping Technology

According to the World Health Organization (WHO), around one half of the population in developing countries do not have access to safe drinking water. Unsafe water accounts for 80 % of all sickness in those countries. Efforts to overcome this problem have made water pumping programs a priority of many developing countries and donor groups. In many regions this goal can only be achieved by the utilization of ground water resources. In remotes areas far away from national electric grids, there are diverse possibilities to make use of this resource: hand pumps, diesel pumps, wind or water powered pumps or solar pumps. In comparison to diesel pumps , solar water pumps are today economically advantageous below an hydraulic equivalent (head H \times Flowrate Q/day) of 2000 m⁴ [11]. The costs are naturally dependent on local prices. The typical heads lie between 1 m -100 m.

The utilization of photovoltaic conversion of solar energy to power water pumps is today an emerging technology, characterized by gradually declining costs and increasing acquaintance with the technology. Since the first installations in the end of the seventies, solar water pumping systems (PVP) for providing domestic, livestock and irrigation water supplies in remote areas have gained enormously in acceptance, reliability and performance and nowadays belong to the most significant applications of photovoltaic energy. This can be mainly attributed to the fact that it is not economically viable to connect such remote locations to national electric grids. It is now estimated that over 12,000 PV pump units made up of different configurations have been supplied worldwide.

A photovoltaic water pump system (PVP) consists of the following main components: the PV array, with support structure, wiring and electrical controls; the electric motor; the pump; and the delivery system, including pipework and storage. These components have to be designed to operate together to maximize the overall efficiency of the system (or, rather, to optimize the cost-effectiveness of the system). An electrical/electronic controller is sometimes incorporated to improve the electrical performance of the system. Energy storage in the form of batteries is rarely used, as it is generally cheaper, more ecological and simpler to store the water to cover periods of low solar input or high demand.

The main barrier to a widespread use of PVP-systems continues to be their high initial cost. The cost of water from these systems is directly related to the cost, efficiency, and reliability of the individual system components and the level of solar irradiation. The cost of photovoltaic modules (at present around \$5/Wp) accounts for between 30 % and 60 % (excluding the cost of well drilling and construction) of the total investment cost depending on the design of the system. Figure 1.1 below gives a breakdown of the component costs.

According to GTZ [16], in 1996 the average investment cost for PVP main components (PVgenerator, inverter, pump) for power demands between 1 kWp to 4 kWp range from 11,000 US\$ to 38,000 US\$ (fob). The cost for operable PVP on site (comprising pumping system, transport, installation, water storage and civil works) range from 22,000 US\$ to 59,000 US\$ for the same power levels above.



Fig. 1.1: Contribution of various components to investment cost of PVP-systems (source: GTZ Energy Division).

While improvements in the cost effective photovoltaic module manufacturing techniques are continuously researched, there still remains a clear need for development towards both improved reliability and efficiency values of solar pumping subsystems in order to extract the maximum power capability of the solar generator at all times. Thus, matching of system components, has been of interest to many workers over the last ten years [2,4,7,8,12,14]. These and other research works have led to a considerable improvement in technology for PVP-systems.

A number of types and sizes of PVP-systems are available commercially, in various stages of product development, that meet the range of existing pumping needs. The significant design variations of these systems are centered mainly on:

- the choice of the solar cell material;
- the type of electric motor;
- the type of pump; and
- the method of source/load matching.

Most commercially available systems use silicon solar cells, of either mono or polycrystalline type. Other types of solar cells, which may be less expensive, are under development. There have been significant advances in the development of techniques which use thin films of semiconductor materials such as amorphous silicon. Other high efficient techniques using thin film cells are being extensively researched, as for example Copper- Indium-Diselenide (CIS) or Cadmiumtelluride (CdTe). PVP technology will certainly benefit from these developments in the future.

The first generation of solar pumping systems, particularly those for low and medium head applications, incorporated basically permanent magnet DC-motors. However, in the course of the last 10 years the asynchronous motor driven by a variable frequency converter has become the standard motor for solar pumping applications mainly due to its simplicity, robustness and small price compared to a DC-motor. Electronically-commutated brushless DC-motors have in the last 5 years or so gained much popularity because they require less maintenance and are more readily adapted to submerged operation than standard DC-motors.

Single-stage centrifugal pumps are frequently used for heads of less than 10 meters. With open wells or surface water sources, these pumps and the motors can float. For higher heads, either multi-stage centrifugal or positive displacement (piston or progressive cavity) types are most efficient. If the pump is above ground or floating, it usually is closed coupled to the motor; if submerged, the pump may either be coupled to a submersible motor or driven by a vertical shaft. Positive displacement pumps ordinarily are submerged except in cases where the lift is small but the total pumping head is high.

For DC-systems, power conditioning is performed either via DC-DC converter units or with direct coupling of motor and PV-generator. Many systems, in particular the high power AC systems use three phase inverters. In order to best adapt to varying insolation conditions, most of the units have maximum power point tracking and variable frequency capabilities; other units use the fixed-voltage control strategy. The use of these devices certainly adds complexity and produces some power losses in the system, but the state-of-the -art of inverters for PVP-systems attains efficiencies as high as 97 % at nominal rating power.

PV-pumping system efficiency has considerably improved. System efficiencies from 1-3 % in 1981 have been raised to 3.5-5% in 1990 [1]. Novel system techniques are available with efficiencies of more than 5% [16]. These improvements are promising and attempts on the component and system level are made to further enhance the system efficiency, as it will be discussed later in this work.

1.2 Applications of PVP-technology

A substantial volume of field experience is now available relating to solar pumps. At this point it is necessary to mention that a complete overview of PVP applications in the last 20 years is not possible to be made here. Therefore, some examples concerning the most significant activities that contribute towards the dissemination of PVP technology will shortly be discussed.

The UNDP/World Bank program

A comprehensive study of solar pumps, involving field and laboratory testing of components and complete systems, was completed in 1983 by consultants for the UNDP and World Bank [15]. The work concluded that there was a considerable potential for the use of solar pumps for irrigation and domestic water supply, but that none of the products then available on the market were yet suitable for widespread use. Extensive recommendations were made on improving performance, reliability and cost. Based on the guidelines provided by this program, several new projected were launched. Some of these projects should provide some very useful field data. The most relevant are described briefly in the following.

The Sahel Program (CILLS project)

The program known as 'Programme Regionale Solaire' (PRS) has been established in the late eighties to provide solar energy systems for the people of the Sahel area. The systems would supply clean water and improve living conditions. Initiated by the 'Comité Inter-Etats de Lutte contra la Sécheresse dans la Sahel', (Permanent Interstate Committee for Drought Control in the Sahel) or CILLS, the program included representatives of Burkina Faso, The Gambia, Guinea-Bissau, Cape Verde, Mali, Mauritania, Niger, Senegal and Chad. Also known as the CILLS project, the program is financed by the European Development Fund. The project anticipated the supply of approximately 1,350 PV-pumping systems together with around 500 other PV systems (for lighting, battery charging and refrigeration). The total installed capacity would be approximately 1.3 MWp.

General aspects of PVP demonstration projects in the Sahel zone are reported by WIP and others in [9]. This study gives valuable information on system operations and maintenance, economic and social aspects and costs of PV pumps. It also gives an overview of the main problems influencing the performance of about 166 PV-pumps operating in Mali over a period of 4 years and conclude that the project is quite a success. The authors also mention the monitoring and evaluation campaign on 10 selected plants to be carried out by WIP. Unfortunately the to the point of this writing there was no published reports about the results of the evaluation, so that up to now it is only possible to conclude that there was a very low failure rate and an excellent acceptance by the people served by the PVP-plants.

The GTZ Photovoltaic Pumping Program (PVP)

In 1989, the BMBF (German Ministry for Education, Science, Research and Technology) and the BMZ (German Ministry for Cooperation) initiated a program, to be executed by GTZ in seven countries (Argentina, Brazil, Jordan, Indonesia, Philippines, Tunisia and Zimbabwe). The project known as 'Testing and Demonstration of small-scale PVP systems' was meant to sample reliable technical and economical data in order to survey the market potential of PVP systems in three continents under diverse cultural and climatic conditions.

The results of the studies carried out by GTZ encompasses technical, economical and social aspects of the implementation of PVP-systems in the seven countries. The studies produced a valuable data bank (cumulated data corresponding to 85 years) and pointed out the main factors affecting the performance of PVP-systems and its components.

The evaluations carried out by GTZ [13] and [16] demonstrate malfunctioning of some of the systems and to a certain extent give the reason for some of the problems, but they do not provide conclusive results. These evaluations are very generalized, usually concerning the results of all PVP-systems installed in the seven countries, and normally considering small periods of operation at the beginning of the monitoring program. However, some of the factors which contribute to the non-optimal performance of photovoltaic systems are specific of some countries, or even of some plants, and have to be individually analyzed in order to detect and possibly quantify their influence on the operational behavior of the system.

Results published by GTZ show, for example, that the measured average daily efficiency of the PVP-systems installed in the seven countries attained only 2 %, which is a small figure when one has in mind that for similar systems operating in other projects [10] efficiencies of up to 4% had been reported. An extensive list of probable reasons for the reduction of systems

efficiencies is also provided, but because they were compiled in a more or less random way, they do not permit a final judgement of the performance of the systems analyzed. The clues which are needed to say whether there are possibilities for improvement of the existing systems or for the design process of future applications are still missing in the evaluations.

The study of the economical and social aspects of introducing PVP-technology in the different countries confirmed and demonstrated that under specific conditions PVP offer the most attractive option for water supply in remote areas [5].

Besides the above mentioned PVP programs, the great number of reports about smaller projects concerning applications of PVP-technology available in the literature demonstrate the increasing application of this new technology in the last decade. According to existing market/economic studies [6], the potential world market for photovoltaic water pumps is enormous, and the contribution which this technology can make for the solution of water supply in dry or remote areas of developing countries is significant. There are clear indications that PVP is viable under certain conditions, but the general applicability and the sustainability of the new technology still must be proven beyond doubt before there can be large scale marketing and widespread dissemination of the technology. This will only be achieved if improvement of components continues to be searched, if a more careful evaluation of the data obtained from field operation is undertaken, and the lessons learned from these experiences be really understood and put into practice.

1.3 Scope and Outline of the Work

The field experiences discussed above have shown that the PVP-technology has reached considerable maturity, the systems have been well accepted by the users, the level of reliability has improved, and that they are economically viable today, under certain conditions. However, quantitative results concerning system performance are few, and the ones which are available, as in the case of the GTZ-program mentioned earlier, that the performance of the systems are far from satisfying. These facts point out that although PVP-systems have proven themselves as one of the most favorable solutions for the supply of drinking water in dry or remotes areas of sunny regions, complete understanding of their operating behavior and design optimization continue to be open questions. A more in-depth and systematic investigation of the performance of individual PVP-plants would certainly contribute to answer some of these questions.

The research done in the present work deals with the installation of Photovoltaic Pumping Systems (PVP), their operation under realistic conditions, the formulation and validation of numerical models of such systems and the evaluation of real applications, in an attempt to contribute to the understanding and optimization of the design and performance of these systems.

In the present work, the operational behavior of different PVP-system concepts are investigated in great detail on the basis of computer simulation. For each system, mathematical models are developed and utilized in simulation calculations whose results are interpreted in a energy flow analysis. Through such energetic analysis, the losses occurring in the system are identified and quantified, thus promoting a precise understanding of the system operational behavior, what leads consequently to its optimization. A pre-requisite for the use of a simulation model for lay-out calculations in the practice is that they should not require much computation time and that necessary model parameters are available or can be easily obtained. A simplified model destined to be used in system lay-out or in the analysis of real systems is presented and applied in the analysis of the performance of real PVP-plants operating in Brazil.

Chapter 2 describes the experimental set-up installed at the University of Oldenburg and documents the field experiments carried out on it to provide the data basis for the development of simulation models. Relevant laboratory tests performed on some of the components will also be discussed here. The chapter also contains, as an illustration of how a PVP works and the problems involved with it, a comprehensive analysis of relevant operation data obtained by field measurements.

In chapter 3, the physical background of the individual components that form a PVP-system will be described, and the detailed mathematical models developed for each of the components will be presented. The validation of these models, by comparison of simulated and measured data, will be treated here.

Chapter 4 demonstrates the realization of the complete PVP-systems models in the block oriented computer simulation software INSEL and presents the analysis of the simulation results using the models. Energetic analysis of the systems under investigation, based on energy flow diagrams of the systems long term performance ('analytical evaluation'), will be presented. This type of analysis permits that all steps of energy conversion can be traced and the loss mechanisms in the system can be identified. Comparison between the detailed model and other simplified models utilized for system layout will be performed. The scope of possible system optimizations will also be discussed in this chapter.

Chapter 5 contains the analysis of the influence of the real use of PVP-systems. Operational data available from demonstration projects in Brazil are evaluated with a new method based on computer simulations. For selected plants an analysis of the various parameters of technical and non-technical nature, influencing the technical performance of PVP-systems was carried out, in order to obtain figures of merit for the evaluation of PVP-systems which can be helpful for the optimization of lay-out processes and operation of future systems applications.

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2 Experimental Work

2.1 Introduction

The experimental investigation of PVP-system has been accomplished in two aspects in the present study. One was the determination of the physical characteristics of system components, in order to obtain the necessary basis for the development of accurate numerical models which are described and utilized in computer simulations in the two following chapters of this work. The second involved a comprehensive analysis of the operational behavior of PVP-plants under field conditions, to gain practical experience with such systems and also to support the modelling of system performance.

Within the mentioned context, the main objectives of the experimental research undertaken in the present work can be summarized as:

- Stationary laboratory measurements of the physical characteristics of the single components of PVP-systems.
- Long time measurements of the systems performance in a outdoor plant facility aiming at:
 - the acquisition of measured data sets for the validation of the numerical models under dynamic operation conditions,
 - the investigation of the operational behavior of PVP-systems and the interactions of their individual components under realistic outdoor conditions.

Most of the experimental research reported in this chapter has been carried out on a photovoltaic pumping test facility operating under field conditions at the University of Oldenburg, accompanied by stationary laboratory measurements of the systems components characteristics carried out at the University of Oldenburg, at the Technical University of Berlin and at the University of the German Armed Forces in Munich. In the following the experimental setups and the tests performed on them will be described.

The Outdoor Photovoltaic Test Facility

The PVP-system of the University of Oldenburg was installed outdoors and put into operation in 1994. The basic plant, representing the actual state-of-the-art of PVP technology, is composed of a 1.9 kWp PV-generator, an inverter, a centrifugal pump supplied by an asynchronous motor, a well and a water delivering system. Figure 2.1 presents schematically the pumping system setup. The original configuration was modified in 1996 when the centrifugal pump was temporarily replaced by a positive displacement pump driven by a brushless DC-motor. The technical data from both PVP-systems components are presented in Table 2.1. These two PVP-system configurations have been investigated in detail under field and laboratory conditions.



Fig. 2.1: Structure of the outdoor PVP-system test facility installed at the campus of the University of Oldenburg. The system is composed of a PV-generator, an inverter, an electrical motor and a pump inside of a well. The construction permits that different geodetic heads can be set, by a mechanism in which pumped water from the well is lifted up to different highs in a tower and returns to the well through pipes. This layout reproduces real PVP-plants installations.

Component	AC-SYSTEM	DC-SYSTEM
PV-generator	Siemens monocrystalline cells	Siemens monocrystalline cells
Generator area	15.36 m ²	3.41 m ²
P _{nominal}	1.91 kWp	0.43 kWp
Power conditioning	3-phase voltage-source inverter with	MPP-tracker integrated in the
	PWM control (Simovert-P from Siemens)	motor electronic commutator.
P _{DC,max}	4.8 kW	0.8 kW
P _{AC,max}	3.5 kVA	
Frequency	0 - 100 Hz	0 - 50 Hz
Motor-pump unit		
Motor	3-phase Asynchronous	4-poles brushless DC-motor 600
P _{nominal}	1100 W	W
<u>Pump</u>	KSB-UPA-100B7/3 Centrifugal pump	Suntron progressive cavity pump
Head	18 m (nominal)	25-90 m (operation interval)
Flowrate	7 m ³ /h (nominal)	2.5 m ³ /h (max.)
Hydraulic system		
Geodetic head	6-15 m (set-up measuring interval)	30 m

Table 2.1: Technical specifications of the investigated PVP-systems.

2.2 Experiments

2.2.1 Field Measurements

Using the above described outdoor plant facility, both PVP-systems configurations (Table 2.1) were operated during summer time under field conditions. The main objective of the outdoor experiments was the acquisition of time series data under dynamic conditions, to validate the models developed for the PVP-systems and their components. Other objectives were the investigation of the system and components behavior under different layouts and control conditions (as for example at different heads and/or different settings of the inverter control unit), to get acquainted with the data monitoring and also to gain general practical experience with such systems.

Figure 2.2 presents schematically the outdoor measurement setup. In this setup the power supplied to the subsystem (inverter/motor/pump) is provided by a PV-generator which was configured according to the power demand of each system investigated. As the figure shows, the following meteorological variables were measured: the solar irradiation G incident on the PV-array plane, the ambient temperature T_{Amb} and the panel backside temperature T_{cell} . The voltage V_{DC} and the electric power P_{DC} were measured between power conditioning devices and PV-generator. In the hydraulic system measurements of pressure P_1 in the well (before pump inlet), the pressure P_2 in the pipe (after pump outlet), and the pump flowrate Q were measured. By the AC-system the electric power P_{AC} , the electric frequency f_{AC} and the electric current I_{AC} were also measured between inverter and motor.



Fig. 2.2: Scheme of the measuring setup utilized in the outdoor experiments realized with both *PVP-systems configurations*. The variables in brackets were measured only for the AC-system.

The results of field measurements will mainly be used for verification of the numerical models for the single components (chapter 3) and for the validation of the complete system simulations in chapter 4. In this way, most of these results will be presented and evaluated in both following chapters, together with the results of model calculations. In the following, relevant results will be presented to illustrate how a PVP-system works and the problems involved with its operation.

Results of the Measured Performance of a PVP-system

As an example of the operational behavior of the AC-system, measurements in one minute mean values from a typical summer day will be presented. The total irradiation on the array plane was 6.7 kWh/m^2 on this specific day. The geodetic head (the height in meters which the pump has to overcome from the watertable of the well to the point of discharge) of the system was 9.2 m and 65 m^3 were delivered by the system. In the following figures 2.3 to 2.8 the most important results regarding the performance of the system are presented and discussed.

In Figure 2.3 the nominal power output of the PV-generator (P_{nom}), the PV-power output (P_{DC}) and the hydraulic power generated by the pump (P_{hyd}) during the day are shown. The nominal power is an idealized power output of the PV-generator and represents the irradiation on the array plane multiplied by the standard test conditions efficiency. The standard test conditions (STC) efficiency is the PV-module efficiency at predefined ambient parameters (1000 W/m², 25° C, AM1.5).



Figure 2.3: The Nominal Power (P_{nom}), the Generator Output Power (P_{DC}) and the Hydraulic Power (P_{hyd}) over the time. The geodetic head is 9.2 m.

Figure 2.3 shows that in the early morning and the late afternoon when the DC-power is not sufficient to attain the preset minimum frequency. Hydraulic power production starts shortly after 07:00 hours. At medium power levels the DC-power almost matches the power expected by assuming STC-efficiency; the inverter fixes the DC-voltage close to the MPP-voltage at intermediate irradiation. At high irradiation levels the generated DC-power is clearly below the power at STC conditions. This is due to the relatively high DC-voltage value which was set in the inverter for the experiment at that time. In following experiments the inverter parameters were modified in order to attain optimized range of operation for the generator (closer to the MPP line at high irradiation levels). A perfect match between PV-power P_{DC} and P_{nom} should however not be expected because the ambient conditions in real operation will always deviate from the STC-conditions. The deviations resulting from this effect will be discussed later.



Fig. 2.4: Calculated I(V)-characteristics of the PV-generator (200 W/m² - 1000 W/m²) with the measured I(V)-working points of the generator and the lines of constant power. The DC-voltage set point is as in Fig. 2.3.

The inverter performs a 'fixed-voltage' control strategy, which means that it does not search the point of maximum power (MPP) but DC-voltage is a more or less linear function of DC-current as shown in Fig. 2.4. This happens above a certain radiation value for which the pump starts to deliver water (in this case about 200 W/m²).



Figure 2.5: The pump head (H_p) *, the geodetic head* (H_{geod}) *and the inverter frequency* (f) *over the time.*



Fig. 2.6: The subsystem efficiency (η_{SUB}), *the PV-generator efficiency* (η_{PV}) *and the overall system efficiency* (η_{TOT}) *over the time. The geodetic head is 9.2 m.*

In figure 2.5 the pump geodetic head, the total head of the system and the inverter frequency curves are displayed over the time for the measurement from the day 25.04.94. It can be seen that only at a frequency over 30 Hz the pump is able to overcome the geodetic head and begin to deliver water (at about 07:10 hours in the diagram). Figure 2.5 shows that exactly at this time point the pump head is greater than the geodetic head. The hydraulic system was

dimensioned to produce minimal head losses, so that more than 90% of the hydraulic power could be utilized to overcome the geodetic head alone.

In figure 2.6 the different efficiencies of the system over the day are presented. The upper curve represents the efficiency of the subsystem, composed of inverter, motor and pump $(\eta_{sub} = P_{hyd} / P_{DC})$. It can be seen that the subsystem efficiency attains the highest values in the early and late hours of the day at lower flowrates, and as the flowrate increases at higher irradiation conditions, the efficiency goes down due to the decrease in the pump efficiency. Although the efficiencies of inverter and motor normally increase by higher flowrates (higher frequencies) this can not compensate the decrease of the pump efficiency. The curve in the middle of figure 2.6 represents the efficiency of the solar generator over the time $(\eta_{PV} = P_{DC} / G \cdot A_{PV})$, with G= solar radiation, $A_{PV} = PV$ -array area). The efficiency of the complete system $(\eta_{PV} \cdot \eta_{sub})$ attains values of about 3.5% in the morning and the afternoon hours and falls to about 2.5% in the middle of the day.

In figure 2.7, the efficiency of the subsystem over the generator power P_{DC} (with the head as curve parameter) is presented. For a geodetic head of 9 m, for example, the pump starts to deliver water from a generator power output (P_{DC}) of 200 W. The efficiency increases steadily by higher DC-powers and reaches a maximum efficiency of 29 % at an input power of 550W, and for further higher power levels it falls. On the other hand, when the pump has to overcome higher heads the behavior is different. As can be seen in the curves for 12m and 15m head, the DC-power threshold increases with the head, but higher efficiencies can be attained at higher P_{DC} levels. These behaviors reflect the problem of mismatch between pump and hydraulic system: the pump characteristics are more appropriate for higher heads, what was predicable enough in this case, since the nominal head of the pump is actually 18m. These results suggest that the water output of the system can basically be determined by the power output above the threshold and the subsystem efficiency and also that a more extensive choice of pump sizes should be available so that systems design can be improved. This point will be closely discussed later in chapter 4.



Fig. 2.7: Efficiency of the Subsystem (inverter ,motor, pump) over the solar generator output power (P_{DC}) with the geodetic head as curves parameter (from left to right: 9 m, 12 m, 15 m).

In figure 2.8, the typical graphic presentation of the pumped water flowrate Q over the solar generator output power P_{DC} is given. The parameter of the curves is again the geodetic head. Interesting in the graphic is also the greater scattering in the measurements at 12 m head. The measurements at 12 m head were done on a day with extreme changes of solar radiation, while continuous irradiation conditions prevailed during the measurements with a head of 9 m, and to a certain extent also with the 15m head.



Fig. 2.8 The flowrate Q as a function of the PV-generator power for different heads (from left to right: 9 m, 12 m, 15 m).

2.2.2 Laboratory Experiments

As already mentioned, a requisite for a detailed and accurate simulation of the performance of a PVP-system is that the characteristic data for the different components must be available. Since these data are not always provided by the components manufacturers, it is therefore necessary to obtain these characteristics from laboratory measurements. In the following, the stationary measurements performed basically on the AC-system will be summarized and the modifications done for the tests on the DC-system will be discussed. The data obtained with the experiments will be utilized to support the development of mathematical models for the components presented in the next chapter of this study.

The characteristic data of the individual components were measured under stationary conditions and the parameters for their physical models, described in chapter 3, were determined. Since the measurements were performed under stationary conditions, the models will ignore transient behavior, so that the effects of any electrical storage units (inductive and capacitative), the moments of inertia in the rotating system and the acceleration of mass in the hydraulic system are neglected. The time constants of the above mentioned effects are however in the order of seconds or less, while typical simulation time steps are 10 minutes or more, so that errors from neglecting the short transients are in fact not important. This point will be better illustrate later in section 2.3.

The data set needed for the complete characterization of both PVP-systems are: the DC current and voltage (I_{DC} , V_{DC}), the motor current and voltage (I_{Motor} , V_{Motor})), the inverter

output power (P_{AC}), the inverter frequency (f), the motor and pump Torque and rotational speed (T, n), the pump flowrate (Q) and the pressure head (H).

Figure 2.9 presents schematically the complete laboratory setup. The modifications undertaken for the measurements of some of the components will be addressed when discussing these measurements. All measured data were recorded automatically with a data logger controlled by a PC.



Fig. 2.9: Basic scheme of the setup for the laboratory measurements. The values in brackets were measured only for the DC-system.

As Figure 2.9 shows, the system was supplied by a variable DC-voltage/current power source followed by the devices for measuring these quantities; then comes the measurement of the power conditioning equipments, namely the inverter in the AC-system and the electronic commutator in the DC-system; for the inverter a power and harmonics frequency analyser device was integrated to the basic setup which allowed the measurements of AC- current and voltage, as well as harmonics analysis of these signals. The current and voltage measurements for the DC-system was done with the help of an oscilloscope; the AC-motor was tested separately and the measuring procedures will be explained later. Measurement of torque and rotational speed of the DC-motor were taken under water on the motor axis; the pump characteristics were obtained by the measurement of pressure and flowrate in the hydraulic system.

Measurement of the Characteristics of the Asynchronous Motor

In order to determine appropriately the characteristic and the parameters of the asynchronous motor, it was necessary to test it independently from the hydraulic system. For this, the motor was separated from the pump and tested according to the procedure suggested by Nürnberg in [7]. The measurements performed on our motor are documented with a great degree of details

in [5], so that here a summary of the test will be given. The measurement setup is presented in appendix A.

The objective of the motor test is to obtain the parameters of the motor, which will be utilized in the next chapter to calculate the electric power and the torque characteristics of the motor (see equations (3.13) and (3.15) in chapter 3). The description of the motor parameters is given with details in section 3.4.1 of this work and will not be treated here. These parameters are defined as:

- R₁ Ohmic resistance of the stator
- R₂ Ohmic resistance of the rotor
- X₁ Leakage reactance of the stator
- X₂ Leakage reactance of the rotor
- X_M Magnetizing reactance

Besides these parameters, the motor iron and friction losses (P_{fe} and $P_{friction}$) are also to be obtained from the measurements.

The stator resistance R_1 was determined by a simple measurement at the motor terminals, under constant temperature according to [1].

The other parameters of the asynchronous motor (R_2, X_1, X_2, X_M) were determined according to procedures suggested in the literature [1,7], namely the motor open-circuit and short-circuit tests, which are the standard tests utilized in the practice. In both tests, the motor was supplied by a sinusoidal power source in order to avoid the effects of frequency harmonics which would distort the results. Additionally, the torque characteristic was also measured with the motor being supplied by the inverter.

The rotor ohmic resistance R_2 and both leakage reactance X_1 and X_2 were determined by the short-circuit test, in which the motor shaft is blocked, i.e. n=0, so that the current which flows through the magnetizing reactance can be neglected (for n=0 is s=1) and the other resistances become small compared to the magnetizing reactance X_M (see Fig. 3.16). In this way, the equivalent circuit can be considered as a simple series connection of the stator and rotor ohmic and inductive resistances, which can be calculated by the measurement of voltage, current and power.

The magnetizing reactance X_M was determined by operating the motor in open-circuit conditions, i.e., no load was applied on the shaft, so that the motor speed is equal to n and consequently the slip is also zero. In this way, the resistance of the rotor goes to infinite and the current flowing through the magnetizing reactance is approximately equal to $I_1 + I_2$. X_M can then be calculated by the measurement of current and voltage of the stator.

The iron and friction losses were determined by operating the motor in open circuit conditions for diverse stator voltages, at 50 Hz frequency, according to the method proposed by Fischer

in [1]. From the measured stator power and current, a function for the losses was obtained by a linear regression:

$$P_{\rm iron, fric} = P_{\rm fric} + 0.00295 \cdot V_1^2 \tag{2.1}$$

where V_1 is the motor stator voltage and the constant 0.00295, in [W/V²], has been determined by the measurements.

Figure 2.10 shows the iron and friction losses obtained from measurements by using equation (2.1).



Fig. 2.10: Determination of iron and friction losses of the asynchronous motor. The separation of these losses is done by linear regression of the measured values (\square). The thick line (—) represents equation (2.1) and the thin line (—) the constant friction losses. (source:[5]).

The measurement of the motor torque-speed characteristic (T(n)), was done by operating the machine in the whole interval from no-load to full-load. The load (torque on the axis) was varied step-wise by changing variable resistances connected to a DC-generator, used as load to the motor (see scheme in appendix A). For each operating point, characterized by a fixed pair of primary frequency and phase voltage , the torque T, the rotational speed, *n* and the electric power input to the motor P_{ele} were recorded.

From the motor measurements the parameters for the motor model could obtained. The values found for those parameters are:

$R_1 = 3.28 \ \Omega$	$X_{\rm M} = 39.56 \ \Omega$
$R_2 = 1.55 \ \Omega$	$P_{fe} = 48 $ W
$X_1 = 1.72 \ \Omega$	$P_{\rm fric} = 8W$
$X_2 = 1.44 \Omega$	

The above parameters will be used in model calculations in chapter 3. The measured motor power and torque will be compared with the simulated values in the same chapter.

Measurements of Pump Characteristics

Pumps are normally described by their H(Q,n)-characteristics. H (in meters) is the total head impressed on the fluid by the pump impeller, Q is the pump flowrate and n is the pump rotational speed. For each pump, there is a combination of these three quantities for which the pump operation is optimal (nominal values). For applications in PVP-systems however, the operation deviates very often from these nominal operation conditions, so that in order to describe the operational performance of a pump integrated in such systems, it is necessary to determine a series of H(Q) curves for the different speeds, imposed to the system by the nature of the power supply (the PV-generator).

Based on the Euler equation for ideal fluid machines [8], the real performance of a pump can be described by the following equations, which are discussed in detail in the next chapter,

$$H = k_1 n^2 + 2k_2 n Q - k_3 Q^2$$
(2.2)

$$T = c_{t1}n^2 + c_{t2}nQ - c_{t3}Q^2$$
(2.3)

In order to apply the above equations, it is necessary to determine the three parameters k_1 , k_2 , k_3 and c_{t1} , c_{t2} and c_{t3} from measurements.

The measurement of the pump H(Q)-characteristics was done according to the DIN norm 1944 [9] for different rotational speeds, utilizing the setup already presented in figure 2.2. The following procedures were carried out during the experiments: the speed of the pump was adjusted by adjusting the inverter frequency from 30 to 55Hz in steps of 5Hz; for each fixed frequency the flowrate of the pump was varied from zero to Q_{max} , by opening the throttling valves, installed after the pump in the hydraulic system, in steps of approximately 5°, from completely closed to completely open positions; after each of these settings, measurements of flowrate, pressure at points before the inlet and after the outlet of the pump (to calculate the pumping head), the power input and the inverter frequency were taken for the different working points.

The torque and rotational speed were measured for each working point with a torque measuring device mounted on the shaft between motor and pump. These measurements were carried out with the motor -pump unit being under water.

The above measurements permitted the determination of the parameters for both throttling and torque characteristic of the centrifugal pump installed in the Oldenburger set-up. These parameters were determined in [4] and [2] with the following values:

k ₁ =0.00926	$c_{t1} = 0.000552$
k ₂ =0.00138	$c_{t2}=0.004524$
k ₃ =-0.13264	$c_{t3}=0.011810$

The measured pump characteristics are presented in comparison with the results of the model calculations with the above parameters in the next chapter.

2.2.3 Measuring Devices and Measurement Accuracy

The measuring devices utilized in both laboratory and field conditions with their technical characteristics and the estimated measurement errors are summarized in Table 2.2.

Measured values		Measuring devices	Measurement	
G	[W/m ²]	CM11-Pyranometer Kipp & Zonen	3 %	
T _{amb}	[°C]	Thermo-resistance sensor PT-100	0.5 %	
T _{cell}	[° C]	Thermo-resistance sensor PT-100	0.5 %	
V _{DC}	[V]	SPC5091/U voltage divider, Amonit	1.0 %	
P _{DC}	[W]	SPC5091/P analogous multiplexer, Amonit	2 %	
I _{AC}	[A]	Leistungs-und Oberwellenanalysator EWS 92/94 Haag (current pliers)	1.0 %	
V _{AC}	[V]	Leistungs-und Oberwellenanalysator EWS 92/94 Haag	2.0 %	
Т	[Nm]	Drehmoment-Meßwelle T34FN, Hottinger Baldwin Messtechnik	0.2 %	
n	[1/s]	Drehmoment-Meßwelle T34FN, Hottinger Baldwin	0.2 %	
Т	[Nm]	Tachogenerator (AC-system)	1.0 %	
n	[1/s]	Dehnmeßstreifen, frequency modulation	0.1 %	
р	[bar]	Pressure sensor PDRC930, Campbell Scientific (semiconductor-diaphragma)	0.4 %	
$\overset{\cdot}{\mathcal{Q}}$	[m³/h]	Pulsmag-V magnetic inductive flowmeter, E&H-Flowtec	1 %	

Table 2.2: Summary of measuring devices for laboratory and outdoor measurements described in section 2.2 on the PVP test facility of the University of Oldenburg.

2.3 Investigation of the Step-Function Response of the PVP Test Facility

In the summer of 1995 special measurements were carried out on the PV-pumping test facility to investigate its step-function response, or more specifically, to find out how fast the pump output power reacts to a sudden change of solar radiation. This information is important for the development of this study, since in case a time delay between the PV-generator power and the pump power would be observed, this effect should be taken into consideration in the analysis of the measured data and specially in the modelling of the plant.

To attain the objective, measurements of hydraulic power and PV-power were taken in the smallest time resolution allowed by the data logger (0.5 seconds), for different geodetic heads and different settings of the inverter parameters (specifically the parameters with which one

can regulate the acceleration and braking times of the pump in correspondence to variations of the solar power).

As an example of the measurements, Figure 2.11 presents one curve of P_{DC} and P_{hyd} , taken in 0.5 seconds interval, at the starting and stopping moments of pump operation (acceleration and braking of the machine) at 14 m head.



Fig. 2.11: The PV-power P_{DC} and the pump hydraulic power P_{hyd} over the time for 14 m head. On the left side the curve represents the acceleration time of the pump and the curve on the right represents the braking time of the pump (source: [6]).

As can be seen in the curves of Figure 2.11, there is no time delay, which could be detected with the time resolution of the measuring equipment, between the DC input power and hydraulic output power of the subsystem, for any of the several combinations of head and inverter parameters tested. Both curves increase and decrease more or less proportionally, and attain their maximum at the same point in time. This information confirms that it should be possible to reproduce dynamic measurements on the PVP-system in a model which does not account for short time transient effects.

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3 Description and Modelling of the Individual Components of a Photovoltaic Pumping System

Computer science simulation methods offer a powerful tool for the analysis of renewable energy systems, due to the possibility of reproducing the performance of a system on the computer. The philosophy behind digital simulation is that experiments which normally should be done on real systems, under high assembling costs and time consuming conditions, can be done numerically in a short time on a computer, thus saving time and investments.

Systems based on primary renewable energy consist of various components which either convert or store energy. Digital simulation serves for the purpose of understanding the operational behavior of these components and the interaction among them, since by simulating the system performance, one can trace all steps of energy conversion and identify the losses throughout the system in detail. Because computer simulation allows a range of system parameters to be varied, and the operating characteristics of the system to be investigated as a function of these parameters, it also may be helpful for optimization in the design process of such systems. Another use of computer simulation, is in the evaluation of operation strategies for the control of a system. Finally, computer simulation permits the extrapolation of a system design to other localities, with different meteorological conditions, and make it possible to compare different systems.

Basis for a computer simulation is a 'model' of a real system which is based on a theoretical analysis of the various physical processes occurring in a system, and of all factors influencing those processes. Mathematical equations (mathematical models) describing quantitatively the system characteristics are formulated from this analysis and translated into computer codes to be used in the simulation process. Apart from pure physical models, empirical data obtained from measurement of system components characteristic can also be used in simulation models.

A photovoltaic pumping system (PVP-system) is a complex system, normally composed of various components, which interact with each other in different ways, but within the limits imposed by certain strategies used to control the system as a whole. Figure 3.0 presents schematically the general layout of a typical PVP-system.



Fig. 3.0: Typical scheme of a photovoltaic pumping system (adapted from [41]).

The modelling of the components of such a system (solar radiation, solar generator, power conditioning unit, motor, pump, well and hydraulic system) involves the knowledge of various disciplines (meteorology, physics, power electronics, mechanical engineering, hydraulics and hydrology), and requires a good understanding of the interactions between them.

For the systems configurations commonly used in solar pumping applications (AC-motors or DC-motors either with centrifugal or positive displacement pumps), a number of simulation programs can be found in the literature [41, 40,39]. But the majority of the existing models, especially for the AC-systems, are extremely simplified and therefore not enough accurate to generate the knowledge necessary to 'understand' the real system behavior. Most of these models are based on the components characteristics available on the manufacturers data sheets and utilize average efficiencies of the components, thus not considering the variations imposed on the system by the solar resource. In this way, no precise models describing the hardware components can be determined.

In this chapter, simulation models for the PVP-system installed at the University of Oldenburg will be presented. Based on extensive measurements of the system components, presented in the previous chapter, and in the theoretical analysis which will be done in the next sections, physical models of the operational characteristics of these components are developed and later implemented in a computer simulation program to establish a model of the complete system. In the next sections, the physical background of each of the individual system components will be described and their correspondent models will be subsequently presented. The models will be validated by comparison of simulation calculations with the data of measured characteristics obtained in chapter 2.

3.1 Solar Generator

3.1.1 Solar Cell

Solar Cells convert the solar radiation into electrical energy. The conversion is however limited to the spectrum of solar radiation that can be utilized. The basic material for almost all the solar cells existent on the market , high purified Silicon (Si), is obtained from sand or quartz (Si0₂). At present, basically three types of technology are used in the production of solar cells: monocrystalline, polycrystalline and amorphous Silicon, with efficiencies ranging from 15%, 13% and 7% respectively. For photovoltaic power generation, crystalline-Si technique is today the state-of-the-art.

A solar generator consists of a number of modules, formed by the interconnection of solar cells, connected together in series and parallel to provide the required voltage and current. The performance of the generator therefore depends on variability of the modules that comprise the generator and the cells that comprise the modules. The operating point of the generator is defined by the intersection of its I-V characteristics with that of the load connected to it.

3.1.2 Modelling of the Photovoltaic Generator

The photovoltaic generator installed in the PV-pumping test facility at the University of Oldenburg has been well described in [4,5]. With an installed area of 15.4 m² of monocrystalline Silicon solar cells, it can produce, by optimal load matching (MPP-tracker) and under the Standard Test Conditions- STC (1000 W/m², 25° C and AM 1.5), a total power output of 1.9 kW, according to the data sheets of the manufacturer.

The PV-generator consists of 36 modules of Siemens type M55, each having a rated peak power of 53 W and containing 36 series connected cells. The modules are connected into 2 parallel array strings, of 18 series modules per string and are mounted fixed with an inclination of 45° facing south. The generator is controlled to operate at a fixed voltage control strategy, instead of a MPP-tracker control. The fixed voltage operation, which is a close approximation to MPPT will be further discussed in the next section.

Electrical Model

For the modelling of the PV-generator the 'Two Diode Model' [12, 63] was used to describe the electrical characteristics of a solar cell, together with a thermal model, which will be explained latter, to calculate the cell temperature. Both models are available in the block oriented simulation system INSEL [56] which was the main software utilized in this work.

The relationship between voltage V_c [V] of a solar cell and current density is given by the Two Diode Model as:

$$j = j_{ph} - j_{01} \left(exp \left(\frac{e_0 (V_c + jr_s)}{\alpha kT} \right) - 1 \right)$$
$$-j_{02} \left(exp \left(\frac{e_0 (V_c + jr_s)}{\beta kT} \right) - 1 \right) - \frac{V_c + jr_s}{r_{sh}}$$
(3.1)

where r_s is the series resistance parameter of the cell $[\Omega m^2]$, r_{sh} is the shunt resistance parameter $[\Omega m^2]$, α, β are diode parameters ($\alpha = 1, \beta = 2$ according to [12]), T is the cell temperature [K], e_0 is the charge of an electron (1.6021×10^{-19} As) and k is the Boltzmann Constant (1.3854×10^{-23} JK⁻¹). The light generated current density j_{ph} [A m⁻²] is given by

$$\mathbf{j}_{ph} = \left(\mathbf{C}_0 + \mathbf{C}_1 \mathbf{T}\right) \cdot \mathbf{G}$$

where C_0 is the coefficient of light-generated current density $[V^{-1}]$, C_1 is the temperature coefficient of light-generated current density $[V^{-1}K^{-1}]$, T is the cell temperature and G $[W m^{-2}]$ is the global radiation on the generator plane.

The dependence of the saturation current densities j_{01} and j_{02} on temperature is given by

$$j_{01} = C_{01}T^3 \exp\left(-\frac{e_0 V_{gap}}{kT}\right)$$
 and $j_{02} = C_{02}T^{5/2} \exp\left(-\frac{e_0 V_{gap}}{2kT}\right)$

where, C_{01} is the coefficient of saturation current density [$Am^{-2}K^{-3}$], C_{02} is the coefficient of saturation current density [$Am^{-2}K^{-5/2}$] and V_{gap} is the band gap voltage (constant=1.12V).

The operation point of the PV-generator is given by

$$V = V_c N_s$$
 and $I = jA_c N_p$

where, A_c is the area of a single cell [m²], N_s is the number of cells in series (whole generator) and N_p is the number of cells in parallel (whole generator).

The set of parameters (C_0 , C_1 , C_{01} , C_{02} , R_s , and R_{sh}) can be obtained by fitting the data available on the modules manufacturers data sheets, but this procedure leads to inaccuracy in the calculations of the power output of the generator due to the variability in the I-V characteristics of the modules that comprise the generator, as explained above. In the present work, the parameters of the two diode model were obtained from laboratory and field measurements of the individual I-V characteristics of the 36 modules that form the generator carried out by Damm in [10]. In the model calculations the parameter set utilized in equation 3.1 is

C ₀ :	0.2841	C ₁ :	1.6400E-0004
C ₀₁ :	14589.34	C ₀₂ :	1.189
R _s :	1.3041E-0004	R _{sh} :	0.08990

The calculated current-voltage characteristics for the solar generator in Oldenburg, utilizing the parameters above are presented in Fig. 3.1, for different conditions of solar radiation. In the plot are also indicated the points of Maximum Power for each insolation and the lines of constant power.



Fig. 3.1: The simulated I-V characteristic of the PV-generator in Oldenburg for different irradiation conditions.

Thermal Model

The I-V characteristic of a solar cell is also influenced by the temperature of the cell. In this work, the cell temperature is calculated by a simplified linear function between the cell temperature T_c and the irradiation G_{PV} suggested by Damm in [10]. Equation 3.2 below describes the model, where the ambient temperature T_{amb} determines the crossing point of the function on the vertical axis:

$$T_{c} = T_{amb} + k_{c} \cdot G_{PV}$$
(3.2)

The parameter k_c can be determined by regression analysis from measured data for the site of the PV-generator. For the PV-generator installed in Oldenburg this parameter was calculated as $k_c=0.03 \text{ W}^{-1}\text{ m}^2\text{K}$. Figure 3.2 shows the measured difference (T_c - T_{amb}) as function of the irradiation G_{PV} and the calculated difference according to equation 3.1 for two days. As can be seen in this figure, a good agreement between simulation and measurement could be attained with this simple model.

The influence of the temperature on the I-V characteristics is illustrated in Figure 3.3, for one cell, as calculated by a Two-Diode model for a PV-module.



Fig. 3.2: Comparison between the simulated (-) and the measured (points) difference between cell temperature T_c and ambient temperature T_{amb} for the generator installed in the PVP-system of the University of Oldenburg. The measured points are minute average values from two days (19.08 to 20.08.1996).



Fig. 3.3: Influence of cell temperature on the PV-generator characteristic [10].

3.1.2.1 Loss Mechanisms

The electric behavior of single cells (or modules) in a PV-generator may be well described by the two diode model given above if the effective radiation is well known. Differences occur due to the fact that the response characteristics of the pyranometers and that of solar cells are not identical and that the generator is composed of different non-identical modules. In this context, the losses occurring in the field operation of a PV-generator have to be considered in order to calculate precisely its real electric power output. For the calculation of the generator output the following corrections were taken into account:

Reflection Losses

When the incidence angle of the solar radiation differs from the perpendicular incidence on the surface of a PV-generator, reflection losses occur which will cause an overestimation of the PV yield under field conditions. The radiation losses due to reflection on the generator surface were considered here as a constant factor, according to [33, 59].

Spectral Losses

Changes of the solar radiation spectrum have an influence on the efficiency of the generator. This occurs because of the Air Mass value changes during the day. Also, a change in the amount of diffuse radiation affects the radiation spectrum [33]. The values of these losses were estimated as 1 % according to [44], and considered constant in the simulation.

Mismatch Losses due to different I-V characteristics

The I-V characteristic of PV-modules from the same type and the same manufacturer can vary from module to module. According to the information of the suppliers, the MPP-power of a module under STC can deviate till about 10 % from the data sheet characteristics. By series and parallel connection of the modules in a generator, these different I-V-characteristics will produce power losses which are called mismatch losses. For quantifying the mismatch losses, calculations were performed in which the generator was first assumed to be made up of 36 identical modules (average of model parameters) and then compared with calculations in which the parameters of the individual 36 modules were used. The results of these calculations showed that mismatch losses would amount to approximately 3%. Figure 3.4 presents as an example the PV-generator I-V-characteristics for the two above conditions in order to illustrate the mismatch losses at two irradiance levels.

Shadowing Effects

Partial shadowing by buildings, trees or other objects can produce significant losses on a PVgenerator power output as it can be seen in the following example. This example also serves to illustrate the influence of shadowing on the operation of the maximum power tracking control of the PV-generator, which will be discussed next in this work (see section 3.2).

On the PVP-generator in Oldenburg, shadowing effects from two sources were observed: from bushes standing about 10 meters in front of the generator (south direction) and from the shadows produced from two metal cables that support a wind generator installed in the near of the generator. The first shadows appeared only in the morning and in the afternoon when the sun was low in the sky and did not contribute much to the losses. The later shadows, on the other hand, caused significant losses on the output power.



Fig. 3.4:. Mismatch Losses in a PV-generator. Comparison of the I-V characteristics calculated at two irradiance levels, for two conditions: a) considering the PV-array as made up of 36 identical modules (module 17); and b) considering all 36 individual modules (all modules) that makes up the generator. Details are explained in the text.

To illustrate these shadowing effects, Figure 3.5 shows the course of the solar radiation measured at the generator plane at one day. Between 14:30 and 15:00 in this curve one can recognize when the shadows of the cables are over the pyranometer which measures the solar radiation. Figure 3.6 presents the comparison from simulated and measured PV-generator output power for this day (with the shadows from the cables) and for another day, when the cables were taken off. A difference in PV-power of about 8 % between simulated and measured power was found in the first day (upper graph), while in the second one (lower graph) the agreement was excellent. The result indicates that the effect of the shadows alone was responsible for a considerable loss in the daily PV-power of the PVP-system, since reflection and spectral losses were considered in the calculations. An estimation of the losses caused by the cables was carried out using a simplified procedure developed by Pukrop [49] confirmed the magnitude of the losses.



Fig.3.5: Daily course of solar radiation measurement showing shadows on the pyranometer.



Fig. 3.6: Simulated and Measured output power of the PV-generator for a day with shadows of two cables supporting a wind generator near by(upper graph, 05.06.96) and for a day without shadows (lower graph, 19.08.96). The shadows fall on the pyranometer at 14:30 and 15:30 hours. The pyranometer signal is used to simulate the PV-generator output.

3.1.2.2 External losses

In a real system the PV-generator output power is normally the input power to an inverter or to any kind of power conditioning unit. In order to calculate this input power, the losses caused by blocking diodes and the voltage drop due to cable resistances have to be considered.

The losses caused by resistance on the connecting cables (ohmic losses) for the PV-generator installed in Oldenburg were calculated based on cables length and diameters. For each string these losses were calculated to approximately 0.1 ohms. This correction was considered on the series resistance of the two diode model. To each string that forms the solar generator a blocking diode is connected in series in order to prevent that in case of a short circuit in one of the strings the current from the perfect string will flow through the faulty string. During operation there is a voltage drop through the diodes of approximately 0.7 Volts. This value was subtracted from the output voltage of the PV-generator in the calculations.

3.2 Maximum Power Point Tracking

The power that can be produced by a PV-generator is primarily dependent on the solar irradiation and, to a lesser extent on the temperature of the solar cells as described by the I-V characteristics for different solar irradiance and temperatures presented in the previous section of this work (see Figures 3.1 and 3.3). Both influencing parameters experience daily and seasonal fluctuations. Because of this dependence, the solar generator can only provide maximum power at specific voltage and current levels. Operation of the generator at its maximum power point (MPP) involves matching the impedance of the load to that of the generator. For this purpose, an electronic device (normally a dc-dc converter) capable of performing the function of a Maximum Power Point Tracker (MPPT), or an approximation to it, has to be connected between generator and load, or has to be included in an inverter circuitry depending on the type of load. Different methods and control strategies to match the operating points of the load to the PV-generator are reported in the literature [11,13,50,67]. Two of these methods, which are relevant for the investigations carried out in the present work will be briefly discussed below: the MPP-tracker, and the Fixed-voltage control method.

3.2.1 Fixed Voltage Control

The fixed voltage control is an easy to implement, quite reliable tracking method for photovoltaic systems. This strategy is a close approximation to the 'true' MPPT and is normally realized by operating the generator with a fixed voltage, normally corresponding to the average voltage range of the maximum power points on the I-V curves. Power losses can occur, when, due to the dependence of the voltage from the temperature and the solar radiation, the voltage value of the maximum power deviates much from the preset value. In this case, the reference value should be corrected through a value which compensates for the influence of temperature and solar radiation in the different times of the year [22].

Variations of the fixed voltage tracking method are presented in [11, 42, 25, 31]. In [11] the reference fixed voltage value is constantly adapted to the radiation in a monthly basis. In [42] the reference value is set fixed over a long time period, based on an empirical factor which

represents the relationship between module temperature and PV-generator voltage. A method is described in [25, 31] in which a combination of constant voltage control and MPP-tracking is made. In this method, the actual value of the generator open circuit voltage is sampled regularly while defining the operation voltage as a percentage of 50 %....90% of the open circuit voltage. The power output is then calculated and the voltage value for which the greater output power was obtained is taken for the next 60 s as constant voltage reference value. In [21] an improved strategy is presented by which the reference constant voltage value is constantly adapted depending on the temperature.

Figure 3.7 shows a simple scheme of a fixed voltage control, where the reference value preset for the generator voltage is then given by the following function:

$$V_{dc,ref} = V_1 + V_2 \tag{3.3}$$

where V_1 is the constant part and $V_2 = f(T)$, the temperature dependent part of the reference value. The controlled output value enters then a pulse width modulator circuit in the inverter which determines the tact ratio with which the switch of the dc-dc converter will be operated.



Fig. 3.7: Basic scheme of a fixed voltage control strategy (source:[21]).

The choice of the algorithm for voltage control depends on the type of load which is to be connected to the PV-generator. In the case of the PVP-system in Oldenburg, the control is included in the inverter as described in section 3.3.2.1. The working point is set by the inverter, based on the open circuit voltage of the generator, under specific irradiation conditions. The user can adjust the working point by changing a control parameter.

A limitation of the fixed voltage control is that it has to be configured for the particular connection of the modules in the generator and the optimum fixed voltage should be adjusted for the type of PV-modules used in order to obtain an optimal output power.

3.2.2 MPP-tracker control

The control method known as the maximum power point tracking (MPPT) is based on a searching algorithm, in which the maximum of the power curve is found without interrupting the normal operation of the PV-generator. This control is not based on preset reference values determined from the system or from operational parameters. The reference control value is obtained by continually searching the maximum power point of the generator I-V-
characteristic. For a certain working point at a time t-1, the corresponding voltage is varied in determined time steps; if this produces an increase of the output power, the searching direction in the next step at time t is maintained, otherwise it will be shifted in the opposite direction. This scheme is known as closed loop tracking. Figure 3.8 shows the basic control scheme of the MPP-tracking method.

The actual working point moves within a certain voltage interval around the maximum power point. This normally causes instability and adds some form of perturbation to the control signal that in some circumstances can influence the system operation.

Basically, the search of the MPP involves both sensing the output current and voltage and multiplying these to calculate the generator output power. How this is actually done depends on the type of algorithm control which is used. Based on different algorithms there are several control methods implemented in MPP-tracking [11, 31, 22]. As with the fixed voltage control, the choice of the algorithm depends on the type of load which is to be connected to the PV-array.



Fig. 3.8: Basic scheme of a MPP-tracker control strategy (source:[21]).

In this work, a MPP-tracker model available in the software INSEL [56] was utilized in the simulation calculations.

3.2.3 Comparison between different MPP-tracking methods

Figure 3.9 shows, as an example, the loci of the operating points for a MPP-tracker and a fixed voltage control on the power characteristic of a PV-generator under varying operating conditions. In the figure, is also to be seen the curve of a third method, namely the scheme based on a percentage of the open circuit voltage (V_{oc}). As can be seen in the curves, the operation with a fixed voltage does not follow the 'true' maximum power points very closely for low solar irradiances and only approximates a little better at very high values of irradiance. For PVP-systems this fact is not crucial, since for the majority of practical applications, the amount of power under low irradiance levels is very small [67]. On the other hand, the scheme

based on a percentage of V_{oc} follows much better the MPP, especially at higher solar irradiance values.

As mentioned earlier, the choice for one or other tracking system depends on the load characteristic, on the local meteorological conditions, on the degree of matching efficiency and finally, on the financial costs. Table 3.1 summarizes the general characteristics of the tracking controls presented in Figure 3.9.



Fig. 3.9: Operating points of different maximum power point control strategies (source: [67]).

Type of MPPT	Efficiency	Characteristics
	(ideal)	
		expensive
'true' MPPT	100 %	highest efficiencies achievable
		independent from PV-array configuration
		very efficient
$V_{op} = \% V_{oc}$	> 98.5 %	inexpensive
°F °C		reliable
		independent from PV-array configuration
		efficient
V fix = Const V	> 92.0 %	inexpensive
		reliable
		PV-array configuration specific

Table 3.1: Comparison of various types of MPP tracking methods (adapted from [67]).

3.3 Inverter

The supply of an electric motor by a solar generator in a PVP-system, demands the use of an inverter which can transform the DC-voltage produced by the generator into a triphasic AC-system with variable frequency and voltage. In principle, there are two main types of DC/AC inverters: the self-commutated inverter and the forced-commutated inverter. In the case of an asynchronous machine, which does not produce reactive power to control an inverter, only a self-commutated inverter can be used. There are two basic types of self-commutated inverters: The inverter that is supplied with controlled current from a DC-source (current-source inverter) and the inverter which is powered from a DC-voltage source (voltage-source inverter). For applications in PV-pumping systems, the latter inverter is considered the best choice [41]. Other types of inverters which could also be used in solar pumping systems are well described in the literature [2, 22, 43,50] and will not be discussed here.

3.3.1 Operation Principles

In a voltage-source inverter, as the utilized in the PVP-system under question, the solar generator is connected directly to the dc link part of the inverter circuit. This inverter can also be supplied from an existing ac utility network through a rectifier. This configuration is classified as a DC- link inverter, because it is a two-stage static frequency inverter in which AC-power, at network frequency, can be rectified and then filtered in the DC link before being inverted into AC at an adjustable frequency. A block diagram of the inverter is presented in Figure 3.10.



Fig. 3.10: Block diagram of a DC-AC inverter with dc link voltage (source: [11])

Figure 3.11 shows the basic circuit configuration principle of an inverter of the type normally used in solar pumping systems. The condensator across the inverter input terminals, serves to smooth the output voltage of the DC source and to reduce the source impedance. At the output terminals of the power side, composed of a three-phase bridge arrangement, a load is connected. A three-phase output is obtained by preserving a mutual phase displacement of 120 degrees between the switching sequences of the transistors in the three legs of the inverter. If the inverter supplies an inductive load, the feedback diodes connected parallel to each transistor, provide a reverse current path for load current that permits a return of energy through the inverter to the DC-supply.



Fig. 3.11: Basic circuit configuration of a photovoltaic pump system inverter (source: [58])

The inverter voltage control is realized by the sinusoidal pulse-width modulation method (Sinusoidal PWM). The sinusoidal PWM inverter, has a control circuit in which a high frequency symmetrical triangular carrier wave is compared with a synchronized sine wave modulating reference wave with the required output frequency. Each phase or half bridge has a comparator circuit which is fed with the reference voltage for that phase and a symmetrical triangular carrier wave which is common to all three phases. This circuit control waveform is shown in Figure 3.12 for one of the inverter half bridges, and the switching instants of the semiconductor devices are determined by the intersections of the two waveforms. This switching action results in an almost sinusoidal output waveform as shown below in Figure 3.12.



Fig 3.12: Control Circuit Waveforms for a Sinusoidal PWM Inverter (source:[32]).

3.3.2 Motor Control

3.3.2.1 Input Voltage

In a voltage-source inverter, the dc link voltage is adjusted in accordance with the demanded frequency to give the desired motor voltage/frequency relationship. In commercial inverters a DC-voltage/frequency characteristic function is normally preprogrammed within the controller unit of the inverter. The controller allows for on site adjustment of the characteristic by providing user definable parameters that can be set to optimize the operation point of the system. Such a characteristic is shown in Figure 3.13 for the Simovert-P inverter from Siemens Solar [58], which is investigated in this work.



Fig. 3.13: V_{DC} (f) characteristic of inverter control. The starting value of the voltage (x axis) and the inclination of the characteristic can be adjusted by the user. The points show the actual behavior of the control for two different parameter settings.

As can be seen in Figure 3.13, the inverter does not control V_{DC} through the MPP-tracker method, but through a linear increase of the DC-voltage with the inverter output frequency f, keeping a preset constant value for the inclination of the curve. The numerical equation describing this function has the following form:

$$V_{DC}(f) = c_{10} + c_{11} \cdot f$$
(3.4)

where c_{I0} is the fix starting voltage, which can be adjusted via a parameter within the controller, and c_{I1} is the constant preset parameter that defines the inclination of the curve. The correct setting of the value of c_{I0} defines the maximal output of the pumping system. The setting of an inadequate value for this parameter may signify losses of more than 50% in daily water output.

The power $P_{DC}(V_{DC})$ of a PV-generator is, qualitatively speaking, a function of the DCvoltage. The power increases up to the MPP-voltage (V_{mpp}), but for generator voltages above the V_{mpp} it tends to fall. Because of this, the control given by equation 3.4 can make the system work in three intervals of the power characteristic $P_{DC}(V_{DC})$:

 $(a) \qquad V_{DC} \ < \ V_{mpp} \qquad \rightarrow \qquad P_{DC}(V_{DC}) \ < \ P_{DC}(V_{mpp}) \ ,$

(b) $V_{DC} = V_{mpp} \rightarrow P_{DC}(V_{mpp}) = P_{DC-max}$

 $(c) \qquad V_{DC} \ > \ V_{mpp} \qquad \rightarrow \qquad P_{DC}(V_{DC}) \ < \ P_{DC}(V_{mpp})$

Due to the fact that the MPP of the PV-generator changes with irradiation and module temperature, the MPP-voltage varies during the day or as well along the year, so that the control described by equation 3.4 will practically never match the ideal case (b) above. The point is how to set the parameter c_{I0} in order obtain optimum system operation. According to Janssen [28] if case (a) happens, the system will not work stable anymore, what means that the starting voltage c_{I0} should be chosen in such a way that the voltage $V_{DC}(f_1)$ must not become lower than in MPP. On the other hand c_{I0} should also not be set too high (c), since the DC-power for voltages higher than the MPP-voltage tends to fall abruptly.

The inverter parameter number 5 (P_5), which allocates a frequency to a particular voltage and also defines the starting voltage c_{10} , can be adjusted by the user from the value zero (corresponding to 300 V) to the value 100 (corresponding to 250 V) [58]. The correct value for parameter c_{10} for the inverter under investigation has been determined, according to the manufacturers instructions, by measurements of V_{DC} and f in small time intervals over several days with different settings of inverter parameter P_5 . From the results of these measurements equation 3.4 becomes:

$$V_{\rm DC}(f) = \left(303 - \frac{P_5}{2}\right) + 0.4 \cdot f \tag{3.5}$$

where the value for c_{I1} (0.4 in [V/Hz]) defines the inclination of the line V/f (see Figure 3.13) and is given by the inverter manufacturer. P₅ has been defined above.

3.3.2.2 Output Voltage

Besides providing adjustable-frequency power to a motor an inverter must also vary its terminal voltage as a function of frequency in order to maintain the proper magnetic conditions in the motor core. The techniques used by the inverter under investigation are known as the constant volts/hertz ratio and the constant voltage strategies. The application of the $V_1/f_1 = \text{const.}$ control is in principle done to achieve constant torque output of the motor. Moreover the type of load which is driven by the motor has to be considered. For the combination of an asynchronous motor and a centrifugal pump, which is characterized by a torque characteristic which is increasing with the square of the speed at higher speeds, the following proportionality has to be satisfied:

$$V_1 \sim f_1^2$$

A constant volts/hertz supply at the motor terminals only gives constant torque if the stator voltage drop is negligible. This condition is reasonably well satisfied near rated motor frequency, but the resistive stator voltage drop becomes significant at low frequencies and causes a reduction in the airgap flux and motor torque. This problem can be overcome by implementing a voltage/frequency characteristic in which the voltage is boosted (increased) above its frequency-proportional value at low frequencies (normally about $f_1 \le 23 \text{ Hz}$) in order to compensate for the stator voltage drop [43]. This strategy can be described by the following function:

$$V_1(f_1) = k_u + a_u f_1^u$$
, if $f_1 \le f_{rated}$ (3.6)

where k_u is the low frequency voltage boost needed to maintain the torque at low speeds and a_u is the inclination of the frequency-voltage characteristic (preset in the inverter).

Above rated frequency the rated voltage must not to be exceeded and hence the inverter control is switched to another mode of operation in which the voltage is maintained constant while the frequency is increased. By increasing the stator frequency with constant stator voltage, the asynchronous motor operates with a reduced volts/hertz ratio and a reduced torque capability. The control strategy is then described by the function

$$\mathbf{V}_{1}(\mathbf{f}_{1}) = \mathbf{V}_{1}(\mathbf{f}_{\text{rated}}) \qquad \text{if} \quad \mathbf{f}_{1} > \mathbf{f}_{\text{rated}} \qquad (3.7)$$

The inverter has preprogrammed in its controller, output voltage-frequency characteristics appropriate to particular loads. Two of such characteristics are presented in Figure 3.14 for the inverter Simovert-P from Siemens Solar [58]. One is for drives with constant torque over speed characteristic while the other is for drives with squared increasing torque characteristic at higher speeds. The latter characteristic is implemented for a centrifugal pump. The nominal operating frequency in this case is 60 Hz. For frequencies below 23 Hz a voltage boost (k_u) is applied to maintain the low speed torque, as mentioned above. The controller allows for on site adjustment of k_u .

Based on the frequency assigned by the maximum power control unit, the inverter controller sets the appropriate output voltage necessary to implement either constant volts/hertz operation or constant voltage operation.



Fig. 3.14: Voltage/frequency characteristics of the inverter Simovert-P developed by Siemens Solar for PVP-systems. Two different characteristics are showed: one for a load with constant torque, and the other for a load with squared increasing torque characteristic.

3.3.3 Power Conversion and Efficiency

The efficiency η_{INV} of the inverter is the ratio between its output power P_{AC} to its input power P_{DC} :

$$\eta_{\rm INV} = \frac{P_{\rm AC}}{P_{\rm DC}}$$

According to Jantsch [29], for the complete power interval from P_{DC} to the maximal power $P_{DC,max}$, the relation between an inverter input and output powers can be given by:

$$P_{DC} = P_{AC} + k_0 + k_1 \cdot P_{AC} + k_2 \cdot P_{AC}^2$$
(3.8)

where

- k₀ represents the load independent or self consumption losses ;
- k₁ represents the load linear losses, i. e., voltage drops in semiconductors;
- k₂ represents the load squared ohmic losses (magnetic and all other losses are included in this parameter)

The standby self consumption, that is, the value to which the operating self consumption is reduced during shut off is not taken into consideration here, since the inverter switches off completely when not in operation. On the other hand standby losses are generally negligible even in cases when the inverter does stay in standby mode [38].

In stand-alone PV systems, where the inverter operates mostly under part load conditions, the efficiency of the inverter is determined mainly by the self consumption losses [52, 53]. The effect of K_2 can be also neglected since the fraction of energy at higher power level is small in PV- systems.

With the above assumptions and making a linear fit with measured data [8] of input versus output power of the inverter under investigation, the parameters k_0 and k_1 could be determined and the final equation for the DC-power is given by

$$P_{\rm DC} = P_{\rm AC} + 30W + 0.0584 \cdot P_{\rm AC} \tag{3.9}$$

3.3.4 The Inverter Model

The simulation of the inverter is based on the analysis and measurements described above. For each of the functions (3.5), (3.6), (3.7) and (3.9), a correspondent block function was defined, and these blocks were connected together to describe the overall behaviour of the inverter.

Figure 3.15 presents a plot of the input power P_{DC} versus the output power P_{AC} based on equation (3.8).



Fig. 3.15: Input power P_{DC} of the inverter as a function of its output power P_{AC} . The fit (—) based on measurements (\square) is described by equation 3.9.

3.4 Motor

The operation of a pump requires a drive which can produce rotation. Most of the pumps are driven by electrical motors. Apart from electrical drives, pumps can sometimes be driven by reciprocating internal-combustion engines (e.g. Diesel engines), gas turbines, steam turbines, and more rarely by hydraulic turbines. The choice of a pump drive depends on various factors (pump type, power range, pump application, etc). For driving photovoltaic pump systems, electric motors, either DC-current motors or AC-current motors, are currently the immediate choice.

A characteristic of a photovoltaic pumping system is that it operates at variable speed. This characteristic demands an adjustable-speed drive that can precisely and continuously control speed and torque with good transient performance and high efficiency.

Concerning motor technology, there are three types of motor currently used for PV pumping applications:

- Brushed type permanent magnet DC-motors (DC-motors)
- Brushless permanent magnet DC-motors (BDC-motors)
- AC-motors

In terms of simplicity the DC-motor is an attractive option because PV-modules produce direct current, and less specialized power conditioning equipment is needed. As already mentioned, the DC-units used for PV applications are normally of the permanent magnet type. In a conventional DC-motor the magnetic field is produced electromagnectically by the field windings. Specially in small machines (less than 1 kW) the losses of energy occurring in the

windings are high and the overall efficiency is consequentely low. If permanent magnets are used to produce the magnetic field, no power will be consumed in the field windings and hence higher efficiencies will be achieved. This increase in efficiency is very desirable for PV systems.

The problem with the DC-motor is that it needs brushes for commutation. The brushes deteriorate with the time and have to be replaced (life time of approximately 1000 hours at nominal operation or between 2000 to 4000 pumping hours) [2, 41], what is very inconvenient specially for submersible motor-pump units and also because this means extra maintenance and costs.

In recent years, there has been a rapid growth in the use of brushless DC-motors (BDC-motor), also called electronic motors, as drives for photovoltaic pump systems [67, 65]. In opposite to conventional DC-motors, the current commutation to produce the magnetic field is done by an electronic device [19, 43]. The control of the electronics is realized by shaft position sensors based on optoeletronic or magnetic principles [61, 46]. The construction principle of the BDC-motor is that of a standard permanent magnet synchronous machine and operates as a self-controlled synchronous motor, or inverted DC-motor with an electronic commutator [43, 13]. For practical reasons the functions of stator and rotor are inverted in a BDC-motor. The excitation is done by the permanent magnets in the rotor, while the motor windings are located in the stator. Because there is no transfer of electrical energy to the rotor, there is no need of brushes also means less maintenance and longer life time of the motor.

The BDC-motor can be used in floating pump systems without special arrangements. However, to use the BDC-motor technology in submersible pump systems the electronic commutator has to be either encapsulated and integrated in the motor casing or installed outside the well and connected to the motor through a cable.

AC-motors such as the cage-rotor induction motor (also called asynchronous motor) are brushless and have a robust rotor construction which permits reliable maintenance-free operation. The simple rotor construction also results in a lower cost motor and a higher power/weight ratio. This is the main advantage of asynchronous motors drives over DCmotors and is one of the reasons why this type of motor is the most used drive in PV-pumping systems applications. However, the induction motor in its standard form has, in contrast to DC-motors, the inconvenience of being inflexible in speed variation. This type of AC-motor runs slightly below synchronous speed and its speed is determined by the supply frequency and the number of poles for which the stator is wound. Therefore, a wide-range speed control of the asynchronous motor is only possible when an adjustable-frequency AC-supply is available. This means that for the use of asynchronous motors in PV-pumping applications there is a need of an adjustable-frequency power electronic device (an inverter) to control speed, which brings an extra cost in the system. The inclusion of an inverter may offset the savings resulting from the replacement of a DC-motor by the lower cost asynchronous machine. However, modern inverters provide excellent performance speed drives, and the initial capital cost is frequently justified by the improved performance and lower running costs.

Table 3.2. summarizes the pros and cons of the above mentioned motors. For the purposes of this work, the basic physical principles and the operational behavior of BDC-motors and the asynchronous motor will be closely examined in the following sections.

Motor Type	Advantages	Disadvantages
Brushed DC	Simple and efficient for small loads.	Brushes need replacing periodically.
	No complex control circuitry needed.	
Brushless DC	Efficient.	Electronic commutation adds extra expense and possible breakdown risk.
	No maintenance required.	
AC-motor	Larger range available for larger loads.	Less efficient than DC units.
	Cheaper than DC-motors.	Needs an inverter, adding extra cost and increased breakdown risk.

Table3.2: Summary of the main advantages and disadvantages of the different types of motors which are commonly used for PVP-applications.

3.4.1 The Asynchronous Motor

3.4.1.1 Operation Principle

The operation principle of the asynchronous motor (ASM) is well known and is extensively described in classical motor literature [13,14,19,43,45], here only the main definitions which are relevant for the simulation model developed in the present study will be addressed.

In the asynchronous motor, the rotor winding is short circuited and receives its supply by induction from the stator. The stator carries a three-phase winding which is directly connected to a three-phase AC-supply. This design establishes an airgap magnetic field of constant amplitude rotating at a constant speed, known as the synchronous speed. The value of the synchronous speed is fixed by two parameters:

- the supply frequency, f_1 cycles/second or hertz,
- the number of pairs of poles p for which the stator is wound.

The synchronous angular speed n_1 of the rotating magnetic field is given by

$$n_1 = \frac{60f_1}{p}$$
(3.10)

where n_1 is measured in revolutions per minutes

Based on the induction law the rotating magnetic field induces a voltage in the standstill rotor which causes a current to flow in the rotor windings. According to Lenz law, the current flowing through the winding conductors of the rotor produces a tangential force which produces a torque in the rotor axis and sets the rotor in movement.

The asynchronous motor runs at a shaft speed n that is less than the synchronous speed n_1 . The speed difference n_1 -n is called the slip speed. The ratio of slip speed to synchronous speed is the most important variable in induction motor operation and is called the per-unit slip s

$$s = \frac{n_1 - n}{n_1} \tag{3.11}$$

The induced voltage and current in the rotor are of frequency f_2 , which is related to the stator frequency through the slip by the following expression

$$f_2 = \frac{n_1 - n}{n_1} f_1 = s f_1 \tag{3.12}$$

The fundamental equivalent circuit of the ASM, presented in Figure 3.16, describes the steady-state motor operation regime and is a simplification method which can be applied for motor analysis when the transient performance characteristics are undemanding and when the motor operates at steady speeds for long periods [43]. This is the case for a motor that drives a pump, for which a very precise and fast response control is not required.

The basic equations of the asynchronous motor can be derived from the equivalent circuit of the machine. A power balance of the motor can be made with the help of the equivalent circuit theory, this results in the motor equations for power and torque which are used in the simulation model. A more detailed description of the equivalent circuit can be found in the literature [13, 14, 43] and the basic asynchronous motor formulae is given in appendix B of this work.



Fig. 3.16: Per phase equivalent circuit of the asynchronous motor. The index 1 designates the stator circuit and the index 2 describes the rotor circuit. The parameters R_1 and R_2 represent the ohmic resistance of the stator and of the rotor respectively, while X_1 and X_2 represents the leakage reactance of the stator and of the rotor. X_m represents the magnetizing reactance. The mechanical power is delivered through the rotational speed-dependent resistance $R_2(1-s)/s$.

3.4.1.2 The Asynchronous Motor Model

As the motor under investigation is installed in a PV-pumping system, its electrical power supply depends essentially on the solar radiation, what means that it varies constantly. In this context, it is necessary that the power demand of the system be constantly adjusted to the variable power production of the PV-generator. A control technique in which the voltage and

frequency applied to the motor are simultaneous varied is utilized in this case. This control strategy ha already been explained with details in section 3.3.3.2 of this work.

For the modelling of the motor performance within a PV-pumping system, the theory of the equivalent circuit showed in Figure 3.16 was used to describe the motor characteristics equations, considering the control strategy mentioned above. A complete derivation of the mathematical equations of the model is treated more fully in [28] and a summary containing the main steps is given in Appendix B, therefore here only the final equations and their physical meaning will be described.

The electrical power demand at the motor terminals, considering the core losses, are calculated by

$$P_{ele} = m_1 ((R_1 R_s^2 + R_s X_m^2 + R_1 X_{22}^2) V_1^2 / \zeta^2 + P_{Fe})$$
(3.13)

 $\mathbf{P}_{\rm Fe}$ is the core power loss, which can be estimated by

$$P_{Fe}(f, V_1) = P_{Fe,N} \left(\frac{f}{f_N}\right)^{-0.4} \left(\frac{V_1}{V_{1,N}}\right)^2$$
(3.14)

where the index N indicates the values of frequency and stator voltage at open circuit [28].

Considering that the torque available on the motor shaft is smaller than the internal torque because of the friction losses T_F in the bearings, the resulting expression for useful torque is

$$T_{motor} = pm_i (R_2 X_m^2 V_1^2 / (\omega_1 \zeta^2) - T_F)$$
(3.15)

where R_2 is the ohmic resistance of the rotor, X_m is the magnetizing reactance, V_1 is the voltage applied at the motor terminals, ω_1 is the primary angular frequency and ζ is an expression relating the parameters of the motor stator and rotor which is given in Appendix B. According to [18] the friction torque T_F for any motor speed can be estimated by

$$T_{F}(n) = T_{F,0} \frac{n}{f_{0}}$$
(3.16)

where n is the rotational speed of the rotor, $T_{F,0}$ and f_0 are the values of the torque and rotational speed determined for the open circuit condition.

Summarizing, the power and torque characteristics of an asynchronous motor operated with the control strategy described can be evaluated by equations (3.13) and (3.15) when the machine parameters are known. These parameters can in principle be obtained from the motor producer, but in the present study they were obtained through the measurements described in chapter 2. For the motor under investigation the parameters values found are

$$R_1 = 3.28 \ \Omega$$
 $R_2 = 1.55 \ \Omega$
 $X_1 = 1.72 \ \Omega$ $X_2 = 1.44 \ \Omega$ $X_m = 39.56 \ \Omega$

The open voltage test performed in the motor measurements (see chapter 2) permitted the calculation of the iron losses and the friction losses. These losses were estimated according to conventional methods described in Nürnberg [45] and Fuest[14]; their values found for a stator frequency f_1 =50 Hz are

$$P_{Fe} = 48W$$
 $P_{Fric} = 8W$

Using the above parameters in equations (3.13) and (3.15), and taking into consideration motor losses, the simulated and measured electric power and torque characteristics as function of the motor angular velocity are plotted in Figure 3.17 for a sinusoidal 50 Hz supply frequency and, in Figure 3.18 when supplied by the inverter with different supply frequencies. Both figures show that the model can reproduce the real operation of the motor with very good accuracy. In Figure 3.18, one can see that for higher torques (close to the tilt torque), the measured T is smaller than the simulated. This behavior can be explained by the assumption made for the motor temperature (30°C) in the calculations. In the interval of higher torques the current flux is very high and the motor heats up considerably, thus reducing the effective power needed to produce torque.



Fig. 3.17: Simulated and measured output power P_{ele} and torque-speed T characteristics of the motor for 50 Hz sinudoisal supply frequency. The symbol (\neg) stands for measurements and while (\times) represents simulations curves.



Fig. 3.18: Simulated and measured output power (top graphic) and torque (bottom graphic) characteristics of the motor supplied by a inverter for frequency $f_1=38$, 50, 60 Hz (from left to right). The symbol (\Box) stands for measurements and (\times) represents the simulated values.

3.4.2 The Brushless DC-motor (BDC-motor)

3.4.2.1 Construction Characteristics and Operation Principle

The term 'brushless DC- motor' is generally applied to a self-synchronous machine in which the air gap flux density and the induced voltage waveform (back emf) are approximately trapezoidal, as in a conventional DC machine [43]. Because of this characteristic, the motor equations for the conventional DC-motor also apply to the BDC-motor. In the following only the main characteristics and the basic equations of the BCD-motor will be addressed. More details can be found in [16, 43, 67] and in appendix B of this work.

The energy transfer in a BDC-motor happens from the stator to the rotor and is realized through a brushless internal rotor with permanent magnet. The rotor magnets are configured radially (Figure 3.19) to establish a trapezoidal rather than a sinusoidal flux density wave in the airgap (a diametrical arrangement establishes a sinusoidal waveform). The relation between the frequency *f* and the rotational speed *n* is given by the number of magnet pole pairs as: p/2 = f/n. The commutation is done electronically. The commutator can be constructed inside or outside the motor case. To limit the amount of electronic commutations the stator is, in most of the cases, built with three phase windings.



Fig. 3.19: Basic construction of a BDC-motor with a radial configuration of permanent magnets as rotor(source:[106]).

The torque function of a BDC-motor requires that the stator and rotor magnetic fields must keep a fix angle of 90 degree, independent of the position of the rotor. Because of this, the time for commutation depends on the position of the permanent magnets in the rotor. The rotor position, as mentioned earlier, can be identified with the help of hall-sonds, magnetic resistive or electro-optical sensors, built in the stator. But in some cases, a method based on the fact that the induced voltage on the stator is proportional to the magnetic field of the rotor is used. This method permits to detect the rotor position by measuring the induced voltage directly in a not energized phase winding. An advantage of this method is also that it allows the complete motor electronics to be installed outside the motor housing, what makes maintenance easier and permits compactness in motor construction. The voltage supplied to the motor terminals is the voltage after commutation, which is after all a trapezoidal alternate voltage.

3.4.2.2 The BDC-motor Model

The modelling of the BDC-motor is based on the equations for voltage, torque and total electric power. For the first two variables the equations are similar to that of classical DC-motors. The electric power equation resulted from a power balance analysis of the motor, in which the copper and the iron losses are considered. The complete derivation of these equations, concerning PV-systems, can be found in Genthner [17], and a summary of the main steps is given in Appendix B, therefore here only the resulting equations will be treated.

Motor and inverter are considered a unit in the model [17, 43]. So that in the following the term motor means the actual motor plus its power conditioning.

The motor torque equation is calculated as

$$\mathbf{T} = \mathbf{c}_{\mathsf{M}} \cdot \mathbf{I} \tag{3.17}$$

where c_M is the motor constant and is given by $c_M = d \cdot l \cdot B \cdot N$

The voltage equation of a BDC-motor is similar to that of a permanent magnet DC-motor, and have the following general form:

$$V_{DC} = 2\pi \cdot c_{M} \cdot n - L \cdot \frac{dI_{Motor}}{dt} + R_{Stator} \cdot I_{Motor}$$
(3.18)

where V_{DC} is the motor terminal voltage, I_{Motor} is the motor current, R_{Stator} and L are the resistance and inductance of a phase winding, n is the rotational speed of the rotor, and the term $V_{emf} = 2\pi \cdot c_M \cdot n$ is the usual induced back emf.

The total electric power (P_{DC}) supplied to the motor, which is transformed in the motor into different powers and power losses (see Appendix B), is described in the motor model by the following function:

$$P_{DC} = 2\pi \cdot n \cdot T + c_{m_1} \cdot T^2 + c_{m_2} + c_{m_3} \cdot n^2$$
(3.19)

The evaluation of the measurements performed on a BDC-motor in the present work revealed that the iron losses can be well described by the following function:

$$\mathbf{P}_{\text{iron}} = \mathbf{c}_{m_2} \cdot \mathbf{n}^2 \tag{3.20}$$

The sum of the ohmic losses P_{ohm} (copper losses) in the stator, in the connecting cables between motor and inverter and in the inverter itself can be calculated as

$$P_{ohm} = R \cdot I^2 = R \cdot \frac{1}{c_M^2} \cdot T^2 = c_{m_1} \cdot T^2$$
 (3.21)

Equation (3.19) describes the model utilized for the BDC-motor in this work. Calculations with the model are presented in the next chapter in comparison with the AC-system.

3.5 Pump

In the design of a solar pumping system the pump itself is the most important component. For PVP-systems, the principles of centrifugal pumps or positive displacement pumps are the most used technologies. Other types of pumps which work according to others principles are not adequate for PVP applications due to their very poor efficiencies [23].

Depending on the application and the type of water source supply (deep well or surface water from lakes and rivers) different pump principles are utilized in solar pumping systems. Centrifugal pumps are designed for a fixed head and their water output increases with rotational speed. Positive displacement pumps on the other hand, have a water output which is almost independent of head but directly proportional to speed.

In the course of the last years a great variety of different pump solutions have emerged. Several investigations regarding positive displacement pumps applications are found in the literature. In [24,60,65] investigations on piston pumps powered by solar energy are presented. Progressive cavity pump solutions are well covered in [7,30,36,64]. Centrifugal pumps analysis are presented in many publications, some examples are in [4,5,6,7,23].

There are various combinations of motor and pump that are suitable for use with solar power. A good classification of PV-pumping system configuration is given in [18]. These are:

- 1. submerged motor/pumps with centrifugal pumps, often consisting of several impellers and therefore termed 'multi-stage'
- 2. submerged pump arrangement with the pump below the water, driven by the shaft from a motor mounted above the water. The pump can be either of the centrifugal principle or could equally be a positive displacement pump, usually in the form of a reciprocating double acting piston pump
- 3. floating motor/pump units with centrifugal pump
- 4. surface mounted pumps with a self priming tank. Positive displacement pumps have better self-priming characteristics.

In the present study two different types of pumps installed in a photovoltaic test facility were analyzed: The centrifugal pump and the progressive cavity (screw) pump. The basic operation principles of these pumps and the mathematical models developed to describe their operational behavior will be presented in the following sections.

3.5.1 The Centrifugal Pump

3.5.1.1 Construction and Working Principle

The centrifugal pump is a fluid flow machine which transforms kinetic energy into pressure . A centrifugal pump is basically comprised of an impeller (rotating part) and a volute or spiral casing (stationary part). The principal parts of the centrifugal pump, in its simplest form, are shown in Figure 3.20.



Fig. 3.20: Sectional view of the basic construction of a centrifugal pump (source:[26]).

The energy transfer is achieved through the flow deflection of the fluid in the impeller (see Figure 3.20). The fluid enters the center of the impeller and is picked up by the blades (or vanes). The rotating motion of the impeller transfers energy to the fluid as it flows outwards through the impeller. In order to be able to estimate the rate of energy transfer to or from the fluid, the flow through an impeller or runner has to be analyzed; the basis for this analysis is given by the velocity vector diagrams which represent the flow as it enters and leaves the rotating elements, and the Euler Turbine Equation which describes the energy transfer from the fluid to the rotating element [47]. Both theories are outlined in appendix C.

3.5.1.2 The Centrifugal Pump Model

H(Q)-characteristic

Pumps are generally described by their H(Q)-characteristic. H (in meters), is the total head impressed on the fluid by the impeller and Q is the pump flowrate. The 'Euler equation' (see appendix C) describes the H(Q)-characteristic of an ideal pump, in which the number of blades are taken as infinite, the blades channels are infinitely thin and no losses due to friction and to the change of regime flow within the pump are considered. For a real pump the H(Q)characteristic can be obtained from the theoretical head H_{thx} with a finite number of blades when the friction losses (hydraulic losses) and the losses due to change of velocity patterns within the pump (shock losses) are subtracted. Detailed derivations of these functions can be found in Harney [20] and Pfleiderer [47]. The main steps of these derivations are given in appendix C, here only the resultant equations and their physical meaning will be presented.

The H_{thx} is given by the function

$$H_{thx} = \alpha \cdot n^2 - \beta \cdot n \cdot Q \tag{3.22}$$

where α, β describe the pump geometry, n is the pump speed and Q is the pump flowrate.

The **hydraulic losses** (friction losses) are caused by turbulent flow occurring in the pump bearings, in the shaft seals and at the impeller shrouds. From measurements it is know that these hydraulic losses are proportional to Q^2 . These losses have the following form [47]:

$$\mathbf{h}_{\mathrm{hx}} = \boldsymbol{\alpha}_{\mathrm{h}} \mathbf{Q}_{\mathrm{x}}^{2} \tag{3.23}$$

where h_{hx} [m] represents the hydraulic losses in meters, α_h is a constant related to the hydraulic efficiency at nominal values (H, Q, n) and Q_x is any flowrate value different from nominal value.

Shock losses occur when the pump capacity changes (which normally occurs at part loads and overloads) and the angle of attack of the flow velocity at the inlet or outlet of the impeller deviates from angle of the impeller blades. According to [48] this loss can be expressed by

$$\mathbf{h}_{sx} = \alpha_s \mathbf{n}_x^2 - \beta_s \mathbf{n}_x \mathbf{Q}_x + \gamma_s \mathbf{Q}_x^2 \tag{3.24}$$

with α, β, γ describing geometric relations at the impeller inlet and outlet and being independent from H_x, Q_x and n_x.

From the above equations the H(Q) equation of a real impeller is then given by

$$H_x = k_1 n_x^2 + 2k_2 n_x Q_x - k_3 Q_x^2$$
(3.25)

Equation (3.5.4) is known in the literature as the throttling curve for a constant rotational speed n. The empirical coefficients k_1, k_2, k_3 represent constant values for a certain pump.

Torque Characteristic

The mechanical power, which is utilized by a centrifugal pump is divided into heat losses, friction losses on the walls of the impeller and in hydraulic power which is transferred to the fluid by the impeller [16]. The derivation of the torque characteristic is given in Appendix C. The final equation, which is used in the simulation, has the following form:

$$T_{Pump} = c_{t1} \cdot n^{2} + c_{t2} \cdot n \cdot \dot{Q} - c_{t3} \cdot \dot{Q}^{2}$$
(3.26)

where c_{t1}, c_{t2}, c_{t3} are empirical parameters which can be obtained from measurements.

Summarizing, equations (3.25) and (3.26) describe the operational behavior of a centrifugal pump in the present work. The coefficients k_1, k_2, k_3 as well as c_{t1}, c_{t2}, c_{t3} for the pump in the PVP-system in Oldenburg were obtained from the pump measurements presented in chapter 2.

It is important to note that although the equations (3.25) and (3.26) have the same numerical form, their individual terms do not have the same physical origin.

The Head characteristic obtained with the model equation (3.25) is shown in Figure 3.21, where the simulated characteristics are also presented to show the good agreement between calculated and measured characteristics. The characteristic for nominal speed (50Hz) available in the manufacturer data sheets is also presented for comparison.

The T-Q-characteristic calculated by expression (3.26) is presented in Figure 3.22 for two different flowrates Q together with the measured curves, showing how well the model can reproduce the real behavior.



Fig. 3.21: Simulated and measured H(Q)-characteristic of the centrifugal pump KSB-UPA 100 7/3 of the PVP-system in Oldenburg for different inverter frequencies (from 30 Hz to 55 Hz in steps of 5Hz). The solid lines were obtained with the model (equation 3.25) and the points are the measured characteristics. The characteristic for nominal speed (50Hz) available in the manufacturer data sheets(+) is also presented for comparison.



Fig. 3.22: Simulated (—)and measured (\Box) Torque-speed characteristics of the centrifugal pump installed in the PVP-system in Oldenburg. The curve on the top is for a flowrate $Q = 3.5 \text{ m}^3/h$, while the curve on the bottom is valid for $Q = 0.5 \text{ m}^3/h$.

3.5.2 The Progressive Cavity Pump (Screw pump)

3.5.2.1 Construction and Operation Principles

The progressive cavity pump, also called helical motor pump or screw pump, is a rotary positive displacement flow machine. Rotary positive displacement pumps have the great advantage over centrifugal pumps that they operate at relatively high efficiency over a wide range of speeds. The developed head is independent of speed and their capacity is basically proportional to speed, which makes these types of pump very attractive for solar pumping applications.

In this type of pump, the housing not only serves as a sealing shell, but also takes part in the process of water delivery. Pumping of water is accomplished by the coordinated interaction of two transporting elements. The rotor made of metal forms a helix with an extremely steep pitch and a small effective core diameter. The stator, composed of elastomere compounds, has also a helix form complementary to the rotor helix, but with twice the pitch. Due to this design, progressive cavities are created between the rotor and the stator. These volumes proceed towards the delivery end of the pump during rotation of the rotor. Figure 3.23 shows construction details of a progressive cavity pump, indicating its geometrical parameters: the stator length h_{ST} , the rotor radius r_{ROTOR} and the rotor eccentricity *e*. These parameters describe the dimensions of the pump, which in turn determine the volume flow.



Fig. 3.23: Construction elements of a progressive cavity pump. (source:[17])

The progressive cavity pump can be characterized by the equations for the pump flowrate and for the torque on its shaft. A complete derivation of these characteristics can be found in Genthner [17], Kernd'l [30] and are also summarized in Appendix C, so that here only the main equations and their physical meaning will be presented.

The pump flowrate Q_{pump} is described by the function:

$$Q_{Pump} = Q_{theo} - Q_L \tag{3.27}$$

where the theoretical pump flow rate Q_{Theo} is proportional to the rotational speed n and the geometric volume of displacement, which is determined by the geometrical design of the helical rotor inside the stator. The leakage flowrate Q_L can be estimated by an expression based on the Navier-Stokes-equation, which takes into account the characteristics of the fluid and the shape dimensions of the gap between pump stator and rotor.

The torque developed in a progressive cavity pump has two causes: first due to the transfer of hydraulic power to the fluid, and second due to the power losses caused by friction. The hydraulic torque is a function of the geometric volume of displacement and the pressure developed in the pump. The friction torque is a function of the rotational speed and the viscosity of the fluid.

3.5.2.2 The Progressive Cavity Pump Model

For the calculations of the pump performance in the simulation model the following expressions, describing the pump flowrate and the pump torque, are used:

The pump flowrate is given by:

$$\mathbf{Q}_{\text{pump}} = \mathbf{V}_0 \cdot \mathbf{n} - \mathbf{c}_{0} \cdot (\Delta \mathbf{p})^2 \tag{3.28}$$

where V_o is the geometric volume of displacement, n is the pump speed, Δp is the pressure difference over the length l and c_{Q_1} is an empirical parameter obtained from measurements.

The model developed for the torque is based on the theoretical principles discussed in details in appendix C and in the laboratory measurements presented in chapter 2 of this work. The final torque function used in the simulation model is given by:

$$T_{P_{ump}} = \frac{V_0}{2\pi} \cdot \Delta p + c_{T1} + c_{T2} \cdot e^{(-c_{T3} \cdot n)} + c_{T4} \cdot n^2$$
(3.29)

where

- $\frac{V_0}{2\pi} \cdot \Delta p = T_{hyd};$
- $c_{T1} = const = T_{friction}$

 $c_{T2} \cdot e^{(-c_{T3} \cdot n)}$ is a function which considers the torque by occasion of a transition from one form of friction to another (static friction, sliding friction, friction of laminar and turbulent flows). $c_{T4} \cdot n^2$ represents the torque caused by turbulent flow in the inlet/outlet as well as within the working area in the cavities.

3.6 Well and Hydraulic System

3.6.1 Well

When water is discharged from a well, the watertable inside does not remain constant. It changes depending on the flowrate and the time of pumping. The difference between the stable waterlevel (static water level) and the instantaneous level affected by the discharge (dynamic water level) is called drawdown. In a drilled well the drawdown reaches considerable orders of magnitude. Thirty meters and more is possible under normal operation.

The dimensioning of a pumping system is based on the expected hydraulic load, i. e., on the discharge times the pressure head. The latter depends largely on the drawdown. If the pumping system is driven by a constant power source like a diesel generator, the drawdown becomes constant after a relatively short initial period, what allows to calculate the total pressure head with constant values of geodetic head. Different from this, a photovoltaic pumping system has to deal with the fluctuating energy of the solar radiation captured on the surface of the photovoltaic generator. Here, the equilibrium of constant drawdown can not be established and a permanently mutual response between the well aquifer system and the pumping system is found. It is then no longer justified to consider the geodetic head as constant.

The facts above mentioned imply that a correct dimensioning and a detailed simulation of PVP-systems are only possible if the dependence of the well water level on the water flow rate in the pumping system is known. For the purpose of the present work, a mathematical model based on the works of Tegethof [62] and Schietzelt [51] is used to describe the behavior of a well in a PVP-system. Before explaining the model itself, some underlying concepts and characteristics of a drilled well should be presented in short. Greater details can be found in [51] and in specialized literature [34, 35].

3.6.1.1 Basic Principles of Well Hydrogeology

Well Construction

Concerning well construction techniques, drilled wells are particularly of interest for PVPapplications because they are normally able to produce water of constant amount and quality along the year even in remote and dry regions. Figure 3.24 shows the basic construction elements of a typical drilled well.

Groundwater Deposit

Groundwater is subterranean water, stored in cavities with a widespread range of magnitude (pores, clefts, cracks, fractures, channels, etc). It is, more or less, in motion. The range of velocity, dependent on the gradient and the material, reaches from cm/year (in porous material) up to magnitudes comparable with surface water flow (in carst material).

According to the water conductivity of the earth layers, three different types of layers are distinguished: The Aquifer, as the water conducting layer, the Aquitard as the layer with a relative low conductivity and the Aquiclude as an impermeable layer. A sequence of these

different layers forms the Aquifer system. The basic types of aquifer systems are presented in appendix D.



Fig. 3.24: The basic construction elements of a drilled well typically utilized in photovoltaic pumping systems (source [53]).

The behavior of the groundwater flow depends on the hydraulic characteristics of the aquifer and thus can be described by hydraulic parameters as conductivity k, the transmitivity T and the and storage coefficient S.

The conductivity coefficient k describes the hydraulic conductivity, assuming values between 10^{-5} to 10^{-7} m/s for clay and between 10 to 10^{3} m/s for gravel [35]. In non homogeneous aquifers the conductivity varies in the vertical direction. Due to this fact the term Transmitivity (T [m²/s]) is introduced, which is defined as the integral of the conductivity over the thickness of the aquifer.

The storage coefficient S (dimensionless) indicates the volume of water stored in or released from a unit volume of medium (aquifer material) per unit pressure head increase or decline. It depends on the compressibility of both medium and water.

3.6.2 Model Describing the Well Drawdown

The Aquifer Drawdown

The well model (drawdown) utilized in this work is based on the basic formula describing the shape of the well depression cone developed by C. V. Theis in 1935 [35]. The depression cone is the plane of the pressure head around a pumped well as showed schematically in

Figure 3.25. The so called Theis equation is the basis for the majority of the methods of evaluation of pump tests in investigations of well aquifers [51].



Fig. 3.25: Behavior of the watertable of a well by the action of pumping (depression cone of a well).

The Theis equation, which is a solution to the fundamental equation of groundwater flow (derived by Jacob in 1940) has the following form

$$s(t, r) = \frac{Q}{4\pi T} W(u)$$
(3.30)

with

$$W(u) = \int_{u}^{\infty} \frac{1}{u'} \exp(-u') du'$$
(3.31)

$$u = \frac{r^2 S}{4Tt}$$
$$u' = \frac{r^2 S_s}{4T(t-t')}$$

where

s(t, r)	=	drawdown at radius r measured from the well axis
Q	=	water flowrate (constant)
r	=	Radius measured from the well axis
W(u)	=	well function
Т	=	transmissivity of an aquifer
S	=	storage coefficient of an aquifer
t	=	present time
ť'	=	time variable $t_o \le t' < t$, $t_o =$ start of pumping

The hydrogeologic parameters T and S are to be determined by a well performance test, which also is necessary to determine the required amount of water and the discharge drawdown ratio, as well as the well losses. The procedures to carry out such a pumping test and the evaluation of its resulting data are well described elsewhere [35, 68, 51] and will not be described here. The results of a well test are summarized in a test report where usually two graphs are plotted: Drawdown versus time and drawdown versus flowrate.

Equation (3.30) is only valid for a pump test at constant flowrate Q. For a well in a PV-system, this formula has to be extended for variable discharges, i.e., in a function of the form

$$\mathbf{s} = \mathbf{s}(t, Q(t)) \tag{3.32}$$

Tegethoff [62] extended equation (3.30) for non constant discharges and applied it to a real PVP-system well in Brazil with quite good results. He considers the drawdown mathematically as a gradient so that the superposition principle can by applied and approximates the daily courses of the flowrate as step functions and considers the drawdown s(t) as the arithmetic sum of n drawdowns caused by n individual pumping action on the interval $t_{o...t.}$ A step function is implicitly given because in this case we deal with discrete values of measurements (datalogger resolution). For illustration, Figure 3.26 shows the approximation of the variable flowrate Q (t) through a step function for a pump test.



Fig. 3.26: Approximation of variable flowrates in PV-pumping by a step function (source[62]).

The derivation of equation (3.32) is extensively described in [62, 51] and will not be treated here. The resultant general equation describing the contribution of the aquifer on the drawdown of a well with variable flowrate takes the form:

$$s(t) = \frac{1}{4\pi T} \int_{t_0}^{t} \frac{Q(t')}{t - t'} \exp\left(\frac{-r^2 S}{4T(t - t')}\right) dt'$$
(3.33)

The integral of the flowrate in equation (3.33) was then approximated to a step function (Figure 3.27) in which Q(t') is considered constant in each 10 minutes interval, which is a typical averaging time for a data acquisition system in PVP applications. This step function is then defined as

$$Q(t') = 1 \sum_{i=0}^{n-1} Q_i \mathbf{1}_{[t_i; t_{i+1}]} \quad \text{with } t_n = t \quad \text{and} \quad \mathbf{1}_{[t_i; t_{i+1}]} = 1 \quad \text{for } t_i < t \le t_{i+1}$$
(3.34)



Fig. 3.27: Definition of the step function Q(t') for a PVP-system (source:[62]).

The variable t in function (3.34) describes the present time and is the maximal value for variable t'. The variable t' takes the values of the measured data from the time t₀ in the past to time t in the present. Substituting this function in equation (3.33), and after some transformations, the final equation for the aquifer drawdown becomes:

$$s(t) = \frac{1}{4\pi T} \left[\sum_{i=0}^{n-2} Q_{i+1} \ln \frac{t-t_i}{t-t_{i+1}} \right] + k_0 Q_n \qquad \text{for } t \ge t_{i+1} \qquad (3.35)$$

where $(t - t_i)$ is the total time passed since pumping beginning and $(t - t_{i+1})$ is the time passed after pumping stop.

Summarizing, expression (3.35) describes the variation of the watertable over the time, by each individual pumping action.

Well Losses

Besides the drawdown caused by the aquifer behavior given by equation (3.35) ('Theis behavior'), an additional drawdown occurs in a real well, which does not depend on the aquifer but on the specific flow conditions inside and in the immediate vicinity of the well [35]. In this way the total drawdown can be described as

$$s_{\text{total}} = s_{\text{aquifer}} + s_{\text{losses}} \tag{3.36}$$

The losses occurring in a well can be calculated as

$$s_{\rm loss} = k_1 Q + k_2 Q^2 \tag{3.37}$$

where $k_1 =$ linear loss coefficient $k_2 =$ square loss coefficient

The laminar losses are caused by an altered transmitivity of the material surrounding the well. In a drilled well there is a space between the earth and the well casing which is normally filled with a gravel pack to permit a good transmissivity and to avoid that sand enters the well. In case a well is not adequately developed ('cleaned') after the drilling process, the pores and clefts can stay closed thus diminishing the transmissivity of the well.

Turbulent losses occur while the water is entering the well or is flowing vertically to the pump. If the well has a casing and water enters through a well screen (filter sections of the casing), losses are largely dependent on the quality of the screen. The constant k_2 describes therefore the square losses caused by turbulent flow in the near of the well and in the filter sections.

Considering the above losses, the final equation describing the drawdown becomes

$$s(t) = \frac{1}{4\pi T} \left[\sum_{i=0}^{n-2} Q_{i+1} \ln \frac{t-t_i}{t-t_{i+1}} \right] + k_1 Q_n + k_2 Q_n + k_3 Q_n^2$$
(3.38)

or, for numerical processing

 k_0

=

$$s(t) = k_0 \sum (t) + k_{1/2} Q(t) + k_3 Q(t)^2$$
(3.39)

with

$$\frac{1}{4\pi T}$$

k₁ =
$$\frac{1}{4\pi T} \int_{t_{n-1}}^{t} \frac{1}{t-t'} \exp\left(\frac{-r^2 S}{4T(t-t')}\right) dt$$

- $k_2 = coefficient for linear losses$
- $k_3 = coefficient for square losses$

$$k_{1/2} = k_1 + k_2$$

$$\sum t = \sum_{i=0}^{n-2} Q_{i+1} \ln \frac{t-t_i}{t-t_{i+1}} = \text{well 'memory}$$

The constants k_0 , $k_{1/2}$ and k_3 can be determined from a pump test, in which the water flow rate Q is increased and kept constant stepwise until the well maximum flowrate is attained. For each step, the well drawdown and the time needed for the water mirror to recuperate (recuperation period) are recorded. The procedures for such a pump test are described in [51] and methods to obtain the well parameters from the test data are well explained in [34, 53]. In the frame of this work, due to some inaccuracy in the pump tests data available, selected pump operation data was utilized. The constant k_0 was determined from the recuperation period of the well, so that equation (3.39) was reduced to

$$\mathbf{s}(\mathbf{t}) = \mathbf{k}_0 \cdot \sum \mathbf{t}$$

For this, a day with a very smooth radiation curve was selected, to guarantee that the assumption $Q_{t_1...t+1} = constant$ is sufficiently fulfilled. From this, the transmissivity T was found by

$$T = \frac{1}{4\pi k_0}$$

After some transformations equation (3.39) could be reorganized as

$$\frac{\mathbf{s} - \mathbf{k}_1 \cdot \sum \mathbf{t}}{\mathbf{Q}} = \mathbf{k}_1 \cdot \mathbf{Q} + \mathbf{k}_{1/2}$$

permitting that the remaining parameters be obtained by means of linear regressions.

Figure 3.28 shows, as an example, the well drawdown calculated with the model (equation 3.40) compared to the measured curves for the PV-pumping system installed in Lagoa das Pedras, Brazil (for the description of the system see table 5.1). Two days are shown: one day with smooth radiation conditions and one more typical day with fluctuating conditions.



Fig.3.28: Calculated and measured drawdown from the well of the PV-pumping system installed in Lagoa das Pedras (Brazil), for different radiations conditions: a smooth day (06.08.93), in the upper graph, and a fluctuating day (23.08.93) in the bottom graph. (from:[53]).

The good agreement between calculations and measurements showed in Figure 3.28 indicate that, despite the simplified assumptions in the parameters determination, the model could estimate the well behavior quite satisfactorily.

3.6.3 The Hydraulic System

The hydraulic system, composed of pipework, elbows, valves, flow measuring devices, etc, produces an additional head that has to be overcome by the pump during operation. These losses are considered in the simulation calculations by the following equation which is based on the Blasius equation for smooth pipes,

$$H_{piping}(t) = C_1 Q^2(t) + C_2 Q(t)^{1.75}$$
(3.40)

The constants C_1 and C_2 represent the sum of the friction loss coefficients for the piping length and for the fittings respectively. These coefficients are normally available in tables and diagrams in text books and handbooks of pump technology [125, 150].

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4 Simulation of the Complete Systems

In the previous chapter of this work, models for the individual components of two PVpumping system configurations were presented and validated by comparing measured and simulated components characteristics. In this chapter, the structures of the complete models based on the individual components will be described and the results of simulations calculations utilizing these models will be analyzed and discussed. An energetic analysis of the operational behavior of the complete systems, considering the interactions of system components and how they influence each other will be carried out. The models will also be used to investigate the effect of variations of the weather conditions and PVP-techniques on the system yield.

The chapter starts with the description of the complete PVP-system model and the computer simulation algorithm for a system composed of an AC-motor and a centrifugal pump (this system will further on be called the 'reference system'). Following, results of simulation calculations done with the model are compared to measurements carried out in chapter 2 to show the accuracy of the model. Then, simulation calculations of the system performance will be done for different weather conditions and the results will be compared in the form of energy flow diagrams to assess the influence of the variation of the meteorological conditions on the energy flow through the system, as well as on the system yield. For this, measured data from Oldenburg and Lagoa das Pedras/Brazil will be utilized.

Following, a comparison between PVP-system output predictions obtained with the detailed simulation algorithm developed in this work and predictions obtained with simplified simulation models will be done. For the comparison, a model based on the manufacturers data sheet and design characteristics was chosen, as well as a simulation algorithm based on the concept of solar utilizability.

The chapter will be concluded with an analysis of the possibilities for system optimization, in which a simulation model of a novel, more efficient PVP-system concept (composed of a brushless DC-motor and a progressive cavity pump) will be presented and the results of simulation calculations utilizing this model will be compared to the the ones obtained for the reference (or standard) system.

4.1 Realization of the Complete PVP-systems Simulation Model

The simulation model of a complete solar pumping system is, in the present work, the combination of its individual components models in modular form, namely

- The Photovoltaic-generator
- The Inverter
- The Pump
- The Motor
- The Well and Hydraulic System

These components, in form of component models, were implemented in the block oriented software INSEL (Integrated Simulation and Environment Language) which was developed at the University of Oldenburg for the simulation of energy systems [28].

4.1.1 Model for the Reference PVP-System

Figure 4.1 shows the simplified flow-chart diagram of the PVP-system composed of an asynchronous motor and a centrifugal pump, which describes the interaction of the hardware system components as it is realized in the simulation model. The simulation algorithm will be shortly explained below. The system technical data is given in Table 2.1 of this work.

The model is fed with meteorological operating parameters, such as the solar irradiance and ambient temperature. An INSEL block generates date and time of the actual simulation time step (constant time increment). The flow rate Q is calculated as a function of three input variables, the solar radiation G_{pv} , the ambient temperature T_{amb} and the total pumping head H.

As shown in figure 4.1, the PV-generator delivers a DC-current I_{PV} dependent on the given operating voltage V_{DC} , the solar radiation G_{PV} on the array plane and the ambient temperature T_{amb} . The interaction of the subsystem (inverter, motor and pump) units is the heart of the simulation algorithm. The inverter transforms the DC-power supplied by the solar generator into AC-power $P_{AC-supply}$ with a frequency f, which is preset by the controller, and feeds the asynchronous motor; the motor transforms the electric AC-frequency into a shaft rotational speed that depends on the slip produced by the load. The pump finally lifts the water with a flow rate Q through the hydraulic system over a given geodetic head.

The electronic control of the inverter adjusts the power demand of the subsystem to the power supplied by the PV-generator by adjusting the AC-frequency. If, for example, there is an increase in solar radiation, with a subsequent increase of the $P_{AC-supply}$, the inverter goes up with the frequency until the power demand of the motor $P_{AC-demand}$ equals the power supplied by the inverter. On the other hand, a decrease of solar radiation leads to a controlled reduction of the AC frequency, until a new power balance is attained.

The simulation occurs in three iteration nested loops as indicated in Figure 4.1. In iteration loop 1, the hydraulic working point between the pump output and the hydraulic system is determined, by calculating the crossing point between the throttling curves (equation 3.25) and the hydraulic system head (equation 3.40), i.e., by solving $H_{pump}(Q) = H_{syst}$ (Q), a flow rate Q is determined for a given geodetic head. Due to the fact that the throttling curves $H_{pump}(Q)$ depend on the rotational speed of the pump, the pump speed *n* is determined in the outer loop 2, in which the mechanical working point between motor and pump is found by solving $T_{motor} = T_{pump}$ according to equations (3.15) and (3.26); On the other hand, T_{motor} is dependent on the frequency *f*, so that the determination of *n* in loop 2 cannot be realized before that, in the outer loop 3, the electrical working point is found by solving $P_{AC-supply}$ and thus calculating the frequency *f*. Finally, the algorithm has also to take into account that due to the fixed relationship between *f* and V_{DC} given by equation (3.4), a change in *f* signifies a new V_{DC} and consequently new P_{DC} and $P_{AC-supply}$.


Fig. 4.1: Flow-chart of the simulation algorithm for a PVP-system composed of a centrifugal pump and an asynchronous motor.

Summarizing, the model of the complete PVP-system searches automatically for each time point i, by given irradiation, ambient temperature and geodetic head, a working point characterized by a triple (f_i , n_i , Q_i), and performs an energy balance for each time step. The simulation does not considers any transitory behavior, that is, each time step is calculated without taking into account the previous step. This is possible, since the time delay with

which the PVP attains a new equilibrium condition after a change of the irradiation, happens in the order of few seconds, and is much shorter than the time when the system operates in stationary conditions.

A similar algorithm for a system composed of a brushless-motor and a progressive displacement pump was also developed in this work. The description of this alternative system configuration together with its simulation model will be presented in section 4.5.3 of this work. The algorithm is similar to that showed in Figure 4.1, but because of the different system construction (motor and electronic control cannot be separated, but form an unit in the BDC-system) only two out of three loops are interconnected.

4.2 Simulation Results

Time step simulation calculations utilizing the model presented in Figure 4.1, for the reference system, were performed. In this section the results of these simulation calculations will be discussed and compared to field data obtained during the measurements carried out outdoors at the University of Oldenburg. The simulations calculations were performed in time steps of one minute, which was the time resolution of the measurements.

4.2.1 Validation of the Model by Comparison of Simulation and Measurements

As an example of the simulation calculations and to illustrate the accuracy of the model, results of simulation calculations and field measurements for a specific day will be discussed. The 19.08.1996 was chosen, because among other reasons, at this day the system operated near optimal conditions, with an average flow rate of about 7.3 m³/h, which is practically the nominal flow rate of the pump (7 m³/h), according to the manufacturer data sheet. The day is characterized by a clear sky with very little fluctuation in solar radiation, what implies that the minute average measured values represents approximately instantaneous values, so that the errors in the comparison between simulation and measurements can be minimized.

Figures 4.2 to 4.5 present the daily course of the most important characteristics describing the system performance for the 19th August 1996. In these figures, curves of the simulated and measured electrical output of the PV-generator $(P_{DC}(t))$, the inverter frequency (f(t)), the total head (H(t)), the pump flowrate $(\mathcal{O}(t))$ and the total efficiency of the system $(\eta_{TOTAL}(t))$ are depicted. The absolute difference between the simulated and the measured pump output $((Q_{sim} - Q_{meas}))$ is also presented in figure 4.2. Overestimations by the simulation will appear as positive values.

The PV-generator was simulated according to the models described in section 3.1.2. The input data for the simulation are the measured irradiation G_{PV} incident on the array plane and the ambient temperature T_{amb} .

The additional losses described in section 3.1.2 were taken into account in the calculations, with the following values relative to the nominal PV-generator power: Reflection losses of 3% according to Sjerps-Koomen in [30], spectral losses of 1% [24,25], mismatch losses were calculated as 3% according to Damm in [10], and the voltage drop in cables and blocking

diodes were estimated to be 1V. Figure 4.2 shows the daily course of the simulated generator power P_{DC-sim} in comparison to the measured power $P_{DC-meas}$. As can be seen in this figure an excellent agreement between model and measurements was found. The deviations in the early and late afternoon can be explained by the fact that the inverter works intermittently in these time intervals, i.e., in case the minimal frequency, preset in the inverter to protect the motor-pump unit (in this case $f_{min} = 30$ Hz), is not attained, the inverter shuts out and tries again and again to reach (from 0 Hz) this minimal frequency, with the result that for f< f_{min} the measured minute average is larger than zero, while in the simulation model the DC-output is considered zero in those time intervals.



Fig. 4.2: The simulated PV-generator output power $P_{DC-meas}$ (—) in comparison to the measured P_{DC-sim} (—) for the 19.08.1996.

In the middle of the day, in the time between about 12h and 16h, the simulation underestimates the generator power output. The main reason for this is that a constant value for the reflection losses along the day was assumed for the simulation calculations. This assumption leads in the simulation to a underestimation of the DC-power by high irradiation values (around noon) as can be seen in figure 4.2, due to the fact that at this time of the day, for a clear day, the angle of incidence of the solar radiation on the array plane (45° inclination) is small, with the effect that the reflection losses decrease in reality [26].

Figure 4.3 presents the comparison of simulated and measured inverter frequency, as an example for the quality of the simulation of the subsystem individual components. As the inverter frequency f together with the pump rotational speed n and the pump flowrate \mathfrak{G} determine the working point of the PVP-system for each time-step in the simulation model, the ability of the model in reproducing the measured frequency is crucial for the accuracy of the complete system model. The calculated relative error $\Delta_{rel} f < 1\%$, for the time interval of relevance (when the system actually pumps water), shows that an excellent accuracy was attained with the model.



Fig. 4.3: Comparison between the measured and simulated inverter frequency $f_{mea}(-)$ and $f_{sim}(-)$ in minute time steps for the 19.08.1996.

Figure 4.4, presents the simulation results of the final output of the complete system. In this figure, the simulated flowrate \mathfrak{G}_{sim} , the measured flowrate \mathfrak{G}_{meas} , the absolute deviation $\Delta \mathfrak{G} = \mathfrak{G}_{sim} - \mathfrak{G}_{meas}$ and the cumulated water volume V are depicted, for the 19.08.1996. At that day, the measured water output was 68.48 m³ and the simulated 68.55m³, at a constant geodetic head of 15m.

As Figure 4.4 shows, an excellent agreement between measurement and simulation was achieved with the complete model. Apart from the start and stopping periods in the early morning and in the late afternoon, the relative deviation between simulation and measurement over a period of about 8 hours stays below 5 %. If one considers that the measurement errors were estimated as 4% [13], the simulation results are in the range of the measurements accuracy.

The absolute errors $\Delta \mathcal{G}$ are also small, as shown in Figure 4.4. Over the whole day, an average deviation of 0.37 m³/h was estimated, what corresponds to about 5 % referred to the pump average flow rate of 7.3 m³/h.

The differences in the early morning and in the late afternoon can be mainly attributed to the fact that the model is very sensitive around the times when the system starts or stops pumping, i. e., for small flowrates. To investigate this point Janssen [17]carried out a simulation run with the model for an interval of very small flowrates, and his results showed that an increase of only 0.1 % in the pump rotational speed produced an increase in flow rate from 0 m³/h to 0.6 m³/h, which demonstrates clearly the sensitivity of the model at pump beginning or stopping.

Another explanation for the high deviations at small flowrates is that the pump operates below the minimal flowrate $(2.3 \text{ m}^3/\text{h})$ given by the manufacturer characteristic, so that eventual additional losses occurring at these periods can not be considered in the model. Besides, the determination of the model parameters are subject to errors due to measuring devices inaccuracies especially for extreme values of pump flowrate.

Concerning the small deviations in the middle of the day they are probably due to the fact that the geodetic head of the system is considered constant (15m) in the simulation calculations for this specific system (the pump is not installed inside a 'real' well in our test facility, so that eventual fluctuations in the water level along the day can not be reproduced in the simulation. Comparison between simulated and measured total head for different days has shown that the simulation slightly overestimates the measured system head, what confirms the assumption made.

Finally, the comparison between the simulated and measured daily volume (bottom graph in Figure 4.4) confirms the good accuracy with which the model can reproduce the daily system behavior.



Fig. 4.4: Comparison between simulation (_____) and measurement (_____) of the complete PVP-system for the 19.08.96 at a geodetic head of 15.0 m; top: Pump flowrate @;middle: absolute deviation $\Delta @;$ bottom: cumulated daily pumped volume V.

4.2.2 The Influence of the Weather Pattern on the Daily Yield

To show how well the model can reproduce the system behavior under different radiation conditions and also to exemplify the influence of the weather pattern on the overall performance of the system, simulation calculations utilizing a set of sixteen days of measured data were selected for comparison with simulated data. Days from the period from 16th August 1996 to 30th September 1996 were chosen because in this time period the system worked without interruptions, according to the same control strategy of the inverter and without any other external intervention. The simulation time step of one minute was also the time resolution of the measurements. The results are shown in Figure 4.5, where simulated and measured daily water volume against daily irradiation for the same water head are compared.



Fig. 4.5: Simulated (•) *and measured* (+) *daily water volume over the irradiated solar energy per* m^2 *and day for the PVP-system of Oldenburg.*

As it can be seen in Figure 4.5, the agreement between simulated and measured daily water output is very satisfactory for all days showed. The relative deviation between simulation and measurements for these days were less than 6%. These results indicate that very realistic estimations of PVP-systems water output for different weather conditions can be obtained with the developed simulation model, what makes it appropriate as a dimensioning method for PVP-systems.

Interesting in Figure 4.5 is also the fact that the daily volume of pumped water can vary for the same sum of irradiation, depending on the pattern of the solar radiation during the day, i.e., on days with practically the same sum of irradiated energy, the daily volume of pumped water is different. This effect is mainly due to different patterns of solar radiation along the day and also to different temperature conditions. These results confirm the high sensitivity of solar

pumping systems performance to fluctuation of irradiation, as it has been demonstrated by a sensitivity analysis of PVP-systems conducted by Wei in [31].

4.3 Energetic Analysis of the Long-term Performance

In the previous sections it was demonstrated that the developed simulation model can reproduce the daily system performance with excellent accuracy. In this section, simulation calculations based on this model will be used to investigate the long term performance of a PVP-system. An energetic analysis of the system will be carried out for a period of one year, using as input measured meteorological data. The influences of the weather pattern on system performance will also be assessed by simulating the system behavior for different sites.

In the energetic analysis, the results of simulations will be used to make an energy balance of each step of energy conversion throughout the system, thus giving information over the composition and spectrum of the energy losses and their dependence on external operation parameters like plant configuration and site characteristics. The results of the calculations will be presented mainly in the form of energy flow diagrams, which can give a comprehensive and clear visualization of the long-term system performance.

The use of energetic utilization factors has proved to be a very useful criterion for the assessment of photovoltaic plants in general, and in particular for photovoltaic pumping systems [18,4,5]. In this and in the next chapter, some energy values will be introduced to analyze or to compare the performance of PVP-systems. They are based on the JRC-Guidelines for the assessment of photovoltaic plants [9], and due to their usefulness in comparing different systems, two of them will be shortly discussed in the following. Other similar energy parameters which are not quoted here will be defined in the text.

4.3.1 Definitions of Energy Values for the Assessment PVP-systems

Energy Conversion Efficiency

The energy efficiency of a system can be calculated by integrating the power produced by this system (P_{OUT}) over a specific time period τ (day, month, year) and dividing it by the integral of the power supplied to the system (P_{IN}) in the same time period. In this way, the energetic efficiency of a day, for instance, represents the average efficiency of the system over this day.

For a system or system component, a balance of the input and output energy can be found by

$$E_{IN} = \int_{0}^{t} P_{IN} dt \text{ , and}$$
$$E_{OUT} = \int_{0}^{\tau} P_{OUT} dt$$

The energetic efficiency is then calculated as the quotient of the useful energy output (E_{OUT}) and the input energy (E_{IN}) as:

$$\bar{\eta} = \frac{E_{OUT}}{E_{IN}} \tag{4.1}$$

The Performance Ratio (PR)

A common value utilized in the evaluation of photovoltaic plants is the performance ratio (PR). This dimensionless number, defined as the ratio between the net energy out of the system to the nominal energy produced by the PV-generator at Standard Test Conditions (STC), describes the utilization of the PV system. For photovoltaic pumping systems, the performance ratio can be similarly defined as the ratio between the hydraulic energy transferred to the pumped water volume (E_{HYD}), and the PV-array nominal energy(E_{STC}), as follows

$$PR = \frac{E_{HYD}}{E_{STC}}$$
(4.2)

with

$$E_{HYD} = \int H \cdot \mathcal{O} \rho \cdot g$$

where, H is the total pumping head (m), \mathcal{G} is the water flowrate (m³/h), ρ is the water density (Kg/m³) and g is the acceleration due to gravity (m/s²), and

$$\mathbf{E}_{\rm STC} = \int \mathbf{G} \cdot \mathbf{A}_{\rm PV} \cdot \boldsymbol{\eta}_{\rm STC}$$

where, G is the irradiation, A_{PV} is the PV-array area (m²), η_{STC} is the PV-array efficiency at Standard Test Conditions (STC: 1000 W/m², 25° C, AM 1.5).

The Performance Ratio (PR) as defined by equation (4.2) serves as a measure of the system performance, and because it is normalized to the nominal energy of the PV- generator it is in first approximation independent from meteorological conditions, what makes it suitable to compare different plants, while the energy efficiency parameter defined above by equation (4.1) is more useful for comparisons with the nominal energy efficiency of a system.

4.3.2 Energy Flow Diagrams of the Yearly Performance

4.3.2.1 The Energy Flow Diagram for Oldenburg Climate

The technical characteristics of the system were already presented with details in Table 2.1, The simulation model utilized for the calculations is the detailed model is presented in Figure 4.1. As input data for the simulation calculations, annual measured solar radiation and temperature from Oldenburg were used. The simulations were performed in time steps of one hour (hourly averages). A constant geodetic head of 15 m was chosen. The most important climatic characteristics of this site can be summarized as:

Climatic Characteristics

Oldenburg, the place of location of the experimental investigations, lies at latitude 53.17° N, longitude 8.15°E and at time zone 23. Based on available measured data for two years (1982 and 1983), the calculated value of the yearly global horizontal irradiation at Oldenburg is 939 kWh/m². 56% is direct radiation and 44% is diffuse. There are large seasonal variations in global irradiation, with the average value in December being only 9% of the value in June.

Figure 4.6 shows the monthly average solar energy collected on the horizontal surface Oldenburg (average of 2 years, from 1982 to 1983).



Fig. 4.6: Daily monthly average of irradiation on the horizontal surface for Oldenburg, Germany(average years 1982, 1983).

Energy Flow

As a result of the simulation, the energetic annual performance for the climatic conditions of Oldenburg is presented in Figure 4.7, in the form of an energy flow diagram. The calculated efficiencies for each system component are also presented in this figure. As input data for the calculations measured irradiation and temperature of the year 1982 were used.

The starting point of the diagram in Figure 4.7 is the annual nominal energy E_{STC} of the PVarray at Standard Test Conditions (STC). The E_{STC} value is calculated by multiplying the annual irradiation on the array plane of the PV-generator with the nominal efficiency of the PV-modules at STC (1000 W/m², 25 °C, AM 1.5). This value is considered as reference and normalized to 100 % in the diagram. For each of the single steps of energy conversion , the net amount of energy available to overcome the geodetic head is calculated in time steps of one hour. The influence of the loss mechanisms throughout the system can be assessed by comparing each step of energy conversion to the anterior step. The yearly radiation on the surface of the PV-generator attained 13.2 MWh. The E_{STC} in this case would be 1.6 MWh. The diagram shows that the annual energy actually used by the system to overcome the geodetic head ($E=Q \cdot H_{GEO}$) mounts up to 17 % of the nominal energy of the PV-generator E_{STC} .

The annual Performance Ratio (PR) of the PVP-system, defined as the net energy to overcome the geodetic head divided by the nominal energy of the PV-generator at standard test conditions, was 17 %.



Fig. 4.7: Simulated annual energy flow of the PVP-system for meteorological data from Oldenburg. The nominal energy output E_{STC} is equal to the energy production of the PV-array at Standard Test Conditions (STC), and is scaled to 100 %.

The analysis of the losses at component level shows:

The **PV-generator** output is reduced to 82. % due to the losses discussed in section 4.2.1. The losses due to reflection, deviation of solar spectrum from AM 1.5 (AM = Air Mass), mismatch losses due to non identical characteristics of the PV-modules, losses caused by wiring and losses due to fixed voltage control of the PV-generator away from MPP are estimated to 10.7 %. The losses caused by temperature and irradiation effects when operating at conditions different from STC are about 7 %.

A centrifugal pump requires a minimum rotational speed of the impeller in order to generate enough pressure to overcome the system head (this effect is called the low power **threshold** in the literature). This implies, in the analyzed PVP-system, that about 12 % of the DC-power cannot be transformed into hydraulic power. It is important to emphasize that this type of 'loss' cannot be avoided in this specific system as some other losses discussed here. It is actually the amount of energy which can not be transformed into useful energy due to the characteristics of the load.

The inverter transforms its input DC-energy into AC-energy with a yearly efficiency of 93%.

As discussed in chapter 3, the main losses in an **AC-motor** are comprised of core losses (iron losses), copper losses and friction losses in the bearings. They were computed to 31 % in our motor. This means that only 69 % of the inverter output energy could be used as mechanical energy at the motor shaft.

The loss mechanisms in **the pump** are due to friction losses and shock losses at the inlet and outlet of the pump impeller and they increase with the second power of speed as discussed in chapter 3. As the energy flow diagram shows, only 45 % of the mechanical energy could be annually transformed into hydraulic energy by the pump. Apart from the PV-generator, the centrifugal pump, with an annual efficiency of 39 %, had the worst efficiency among the system components. 3 % of the energy was used to overcome the fricton losses offered by the piping system.

General Assessment of the Plant Annual Losses:

The annual losses relative to the nominal energy throughout the system are presented in Figure 4.8. The values were taken directly from the energy flow diagram in Figure 4.7.



Fig. 4.8: Annual energy losses and not utilized energy for Oldenburg conditions. The percentage values represent the differences between the corresponding energy conversion steps of the energy flow diagram in Figure 4.7.

The expected losses calculated for the PV-generator and for the inverter are realistic if compared to similar investigations on PV-systems by other authors. They are in the same level of the losses calculated for seven PV-plants by Wiemken et al. in [2].

The motor losses are not high if compared with the typical values given in the literature, which rate asynchronous motors with maximum efficiencies of about 70 %, for the power range used in solar pumping systems.

The pump efficiency of 39 % is far below the maximum of 60-65 % given in the literature and in the pump data sheets [15,27], but is somewhat in the range of efficiencies of 40 % given by Whitfield in [32] and measured by Alonso in [1], which can be considered quite low.

4.3.2.2 The Energy Flow Diagram for Lagoa das Pedras

For a system with the same configuration and dimensioning values of the PVP-system installed at Oldenburg (see Table 2.1), but under meteorological conditions of Lagoa das Pedras, in the Northeast of Brazil, simulation calculations were performed to assess the influence of the weather conditions on the performance of the system. The simulations were performed in time steps of one hour (hourly averages). A constant geodetic head of 15 m was chosen. The most important climatic characteristics of this site can be summarized as:

Climatic Characteristics

Lagoa das Pedras lies at latitude 3.9° S and longitude 40° W, in one of the most dry regions of Brazil. April to November is the dry season and the wet season is from December to May. The daily solar irradiation on a horizontal surface is in average between 4.3 kWh/m²d and 5.8 kWh/m²d. The rainfall rate stays in average between 171 mm/y, with a maximum of 660 mm in March and a minimum of 2.1 mm in October. The annual average temperature is 28°C.

Figure 4.9 shows the monthly average solar energy, collected on the horizontal surface for Lagoa das Pedras (average of 3 years, from 1992 to 1994).



Fig. 4.9: Daily monthly Average of irradiation on the horizontal surface for Lagoa das Pedras, North East of Brazil (average years 1992, 1993).

The results are presented also as an energy flow diagram in Figure 4.10. For comparison purposes, this figure also contains the values of the diagram for Oldenburg meteorological conditions in the form of a table.



Fig. 4.10: Simulated annual energy flow of the PVP-system for meteorological data from Lagoa das Pedras, Brazil. The nominal energy output E_{STC} is equal to the energy production of the arrays at Standard Test Conditions (STC), and is scaled to 100%. For comparison, the values of the energy flow for Oldenburg are presented in the table at the right hand side.

Figure 4.10 shows that for the climatic conditions of Lagoa das Pedras, the PVP-system would convert 21% of the nominal (STC) energy into useful energy to pump water. The increase in losses in the PV-generator output energy in relation to the losses found for the Oldenburg weather comes mainly from the effects of higher irradiation and temperature characteristics of the site, since for the other PV-losses the differences should not be significant according to values obtained under field conditions and reported in [30]. Another reason that may have also contributed a little for the increase in PV-losses in the simulation for the Brazilian clime ,is the fact that the MPP control (made by fixed voltage strategy in this case) was optimized for the climatic conditions of Oldenburg.

A positive balance for the site Lagoa das Pedras was, as expected, the lower energy threshold caused by the pump. Here 73 % of the available DC-energy could be used to pump water. The energetic threshold efficiency was 7%. The inverter attained a better efficiency than for the weather in Oldenburg. With annual 92 % efficiency it converted 67% of the nominal energy into AC-energy.

Motor and pump attained both better efficiencies than that obtained for Oldenburg calculations. The losses in the pump are significantly lower for Lagoa das Pedras. This is due to the fact that for this site the pump works frequently in the near from its rated values.

The percentage of the individual losses relative to the nominal energy at STC are presented in Figure 4.11 for Lagoa das Pedras, which permits a direct comparison to the losses calculated for the Oldenburg weather in Figure 4.8.



Fig.4.11: Annual energy losses and not utilized energy for Lagoa das Pedras. The percentage values represent the differences between the correspondent energy conversion steps of the energy flow diagram of Figure 4.10.

Monthly Performance Ratio

Figure 4.12, presents the monthly Performance Ratios for the system, resultant from the simulations under both climatic conditions of Oldenburg and Lagoa das Pedras. In this figure the seasonal trends in the utilization of the system can be well visualized.



Fig. 4.12: Simulated Monthly Performance Ratios for the PVP-system based on meteorological data from Oldenburg and Lagoa das Pedras.

As can be seen in Figure 4.12, for Lagoa das Pedras the utilization of the system is practically constant along the months. This comes basically from the fact that there are no significant seasonal changes in that site. This means that the offer of solar energy does not vary much over the year, what is common for locations in the proximity of the equator. The lack of rains during the year whose data was used in the calculations makes the effect even more pronounced.

For the results obtained for Oldenburg the situation is quite different. As the graph 4.12 shows, there are variations of the system Performance Ratio from month to month and between the months in winter and summer times. The trend of the curve reflects the fact that monthly irradiation sums are higher in summer times, implying a better system utilization than in the winter.

The fact that for Lagoa das Pedras the monthly Performance Ratios are always higher than for Oldenburg, reflects the fact that the system works often in part load in Oldenburg, because of the different levels of fluctuations of the solar radiation, characteristic for this location.

4.4 Comparison of the Results of the Detailed Simulation Model with other Simulation Methods in Predicting PVP-system Output

The results presented in the previous sections of this chapter showed how much the precision of the design and analysis of the performance of a PVP-system can benefit from numerical simulations based on a very detailed system model, in which each of the system components are individually described by adequate physical model. This method has however the prerequisite that detailed informations have to be available from the components manufacturers or, that measurements of each individual component characteristics have to be made, which for certain objectives is not possible or justified, besides it may require considerable computation time. Bearing this in mind, two simplified modelling approaches were investigated and compared to the detailed model developed in this work.

At this point it is necessary to mention here that the original idea was to compare the output predictions of the detailed simulation with the standard dimensioning methods such as the nomograms prepared by some PV-pumps suppliers like Siemens Solar or Grundfos for example, but this could not be done, since for the specific system under investigation (table 2.1) such a nomogram is not available because the pump UPA100- 7/3 belongs to the newest generation of pumps produced by the company KSB, and for these, and other new pumps, the method utilized for system design, is now based on computer simulations instead of the nomograms, according to information given by Siemens Solar to the author. This piece of information demonstrates that simulation methods are really becoming common practice in the design process of PVP-systems, despite of the fact that probably the majority of the existing simulation models are based on not more than the nomogram information.

First a comparison with a model on data sheets from manufacturers will be made. Then, a comparison with the results obtained with a simulation algorithm based on the solar

utilizability concept will follow. The meteorological input data utilized in all calculations were that of Lagoa das Pedras in Brazil.

Before discussing the results of the simulations, a short description of the simplified model will be made, and the concept of utilizability and its application in PVP-systems design and performance predictions will be shortly addressed.

4.4.1 Simulation Based on a Simplified Model

The simplified simulation model utilized for the comparison was the software DASTPVPS (Design and Simulation Tool for Photovoltaic Pumping system) [11]. This program was especially chosen for comparison, because it is the program which is nowadays utilized by the firm Siemens Solar for the design of PVP-systems. The main features of DASTPVPS are explained in detail in [11], here it is important to mention that in this program PV-generator output power is calculated with the one-diode model, the inverter, pump and motor are modeled as a unit. The input data for the subsystem simulation are the nominal data from the manufacturers data sheets.

The comparison of the results obtained with both simulation programs is presented in Table 4.1, as monthly average pumped water volume.

Month	Detailed model	Simplified model	Deviation
	Monthly average volume [m³/day]	Monthly average volume [m³/day]	[%]
1	43.0	48.3	-11.0
2	42.7	46.0	-7.1
3	49.3	47.2	+4.3
4	53.6	56.8	-5.6
5	51.0	54.6	-6.6
6	55.2	58.7	-6.0
7	54.8	57.6	-4.9
8	57.0	60.9	-6.4
9	58.6	62.1	-5.6
10	49.3	55.2	-10.6
11	47.4	51.6	-8.2
12	43.3	46.7	-7.2

Table 4.1: The monthly average water volume of the Oldenburger PVP-system predicted by the detailed simulation model presented in Fig. 4.1 and by a simplified model which is commonly utilized in PVP-system dimensioning.

Table 4.1 shows that the differences in monthly water output predicted by the detailed model and the DASTPVPS simulation are in the range from -11% to +4.3% with an annual deviation of 67%. In general, the simplified model predicts higher values of system water output than the detailed model developed in this work. This may be explained by the fact that it does not consider the dynamic interactions of the system components as the detailed model does. On

the other side, considering that the DASTPVPS software is quite easy to be used, needs only information which are normally available from fabricants of PVP-systems hardware, and that its computation time is relatively short, it can be said that it is perfectly acceptable for lay-out processes in the practice, but for any deep analysis of operational system behavior it has limitations.

4.4.2 Comparison with a Simulation Method based on the Solar Utilizability Concept

The concept of solar utilizability (Φ) was first introduced in the solar technology as an aid to predict the long term performance of solar thermal systems [12]. In the last years, the use of the utilizability concept has been extended to predict the performance of photovoltaic energy systems, with some authors making use of this method for the design and analysis of PVPsystems [29,7,3,23]. In a solar collector, the critical level would be the insolation threshold, over which the system starts to produce useful heat; in a PVP-system, the critical level would be the insolation threshold of the pumping system, i.e., the intensity at which the system starts to pump water. In a simple case, where the pumping rate is linearly related to the insolation, the pump output is proportional to the utilizability value corresponding to a critical value equal to the threshold of the system. For a nonlinear pumping rate, the analysis is more complex.

In a study conducted by CastroVilela in [8], a simple algorithm based on the utilizability function for estimating long-term performance of PVP-systems has been derived, which permits the analysis of systems characterized by a nonlinear relationship between pumping rate and insolation, including the linear systems as special case. The method proposes a general mathematical solution, with which physical quantities like water flowrate and hydraulic power can be integrated along the time. The analysis assumes that the relationship between flow rate and insolation of the system is known, or can be obtained by theoretical calculation and uses monthly average insolation as input data. The derivation of the method is described with details in [8], but here a summary of the methodology utilized should be given in order to illustrate the basis of the calculations done in the present work.

Solar radiation utilizability is defined as the fraction of total radiation incident on a surface that exceeds a specific intensity level called the critical level, and can be calculated for a solar collector directly from radiation time series as proposed by Klein [20] in the following function,

$$\Phi(I_c) = \frac{\frac{1}{n} \sum_{i=1}^n \int_{t_{c-}}^{t_{c+}} (I_{col} - I_c)^+ dt}{\frac{1}{n} \sum_{i=1}^n \int_{t_{c-}}^{t_{c+}} I_{col} dt}$$

where,

n number of days in the period considered (month/year) I_{col} hourly radiation values incident on the collector (W/m²)

 I_{col} hourly radiation values incident on the co I_c critical radiation level (W/m²)

 t_{c-}, t_{c+} surrise and sundown on the collector (s)

The index ⁺ in the formula indicates that only positive values of $(I_{col} - I_C)$ are considered in the sum. The sum extends over n time steps of duration Δt in the period considered for the balance. The numerator represents the sum of the total radiation which is above the critical level, and the denominator is the sum of all radiation incident in the plane of the solar converter.

According to Gordon in [14], the utilizability function should obey the following properties:

$$1) \quad \Phi(I_c = 0) = 1$$

$$2) \quad \Phi(I_c = I_{\max}) = 0$$

3)
$$\frac{d\Phi}{dI_c} = \frac{-t_{op}}{t_d}$$

4) $\frac{d^2\Phi}{dI_c^2} = P(I_c) \ge 0$

where t_d is the average duration of the day in the given period, t_{op} is the time of operation of the system and $P(I_c)$ is the probability distribution of I_{col} .

Making use of the above listed mathematical properties of the utilizability function and considering that the flow rate or the hydraulic power of a solar pumping system can be described as a function which depends on the level of solar radiation and that the latter is a stochastic variable dependent on time, a generic form of this function was suggested by Vilela [8], which can be written as

$$F = t_d \int_{X_c}^{X_{col,\max}} f(X)P(X)dX$$
(4.3)

where X is a dimensionless parameter given by $X = \frac{I_{col}}{I_{col}}$, with I_{col} being the monthly average

of the hourly radiation.

According to the property (4), the second derivate of the utilizability function gives the distribution of probability of the solar radiation on the plane of the PV-array as

$$P(X) = \frac{d^2 \Phi}{dX^2} \tag{4.4}$$

Inserting expression (4.4) into equation (4.3), the quantity F can then be written as

$$F = t_d \int_{X_c}^{X_{col,\max}} f(X) \frac{d^2 \Phi}{dX^2} dX$$
(4.5)

Taking into account that a function $f(I_{col})$ must be zero for $I_{col}=I_c$, the dimensionless function f(X) can be written as

 $f(X) = (X - X_c)g(X)$, where g is any function of X.

Solving equation (4.5) by partial integration, for an appropriate f(X), a general solution could be found, which was used to calculate pump system parameters as mechanical energy or pumped volume, for instance. For this, the pump water flow rate was assumed to be approximated by a second grade polynom, which is equal to zero for X=X_c and can be written as

$$Q(X) = f(X) = a + bX + cX^2$$

Finally, the monthly average daily volume is calculated by the following expression:

$$V = t_d [g(X_c)\Phi(X_c) + 2\int_{X_c}^{X_{col,max}} g'(X)\Phi(X)dX] = t_d [(b + 2cX_c\Phi(X_c) + 2c\int_{X_c}^{X_{col,max}} \Phi(X)dX]$$
(4.6)

where the utilizability factor $\Phi(X_c)$ is determined by using a simplified functional formula proposed by Collares Perreira et al. in [7].

Using the above described algorithm in a simulation program, calculations of the characteristic values of a PVP-system with the same configuration of the reference system installed in Oldenburg (see Table 2.1) were carried out. As a result of the calculations, Table 4.2 presents the monthly average water volume in comparison with the values obtained with the detailed model developed in this work.

Month	Detailed model	Utilizability method	Deviation
	Monthly average volume [m ³ /day]	Monthly average volume [m³/day]	[%]
1	43.0	46.8	-8.1
2	42.7	50.0	-14.0
3	49.3	53.2	-6.6
4	53.6	58.8	-8.8
5	51.0	57.6	-11.4
6	55.2	59.7	-14.5
7	54.8	57.6	-4.9
8	57.0	62.3	-8.5
9	58.6	63.1	-7.1
10	49.3	58.2	-15.3
11	47.4	53.5	-11.4
12	43.3	45.7	-5.3

Table 4.2: The monthly average water volume of the Oldenburger PVP-system predicted by the detailed simulation model presented in Fig. 4.1 and by a simplified model based on the solar utilizability concept.

The deviations between the utilizability method and the detailed model lay in the range of 5% to 14%. The utilizability predicts, as the other simplified model, higher values for pump output, which may be explained by the fact that it uses monthly average insolation as input data and that it does not consider the dynamics of the well. Considering the simplicity of the method and the economy in computer time, the results in Table 4.2 show that the use of the utilizability concept can be very useful to estimate long-term system output. The method is still an approximation, but can perhaps be used in the preliminary design phase of PVP-plants

applications, for estimating its potential at a specific location for which limited data are available. For a more deep investigation of system behavior however, the method has limitations.

4.5 Towards PVP-Systems Optimization

4.5.1 Components Efficiency

The assessment of energetic losses at component level of the reference PVP-system performed in the previous section have shown that the annual losses in the motor and pump units are dominating after the losses in the PV-array. As already mentioned, any improvement done in these system components, which correspond to only about 10 % of the total cost of the system, would contribute to overall efficiency. Improvement of overall efficiency would imply the need of less photovoltaic modules which are responsible for the highest part of the investment involved in the applications of solar pumping systems (without considering the well). The search for possibilities to increase motor and pump efficiencies and system efficiency in general has been the subject of several authors [15,32,5,3]. Most of these autors agree that changes in the design parameters of existing motors and pumps are the main points to be assessed in order to enhance efficiency. Concerning efficiency Hermann in [15] suggests a series of technical measures which would bring about 5 % more in pump and motor efficiencies. Similar procedures are recommended by Whitfield [32] and Koner in [21].

Besides the improvement in motor and pump, improvements in power conditioning devices are also important to increase PV-pumping system performance, but due to the high level of efficiency already attained (maximum over 95 %) for such devices as inverters or DC power regulators for PVP applications, the chances for improvement in this area are small and probably only possible through the implementation of new semiconductor elements.

Parallel to efforts towards improvement of the individual components of a PVP-system, an important task in system optimization has to do with the improvement of efficiency of the system as a whole, that is, to find the best coupling efficiency between the load and the PV-array. Concerning this topic, the experimental and analytical analysis of two maximum power point tracking methods done in the present work revealed that, although the nominal efficiency of a fixed voltage control is somehow lower than the efficiency of a MPP-tracker, the real gain in efficiency that could be obtained with the use of a MPP-tracker seems to be not so significant as expected (see flow diagrams in Figure 4.14).

The fact just mentioned speaks, a priory, favorably for the fixed control technique for PVPsystems, even more if one also considers the lower energy consumption and the low price if compared to a MPP-tracker. However, users must be very careful with the operation of a fixed voltage control. It is extremely important to set the right DC-voltage for the irradiation levels prevailing at the site of application. Errors in the setup can lead to inefficient system operation, with large losses in PV-energy utilization as demonstrated in section 2.2.1 of this work. An optimal adaptation of voltage range made for the PV-array in the experiments realized on the reference PVP-system installed in Oldenburg, produced an improvement of about 7 % in array energy utilization. This experience points out that the apparent economic advantage of a fixed control tracker has to be confronted with the simplification in PVP- system operation offered by a MPP-tracker, especially if the system is to operate in remote areas where there is no specialized staff.

Another approach to attain higher PVP-systems efficiencies is to look for alternative systems concepts. Slow speed motors and more efficient displacement pumps can substitute the standard AC-motor and centrifugal systems. In the course of the last years the importance of brushless DC-motors (BDC) has been steadily increasing as electrical drive for photovoltaic pumping systems. Displacement pumps are pointed out by several researchers as one of the most interesting alternative to centrifugal pumps, due to their deep well pumping advantages [34,19]. Combinations of a BDC motor and a progressive cavity pump are commercially available by pump manufacturers in Australia and in France with nominal efficiencies above 6%, and are considered nowadays the most concrete new concept for PVP-system applications [19,33,34].

4.5.2 Alternative System Concept: BDC-motor and Progressive Cavity Pump

We investigated the operation of a system composed of a BDC-motor and a progressive cavity pump under field and laboratory conditions. As with the AC-system, a complete simulation model was developed and simulation calculations were made with the model. Details of this investigation are presented by Genthner in [13], here the main results of the simulations are presented and a comparison with the investigated standard AC-system configuration is made. The system technical specifications are presented in Table 2.1, in chapter 2 of this work, and the scheme of the simulation algorithm is presented in appendix E.

Simulation Results

Figure 4.13 presents one day course of the simulated and measured pump output in the upper diagram, and the calculated absolute deviation between them in the lower diagram. The simulation time step was one minute, which was also the time step of the measurements. The chosen day was the 19th April of 1996 and at this day a 2.44 kWh of electric energy was supplied to the subsystem (motor +pump + electronics) and a total pumped water volume of 16.09 m³ was measured. The simulated daily water volume was 15.87 m³.

The average deviation between simulated and measured water flow rate was found to be 0.06 m³/h as can be taken from figure 4.13. The somewhat higher waterflow measurements at the first hours of system operation is a systematic measuring error due to the empty pipes at the beginning of the day. As can be seen in the diagram, in the middle seven hours of system operation the deviations are less than 3 %, being even 2.5 % at the middle of the day. Considering that by extreme values of the measured interval there are effects which are not considered in the model equations, the simulated values are in excellent agreement with the measured ones.



Fig. 4.13 Simulated and measured water flow rate for the PVP-system composed of a BDCmotor and a progressive cavity pump. In the upper graph the thick curve represent the measured values and the thin curve the simulated values; the lower graph presents the deviations between simulation and measurements.

In the following the results of the simulated long term performance utilizing the model will be analyzed and compared to the results from the reference system (AC-motor driving a centrifugal pump) in order to identify the differences in efficiency and loss mechanisms occurring in these systems.

Annual Performance and Comparison to the Reference System

The results of the simulations of the annual performance of the BDC- system are presented in the form of an energy flow diagram in figure 4.14. For the sake of comparison the energy flux diagram for the AC-system is also presented in this figure. The series of input data for the calculations for both systems are identical (hourly values of irradiation and temperature of Lagoa das Pedras, in the Northeast of Brazil). The mean irradiation was 5.3 kWhm⁻² d⁻¹ and the mean ambient temperature was 27 °C. Both hydraulic systems were designed to match the nominal operation of the subsystems.



Fig. 4.14: Comparison of the energy flow diagrams of two PV-pumping system concepts. The values inside the diagrams correspond to the amount of energy left after each energy conversion step, normalized to the nominal PV-array energy at STC (E_{STC}). The values on the sides of each diagram give the efficiency of the correspondent component. E_{OUT} describes the net hydraulic energy produced by the system.

The annual performance ratio (PR) for the BDC-system (system 1 in Figure 4.14), calculated according to the definition given in section 4.3.1 was 48%, while for the standard system configuration (system 2 in Figure 4.14) it attained 21 %. The PR values serve as a measure for the overall system performance. Analyzing the losses at component level shows:

The largest share of the losses between E_{STC} and the useful PV-energy E_{PV} in both diagrams is due to operation at conditions different from STC, namely temperature and irradiation effects (about 13 %); as well as spectral, reflection and mismatch losses (about 7 %).

In centrifugal pumps a minimum rotational speed of the impeller is required to generate the necessary pressure head. As the diagram for the AC-system shows, this implies that 7 % of the DC power cannot be transformed into hydraulic power (threshold). A progressive cavity pump on the other hand needs a high starting torque, which in this case is overcome by the motor thanks to its electronic power conditioning unit, that solves the problem at very low electric input power. Therefore the threshold in the DC-system results in losses of only 1 %.

The inverter losses are in the range of 8 % of its power input for the AC-system. The power conditioning of the DC-system and the correspondent losses is included in the motor unit.

The main losses (core losses and copper losses) act in the asynchronous motor in both rotor and stator while they occur in brushless motors (BDC) only in the stator. This is the main reason why motor losses in the diagrams amounted to 33% for the asynchronous motor, while they were only 10 % for the BDC-motor.

Hydrodynamics losses are the main losses in the centrifugal pump and they increase with the second power of the pump speed. Beside this, centrifugal pumps need relatively high speed to overcome system head. In a progressive cavity pump the main losses are due to friction between rotor and stator. These losses are almost linear with the rotational speed of the rotor. The result of these different characteristics can be seen in the energy flux diagrams above, where the progressive displacement pump attained an efficiency of 69 % which is significantly higher than the centrifugal pump which reached only 49 %.

In the simulation calculations both hydraulic systems were designed to have an efficiency of 97 %.

The results above discussed demonstrate the superiority of a BDC-motor/progressive cavity pump system over the standard asynchronous motor/centrifugal pump system, in an energetic point of view. The efficiencies encountered for the former system are confirmed by other authors, as for example by Wichert in [34] and Lawrence et al. in [22].

The final decision for one or the other PVP-system concepts depends of course on the type of application, but the financial aspects must be considered. Calculations done for both PVP-system concepts analyzed in the present study revealed that although the subsystem of the standard AC-system has a much more favorable price than the BDC-subsystem (about 45 % less investment costs per m^4/d), its poorer efficiency will demand more PV-panels for the same application, and this additional cost makes finally the price per m^4/d of the complete BDC-system about 15 % less than that of the actual standard system [13]. These results have shown the great potential of PVP-system concepts based on BDC-motors/screw pumps. Availability on the market is still an open question, and it is necessary that more long-term field tests with such systems to be undertaken in order to support the enlargement of their production.

4.5.3 Sensitivity of a PVP-system to a Change in Geodetic Head

An aspect which is not directly connected with the optimization of a PVP-system, but that must be considered in the search for optimization in the design of such systems, is the sensitivity of the system efficiency to a change in water head. The relation between these two parameters has to be well analyzed not only because of the efficiency aspect, but also because changes in water level can occur during the year and the operation of the system at a head much bigger than the design head (in case of larger drawdowns, for instance) can exceed the limits of the well capacity and probably damage it.

For the two PVP-systems configurations analyzed in this work, a sensitivity analysis concerning changes in system head has been performed [13]. The results are presented in Figures 4.15 and 4.16 below.

Simulation runs, utilizing both models were carried out, in which the system head was varied from 50 to 150 %, where 100 % means a head of 30 m for the BDC-system (system 1 in Figure 4.15), and a head of 15 m for the AC-system (system 2 in Figure 4.15). For the simulations, minute average data of solar radiation based on a Standard Solar Day with a daily irradiation of 5 kWh/m² and 11 hours sunshine duration was used. The temperature was taken as constant at 25° C.

As results of the simulations, the daily water volume against head, for both systems, is presented in Figure 4.15. For a constant efficiency, the curves would be inversionally proportional to the head. In Figure 4.16, the system efficiency of both systems are showed as a function of the head.



Fig. 4.15: Simulated daily water volume as function of the relative system head. The relative head of 100 % corresponds to 30 m for system 1 (BDC-motor/screw pump) and 15 m for system 2 (AC-motor/centrifugal pump). (source: [13]).



Fig. 4.16: Simulated efficiency of both PVP-systems as a function of the system head. The thick curve represents the efficiency of system 1 (BDC-motor/screw pump) while the thin curve represents the efficiency of system 2 (AC-motor/centrifugal pump).

As showed in Figure 4.16, the efficiency of system 1 increases steadily with the system head. This behavior was predicable, since in this case one is dealing with a displacement pump. This type of pump operates with maximal efficiency at higher heads, because at large heads its rotational speed diminishes, which leads to higher torques. At lower heads, it behaves the opposite. This result shows that progressive cavity pumps are quite insensitive to changes in system head, and because they work best in the upper part of its operation interval, it is specially appropriate for system with high heads.

On the other hand, centrifugal pumps are very sensitive to variations of system head as the curve of system 2 in Figure 4.16 shows. This curve demonstrates the typical behavior of PVP-systems based on centrifugal pumps, for which the efficiency diminishes when operating in conditions different from its nominal operation interval. This behavior is an effect of an increase of the shock losses caused by variation from nominal rotational speed. Another effect from increase in system head in centrifugal pumps, is an increase of the power threshold of the system, as has been demonstrated earlier in chapter 2 of this work.

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5 Evaluation of Real Application Experiences with PVPsystems

5.1 Introduction

As with the majority of photovoltaic systems, the performance of a PVP-system operating in the 'real word' is influenced by several factors, intrinsic and extrinsic to the system itself, which normally contribute to deviations from projected system behavior. Besides the pure technical aspects like plant layout configuration, component efficiencies or the climatic characteristics of the place of location of PVP-systems, the cultural and economics aspects, in some cases, can be the main constraints for the system not achieving its expected performance, what in many cases leads to acceptance problems or even to complete failures in the application of the PVP-technology.

In chapter 1 of this work, an overview of the most recent and important experiences with PVP-projects in different parts of the world was given. From these experiences it has been concluded that despite of all efforts put into measurement campaigns and operational data analysis in these projects, there was still a need for a more in-depth investigation of the performance of existing PVP-plants, in order to obtain information and resources to promote performance improvements in existing and in future applications of photovoltaic pumping technology. This requires that installed systems are monitored and evaluated in a systematic way in a wide variety of situations, necessitating the use of an evaluation methodology which can be generally accepted.

In this chapter, a systematic method to evaluate the performance of existing PVP-systems is proposed and applied in the evaluation of the long-term performance of solar pumping systems operating in the Northeast of Brazil. The method is based on simulation calculations and measured data sets from the plants. Energetic analysis, similar to the ones performed in chapter 4 for the experimental setup, are carried out, permitting to identify and quantify systems losses. In this way, possibilities for performance optimization can be assessed. A distinction between technical and non-technical problems affecting system operation can be made with the method.

As important part of the method, a comprehensive analysis of general problems concerning the introduction of PVP-technology in remote areas is made, based on the brazilian experience in the frame of the GTZ PV-pumping project. This analysis encompasses social-economic aspects as well as organizational and technical ones.

The chapter starts with a general description of the evaluation procedures and then, the technical characteristics of the selected plants are given. Following, the preparation of the data sets that will be used as input for simulation and analysis is presented and the approach taken for the modelling of the systems is discussed. The results of the simulation are analyzed and compared to measured data. In the next step, important aspects of field experiences are addressed. The chapter ends with recommendations for lay-out and analysis of PVP-systems.

5.2 Evaluation of Measured Data with the Help of Computer simulation-An Analytical Evaluation

5.2.1 The Method

On the basis of the available operational data a comprehensive evaluation of the performance of some selected PVP-plants will be carried out in a systematic way by analyzing monitored data with the help of numerical modelling. The methodology which will be utilized for this investigation has been partially inspired by the method applied in the evaluation of the measured performance of several photovoltaic plants within the frame of the Measurement and Documentation Program (MuD) implemented by the German Federal Ministry for Education Research and Technology (BMBF) at different locations in Germany [1]. The method, originally developed for photovoltaic electrical systems (only PV-generator and inverter performance), will be here extended to PVP-systems, i.e., encompassing also the mechanical and hydraulic characteristics, besides some non-technical aspects which influence the system performance.

The backbone of the evaluation is the modelling and simulation of the operational behavior of the selected PVP-systems. Analogous to the analysis performed in chapter 4, results of the simulation calculations will permit that most steps of energy losses inherent or external to the system to be traced and, where possible, quantified. This procedure will produce rated values for the interpretation of the system energy conversion steps ,which are based on the system configuration lay-out, the characteristics of its components and the meteorological characteristics of the site of location.

The comparison of the numerical simulation results with the measured operation data permits an assessment of the real system behavior as well as to distinguish the avoidable losses from the unavoidable losses occurring in the system. Besides this, the comparison will also serve to validate the simulation model. Therefore, the accuracy of the models and predictions of systems performance can be improved. Finally, the results of this analytical evaluation will produce elements for recommendations concerning measurements, assessment, dimensioning and operation of PVP-systems technology in the future.

Figure 5.1 summarizes schematically the main steps of the evaluation method.



Figure 5.1: Different phases of the evaluation of field data from the selected PVP-systems (adapted from [1]).

As illustrated in Figure 5.1, the evaluation of the system performance will be done in 3 main steps:

- 1. in a first step the raw data will undergo consistency and plausibility checks before they can be used as input for the simulation calculations;
- 2. the data-set that survived the 'cleaning process' mentioned in step 1 will be further analyzed and used as input for the simulation of the system. The comparison between the simulation results and the measured data allows that possible system weaknesses can be detected;
- 3. the raw data which was excluded in step 1, but are relevant for the understanding of the plant performance will be analyzed and, when possible, quantified.

To check for the internal consistency of the data base mentioned in item 1, a computer program was developed with which the raw data has been first read and according to defined criteria, errors caused by sensor offsets and calibration values , by missing data or for measured values which seem to be completely irreal are identified and filtered.

The data set will then go through plausibility checks, in which it will be investigated if, for example, the measured values of the PV-generator power is in accordance with the measured irradiation and module temperature, and if the values of the pump output are within the expected range at different irradiation levels (± 10 % of the design value).The procedure to

determine plausible limits for the DC-power was based on the method developed by Wiemken et al. and is well documented in [1] and [3]. The limits for the system output were defined based on the values (rated values) of the initial acceptance tests of the pumps, carried out by TÜV and GTZ, prior the time of installation of the systems [10].

The simulation calculations of the system operational behavior and the comparison with the measured data are based on data from which some periods have been filtered out in the first step (if not mentioned otherwise). These periods, represent times where evident unsystematic distortions of the system power appear, which have been caused by plant outages, component failures, errors in the data acquisition and measuring sensors, as well as short time operation troubles due for example to shadowing of pyranometers, by errors which occurred within the averaging interval, by control problems of the MPPT, etc. This new data set is shorter than the original data, since it contains only periods free from disturbances in system operation and in the data acquisition process. In this way, this new data represents sort of 'normal' or 'expected' operation conditions, without meaning that it represents also optimum operation mode, since eventual permanent system operation disturbances, which will only be detected in further stages of the evaluation, are still part of the data.

Finally, the data set which was filtered out by the plausibility check will be also analyzed, since these data may contain important clues to explain system performance, but due to their nature cannot be reproduced by computer simulation.

5.2.2 The Selected PVP-systems and the Sites Meteorological Conditions

From the five PVP-systems installed in Brazil, which were automatically monitored in the PVP-project executed by GTZ, two were selected for detailed analysis in the present work: the systems installed in the villages of Lagoa das Pedras and in Cajazeiras.

The reason for this selection was in the first place the availability and quality of the data. As it will be made clear in the next sections the monitoring program in Brazil was in general very problematic. The many data gaps and errors in the measurements happened there make the handling of the data a very careful and time consuming task in order to avoid false conclusions. For some of the plants only a couple of months of data are available.

Apart from the above criteria, the system installed in Cajazeiras had the highest availability of measured data and there occurred no changes in the system configuration in the time period for which measured data are available. On the other hand, important variables like temperature and inverter frequency were not measured in this system. In the system at Lagoa das Pedras, these measurements are available but the addition of two more PV-modules in the middle of the measurement campaign does not allow enough continuous data for a long term (a year, for instance) evaluation.

Thirdly, the operational behavior of these two plants are representative of the majority of the other 13 plants installed in Brazil regarding PV power peak installed (12 out of 13 PVP-systems installed are designed for generator power between 700-800Wp) and system heads (static heads from 15-40m). Besides, the environmental, social and economic conditions are also very similar.

Meteorological Conditions

Lagoa das Pedras and Cajazeiras lie at latitudes 3.9° and 4° south and longitudes 40° and 39° 20' west and are located in one of the most dry regions of Brazil. April to November is normally the dry season and the wet season is from December to May (when there are no droughts, what is very common in this area). The daily solar irradiation on a horizontal surface is in average between 4.3 kWh/m²d and 5.8 kWh/m²d. The annual average temperature is 28°C.

Figure 5.2 shows the monthly average solar energy collected on the horizontal surface for Cajazeiras (average of 3 years, from 1992 to 1994).



Fig. 5.2 Solar energy collected on the horizontal surface at the location Cajazeiras in the Northeast of Brazil (averages from 1992 to 1994).

Systems Description

The selected plants were installed between 1990 and 1991. Figure 5.3 presents schematically the configuration lay-out of these systems and Figure 5.4 shows how the system in Cajazeiras looks like in the reality. All the systems installed in Brazil are composed of a PV-generator, a DC/AC-inverter, a centrifugal pump driven by an asynchronous motor and a deep well.



Fig. 5.3 Scheme of the PVP-system in Lagoa das Pedras and in Cajazeiras, Brazil

Fig. 5.4 View of the PVP-system installed in Cajazeiras. In the foreground, the pipework and the water fountain can be seen. In the background, the storage tanks with the PV-generator installed over them are shown.

Technical Data and Monitoring of Selected PVP-plants

Table 5.1 summarizes the components technical data (design data) from the two systems which will be closely investigated in this work.

The monitoring systems installed in the brazilian PVP-systems are standard systems similar to all systems utilized by GTZ in the other 6 countries involved in the international PVP-demonstration program. Five pumping stations were monitored automatically, with a PC-based data acquisition system (data logger MODAS-1220, from the company NES, Germany) for about five years. The time resolution of measurements for all systems was 1 sample taken every 2 seconds, with average output every 10 minutes.

Table 5.2 summarizes the variables that are monitored and the devices that are used to measure them. Here only the variables that are relevant for the investigations that will be carried out later in this work are shown. The monitoring system in question was installed in Lagoa das Pedras; in the other measuring stations, including Cajazeiras, the inverter frequency, the ambient and panel temperatures, the wind speed and the irradiation on the horizontal plane were not recorded. Besides the measured variables presented in table 5.2, the data logger also records calculated variables in special channels, like the PV-generator power, the hydraulic power and the system/component efficiencies.

global irradiance(horizontal) $[W/m^2]$ Kipp CM11 pyranometerca. 3 %global irradiance(inclined) $[W/m^2]$ Kipp CM11 pyranometerca. 3 %ambient temperature $[^{\circ}$ C]thermoresistance PT-100ca. 1°Cpanel temperature $[^{\circ}$ C]thermoresistance PT-100ca. 1°Cwind speed $[m/s]$ anemometerca. 2 %PV-generator voltage $[V]$ voltage dividerca. 0.5 %PV-generator current $[A]$ shunt resistanceca. 0.5 %inverter frequency $[Hz]$ signal transformer + digital countervery accuratewell water mirror $[m]$ pressure sensorca. 1 %water flow rate $[m^3/h]$ water counter with Reed-contactca. 2 %	<u>Variable</u>		Measuring device	<u>Measurement</u> tolerance
in a contract and the second contact and the	global irradiance(horizontal) global irradiance(inclined) ambient temperature panel temperature wind speed PV-generator voltage PV-generator current inverter frequency well water mirror water flow rate water requirement	[W/m ²] [W/m ²] [°C] [m/s] [V] [A] [Hz] [m] [m ³ /h] [m ³ /h]	Kipp CM11 pyranometer Kipp CM11 pyranometer thermoresistance PT-100 thermoresistance PT-100 anemometer voltage divider shunt resistance signal transformer + digital counter pressure sensor water counter with Reed-contact water counter with Reed-contact	ca. 3 % ca. 3 % ca. 1°C ca. 1° C ca. 2 % ca. 0.5 % ca. 0.5 % very accurate ca. 1 % ca. 2 % ca. 2 %

Table 5.2: Overview of the variables that are monitored and the corresponding measuring devices as implemented in the PVP-system installed in Lagoa das Pedras, Brazil.
Component/Parameter	<u>Unit</u>	Lagoa das Pedras	<u>Cajazeiras</u>
Daily water demand	[m³/d)]	4.7	15
Hydraulic equivalent	[m ⁴]	182	360
Total pumping head	[m]	36.4	24
Well/Tank Characteristics			
Borehole depth	[m]	70	60
Drawdown at Q _{max}	[m]	28	16
Well diameter	[inches]	6	6
Height of water tank	[m]	4	4
Water tank capacity	[m]	10	25
Distance well-tank	[m]	2.5	8
PV-generator characteristics		Siemens M50	Siemens M50
PV-power installed	[Wp]	800	700
PV-array area	[m ²]	5.76	5.04
modules series/parallel	-	8s/2p	7s/2p
open circuit voltage	[V]	172	151
MPP voltage	[V]	118	104
MPP current	[A]	6	6
Inverter		Grundfos SA1500	Grundfos SA1500
Output voltage	[V]	100-140	100-140
Maximum power	[kW]	1.5	1.5
Minimum operation voltage	[V]	100	100
Motor	Grundfos	Grundfos	Grundfos
Nominal Electrical Power	[W]	550	550
Pump	Grundfos	GF SP 8A-5	GF SP 5A-7
Delivery head range	[m]	2-28	2-50
Pump depth	[m]	36	21

Table 5.1: Technical data of the PVP-systems installed in Lagoa das Pedras and Cajazeiras in the frame of the PVP-project executed by GTZ in Brazil [source: GTZ].

5.2.3 Selection of the Data base

Data for a period of 3 years (between 1992 and 1994) but with several gaps were made available by GTZ for the analysis. The quality of the measured data was a crucial problem for the selection of the data base. Apart from irradiation and temperature measurements, which are quite reliable, the measurement of the hydraulic quantities were very problematic and the corresponding data had to be carefully examined before any interpretation could be done.

Prior to the plausibility check mentioned in section 5.2, a careful control check of the original data was performed based on some information documented by the systems operator (unfortunately an operation log book was not available). This reduced dramatically the time period which could be used for further evaluation. After this first check the time period selected for evaluation of system was:

Cajazeiras: September 1992 - December 1992 ; January 1993 - August 1993

In these time periods there are the following data gaps: 6 days in Nov/92, 0.5 day in Dec/92, 1 day in Jun/93 and 8.5 days in jul/93. These gaps are normally assumed as 'missing data' by GTZ, the reasons are not documented, but the most probable explanation is that the data transmission from the logger was not done on time (the Modas-logger stops reading the data when its memory is full). These data gaps mean that only about 11.5 months of data is utilized in the investigation. These data sets went then through the plausibility check aforementioned in section 5.2 and this procedure resulted in further reduction of the data.



Fig. 5.5 Monthly availability of the new data set after consistency and plausibility checks. The first eight months are from the year 1993 and the last four from 1992. This data set represents normal (acceptable) system operation and will be used in the analysis and simulation of plant operation.

Figure 5.5 gives the monthly availability of the new data set after consistency and plausibility checks, and Figure 5.6 shows that for the entire time interval of one year about 87.7 % of the original data survived the filtering process. If not mentioned otherwise, this is the data base which will be used for simulation calculations and evaluation of operational data in the following sections.



Fig.: 5.6 The operational data undergoes consistency and plausibility checks before simulation. The new data set obtained (87.7 % of original data) represents normal system operation, or at least with no apparent trouble. One record contains 6 sets of data, because data were recorded every 10 minutes. This new data set is further analysed and compared to the simulated values.

As illustration of the effect of the filtering process on the original data base, Figure 5.7 shows measured values of the photovoltaic generator power plotted against the corresponding irradiation values for the PVP-system in Cajazeiras for a period of 3 months. In this figure, the values marked with the symbol ' \Diamond ' represent the data values that survived the plausibility check and will be used for analysis and simulation calculations. In the entire period analyzed they amount to 87.7 % of the original data, as shown in figure 5.6. above. The values marked with the symbol '+' make up the 12.3 % which were discarded by the 'cleaning' process.



Fig. 5.7: Illustration of the procedure for the filtering of the raw data for 3 months measured data for the PVP-system located in Cajazeiras, Brazil. The array output power (P_{dc}) is plotted against the irradiation. The values which lie within the plausible operation limits are marked with ' \diamond ' and the values outside the limits are marked with '+'. Only the data within the plausible interval will be considered in the simulation calculations. The values outside those limits that are relevant for the evaluation will be analyzed separately.

5.3 System Modelling

Considering the fact that one of the main objectives of the present work is to suggest a method which could be generally accepted and utilized for design and analysis of PV-systems, a prerequisite for system modelling is that all input data necessary for the simulation calculations can be obtained easily, i. e., the modelling of the plant should be made based only on informations which are contained in the components manufacturers data sheets, in lay-out values and in measured operational data.

For the above mentioned reasons, the structure of the model which is utilized in the present investigation differs from the approach taken for the simulation model developed for the PVP-system installed at the University of Oldenburg, in the sense that the inverter, the motor and the pump are considered as one unit and are described by a single characteristic, that it will be explained later in section 5.3.2. The model is in this way simplified, but applicable to most commercially available PV-pumping systems and still enough accurate for the objective of the proposed evaluation method.

Figure 5.8 summarizes the input data necessary for the simulation model. Besides the layout data of the PVP-plant, the characteristics of the system components contained in data sheets from manufacturers and some assumptions of system losses, time step measurements of the system meteorological parameters as Global Radiation and Ambient Temperature will be utilized in the simulation calculations. The model outputs will be energy yield values, system losses and system efficiencies for the chosen time period in different resolution (hourly, monthly, yearly, for example).



Fig. 5.8: Simplified block diagram of the simulation model, showing the input and output data that are utilized.

5.3.1 The PV-generator

The model used for the PV-generator output was already presented in chapter 3. The parameters necessary for the model can be obtained from the typical I-V characteristics of the modules which are available in the manufacturer data sheets. For the majority of PV-modules existent in the market these parameters are already available in INSEL [19]. A procedure to determine these parameters can also be found in Pukrop [16].

Table 5.3 summarizes the set of parameters for the solar module SM 50 utilized in the simulation of the PV-generator of Cajazeiras, and figure 5.9 shows ,as illustration, the I-V characteristic of one module for different radiation levels calculated with INSEL parameters compared to the values taken directly from the manufacturer characteristic.

To calculate the real output power, the same assumptions for the losses discussed in detail in chapter 3 were also made, so that I-V-characteristic mismatch, reflection and spectral losses, MPP-mismatch, losses in diodes and cables are taken into consideration in the calculations.

Parameter	Value	Unit
	0.306	\mathbf{V}^{-1}
C ₁	0.179E-04	$V^{-1} K^{-1}$
C ₀₁	1.708E-04	$A m^{-2} K^{-5/2}$
C ₀₂	1.880	${\rm Am}^{-2}{\rm K}^{-5/2}$
r _s	1.381E-4	Ωm^2
r _{Sh}	0.130	Ωm^2

Table 5.3: Specific parameters for the model of the I-V characteristic of the PV-module SM 50 utilized in simulation of the PVP-systems under investigation in this work.(source: INSEL manual[16])



Fig. 5.9: I-V characteristics of the PV-modules S M50 at module temperature 25 °C, with values of insolation from 200 to 1000 W/m². The points marked '+' were taken from module data sheets provided by the manufacturers. The solid lines represent the output calculated with the model.

5.3.2 The Subsystem (Inverter, Motor and Pump)

The term 'subsystem', which will be further utilized in this investigation, is largely utilized in the literature of PVP-systems to describe the part of the system composed of inverter, motor and pump. In the data sheets of the manufacturers these three components are characterized as a unit by the so called 'instantaneous output ' characteristics of the pump system. These characteristics display the relationship between water output (Q) and the inverter input power (DC power) with the head as parameter $Q(P_{dc},H)$ and encompasses the essential informations about the operational behavior of the complete subsystem. There is no separate information about each component, so that a quantitative description of them is not possible, as it was

realized with the components of the reference system analyzed in chapter 4 of this work, where each characteristic was obtained through detailed laboratory tests.

The subsystems of the PVP-plants investigated in this work are composed of motor-pumps type SP 5A-7 and SP 8A-5 from the company Grundfos and inverters type SA1500 of the same manufacturer. In Figure 5.10 the subsystem characteristic provided in the data sheet for the pump SP 5A-7 is shown. The modelling of the subsystem under investigation was based on data from the pump characteristics measurements made by TÜV, however a simulation run utilizing data directly from the characteristic shown in figure 5.10 gave very good results, what confirms the results presented by TÜV in [21].



Instantaneous Output

Fig. 5.10: Data sheet characteristics of the Grundfos motor-pump system type SP5A-7 with inverter type SA1500 utilized for the subsystem model. The pump flow rate Q in $[m^3/h]$ for different system heads is plotted against the inverter input power P_{DC} in [W] (source: Grundfos).

5.3.3 The Well and the Hydraulic System

A characteristic of submersible PVP-systems is that the hydraulic load varies with the time and pump flow rate, as a result of a permanently mutual response between the well aquifer and the pumping system. Due to this effect, in order to preview or to analyze the performance of a PVP-system one has to consider the behavior of the well during system operation. Well behavior and the model of the well used in the simulations in this chapter is presented in chapter 3 of this work by equation (3.40). The model considers the dynamics of the water table during pumping, as well as the influence of the aquifer. The hydraulic system, composed of pipework, elbows, valves, flow measuring devices, etc, produces an additional head that has to be overcome by the pump during operation. These losses are considered in the simulation calculations by the equation (3.41) presented in chapter 3 of this work. For the PVP-system under question the values of these coefficients are 4.38E- $02 [h^{2}/m^{5}]$ and 6.76E- $02 [h^{1.75}/m^{4.25}]$ respectively.

5.4 Simulations Results

5.4.1 Validation of the Simulation Model

To demonstrate the accuracy of the model, the daily course of the PV-generator output power (P_{DC}) and the pump output flow rate \bigotimes for the day 07.02.92, for the system installed in Cajazeiras, are presented in Figures 5.12 and 5.13 respectively. The time step of the simulation was 10 minutes, which was also the time resolution of the measurements.

The PV-generator Output Power

The PV-generator power was calculated with the 2-diode model utilizing measured irradiation and ambient temperature as input data. The magnitudes of the losses listed in section 5.3.1 were considered as following in the simulation of the PV-generator of Cajazeiras: 3% for mismatch [9]; 2 % for reflection losses according to [18], the spectral losses by 1% [14]. A correction of 1% was considered to for accumulation of dust on the generator surface according to [22] and the voltage drop in the bypass diodes and cables was considered as 0.9V (0.2 V for cables and 0.7 V for diode losses).

For the PVP-system installed in Cajazeiras, there was no measurements of temperature, so that the ambient temperature utilized as input to the simulation was derived through an approximation method proposed by Tegethoff in [22]. Based on ambient temperature measurements of Lagoa das Pedras (about 25 Km away), the daily profile of the temperature from sunrise to sunset for Cajazeiras was calculated by two parabolas describing respectively the ascendant and descendent branches of the temperature distribution along the day. The parabolas are described by the following equations:

$$T_{a} = \begin{cases} T_{max} - a(t - t_{max})^{2} & \text{for } t \leq t_{max} \\ T_{max} - 2a(t - t_{max})^{2} & \text{for } t \geq t_{max} \end{cases}$$

with

 $T_{max} = 34.8$ °C, $t_{max} = 830 \text{ min} (13:50 \text{ h})$, $a = 5 \cdot 10^{-5} \circ \text{C} / \text{min}^2$ Where T_{max} is the average maximum temperature and is considered as the crossing point of the two parabolas, t_{max} is the time when the maximum temperature is attained and the constant 'a', describing the curvature of the parabolas, was obtained by a square regression. Figure 5.11 shows the average temperature profile for a month of temperature measurements in Lagoa das Pedras and the calculated profile utilizing the above equation. The deviations of model and measurements earlier than 06:00 hours and after 18:00 hours are unimportant because that system is not working before and after sunset.



Fig. 5.11: Average daily temperature profile in Lagoa das Pedras from 7.5.93 to 14.06.93. *The temperature profile from sunrise to sunset is approximated by ascendant and descendent parabolas. (source: [22]).*

The method presented above gives a very good approximation for generating temperature data for locations where the distances to the reference location are not too large and the geographic characteristics of the places are similar. This is the case for the site locations here examined. Methods to generate temperature data basis from radiation data, also for places with very different geographical characteristics are also to be found in [7,16].

In figure 5.12 the simulated and measured output powers are displayed over the time.

As shown in figure 5.12 an excellent agreement was achieved between the simulated and measured PV-generator output power for the day under question. For this day a deviation of less than 2% was found between the total electric energy simulated and the measured energy. This deviation value is, as expected, in the same range of the value found in the simulation of the system analyzed in the previous chapter. The deviations in the early morning and in the late afternoon are to be explained by the increase of reflection on the module surface and higher air mass value at these times due to the smaller incidence angle of solar radiation. The differences at the middle of the day may be partly due to the uncertainties from the method utilized to generate the ambient temperature time series, part of the deviations must be attributed to uncertainties in the measurement of the radiation.



Fig. 5.12: Daily course of the PV-generator output power. The measured DC-power in 10 minutes average ($P_{DC-meas.}$) for the 07.09.92 is compared to the simulated values (P_{DC-sim}).

The Pump Output (the subsystem performance)

To show how well the model reproduces the system output, in Figure 5.13 the simulated and measured water flow rate of the pump are depicted over the time for one day (the 07.09.92).



Fig. 5.13: Measured (Q_{meas}) and simulated (Q_{sim}) water flow rate for the day 07.09.92. Both values were calculated in time steps of 10 minutes.

As can be seen in Figure 5.13, a very good agreement between the simulated and the measured PVP-system output was achieved with the simplified model. The deviations at the beginning and at the end of the pumping period can be partially explained by the high sensitivity of the simulation model for small flowrates (a small change in the centrifugal pump speed produces a high change in the pump flow rate at pumping beginning as shown in [12]), besides the inaccuracy of the measuring instrument at the low flowrates also contributes to the deviations.

The deviations in the middle of the day are partially caused by the inaccuracy in the calculation of the PV-generator output. In addition uncertainties in the calculation of the system head may have to be accounted for, especially when one considers that the parameters for the well drawdown model were obtained from operational data, since well test data were not available for this system. The calculated relative error for the cumulated water volume during the whole day was below 7 %, which is very good considering the uncertainties of the measurements and the assumptions made.

5.4.2 Analysis of the Annual Performance

As a result of the simulation calculations for the long-term, the energetic annual performance is presented in figure 5.14 in the form of an energy flow diagram. The starting point of the diagram is the annual nominal energy at standard test conditions (E_{STC}). This value is obtained by multiplying the annual irradiation on the array plane with the nominal efficiency of the modules at STC (1000 W/m², 25°C, AM 1.5). This value is treated as reference and normalized to 100 %.

A PV-generator efficiency of 77 % referred to the STC-energy was found. The annual losses when operating at conditions different from STC (temperature and irradiation effects on the module efficiency) amount to 13 %. Losses due to I/V-mismatch, reflection, spectral, cables , diodes and MPP-mismatch are responsible for the other 10 %.

The energy that cannot be used due to the low power threshold of the pump amounts to 6.2 % of the E_{STC} , so that only 92 % of the energy produced by the PV-generator (70.8 % of E_{STC}) reaches the inverter input and can be transformed into hydraulic energy.

The subsystem (inverter-motor-pump) plus the hydraulic losses produced by the pipework attains an yearly efficiency of 28 % so that the useful energy out of the system is reduced to 19.8 % of the E_{STC} energy.

The Performance Ratio (PR), already discussed in chapter 4 of this work, serves as figure of merit for the assessment of the system performance. For PVP-systems, it is defined as the net energy used by the pump to overcome the systems geodetic head $(H_{geo} \cdot Q \cdot \rho \cdot g)$ divided by the energy E_{STC} that the PV-generator would produce under STC efficiency conditions (1000 W/m², 25° C, AM 1.5). An annual performance ratio of 0.198 was obtained as value for the system configuration analyzed. This value is very close to the 21 % value from fig. 4.10 which was calculated for an equivalent system, made from components of other manufacturers and operated under the same meteorological conditions.

In Figure 5.15 the monthly unfold of the performance ratio is presented. The trend of the curve shows that the performance of the system does not vary much along the year. This result was expected, since there are no extreme seasonal changes at the site location of the system investigated. The variations of the monthly values in relation to the annual value stayed in the range of -4.0 % to +1 %.



Fig. 5.14: Energy flow diagram for one year simulated data for the PVP-system installed in Cajazeiras.



Fig. 5.15: Simulated monthly Performance Ratios for the PVP-system at Cajazeiras, Brazil.

5.5 Evaluation of the Measured Operation Data

In this and in the next section the analysis will concentrate only on the measured data set which survived the plausibility checks as it was explained in section 5.2 (see also fig. 5.1). Because of this, it is important to bear in mind that the absolute and normalized energetic values in the results of the measured, as well as the simulated performance investigations are representative of 320 days.

Because of many data gaps and uncertainties in the hydraulic data from the PVP-system of Lagoa das Pedras, the evaluation of PVP-system performance, especially for the long term period, will be mainly made for the system installed in Cajazeiras.

5.5.1 Operating Results During One Year

Table 5.4 presents the overall performance data for Cajazeiras during the period

	<u>Unit</u>	<u>Total</u>	<u>Daily</u> average
<u>Solar Energy</u> : -array plane 15°	[kWh/m²]	1086	5.3
PV array Energy:			
-actually prod.	[Wh]	610318	2529
-nominal at STC	[Wh]	805934	3179
Pumping Performance:			
-water vol. pumped	[m ³]	2971.7	11.3
-head	[m]	-	21.4
-hydraulic energy	[Wh]	152322	621

August 1992- December 1992 and January - July 1993.

Table 5.3: Operating results for the PVP-system installed in Cajazeiras for one year (during 1992 and 1993).

Figure 5.16 shows the measured monthly distribution of the pumped water volume and the consumed water volume for the same period presented in Table 5.3. For some of the months in figure 5.16, the consumed water is not presented. The reasons is that the measurements for those months were not reliable (most probably due to problems with the measuring sensor as already mentioned).



Fig. 5.16: Monthly water output and water consumption for a period of one year for the PVPsystem in Cajazeiras. The reason why there are no measurement of water consumption for some of the months shown here is explained in the text.

Figure 5.16 shows, in the months 1,5,6,7,8,9,10 and 12, that water production keeps with the water demand. $V_{consumed}$ is however systematically 5-10% lower than V_{pumped} . The reason of this behavior is probably that, as the author could observe during a visit to the site, a member of the community had been sometimes collecting water in a point before the sensor for water consumption, with the effect that at that times this sensor was sort of 'turned off' during measurement. In the months 2,3,4 and 11 one can assume total or partial failure of the water sensor $V_{consumed}$ (problems with water flow meters happened very often in the Brazilian project as could be detected by the handling of the data itself, and was confirmed at the site by the author).

The problems regarding the system dimensioning will be discussed later in connection with other aspects in the next sections of this chapter.

Energetic Balance of Measured Operation Data

The energy flow diagram of the system, as calculated from the measured operation data, is given in Figure 5.17, for the investigated time period. The starting point of the diagram is again the annual nominal energy at standard test conditions (E_{STC}). Since the meteorological data base is identical to the data base of the measured performance, E_{STC} has the same value in Watt-hour as in Figure 5.14.



Fig.:5.17 Energy flow diagram for one year measured operational data for the PVP-system installed in Cajazeiras, Brazil.

The measured energetic performance values show that about 75.7 % of the STC energy is available at the inverter input. The energy that cannot be transformed into hydraulic energy because of the threshold power limit of the pump is about 5 % of the STC energy, and the useful energy output of the system amounts to 18.9 % of the nominal energy during the year.

The energetic values in Figure 5.17, are somehow low if compared to results of investigations of similar PVP-systems as in [13] and [4] and the measured data alone do not give information whether and which losses in the system are avoidable or not. These questions and the pattern of the losses throughout the system will be discussed later in connection with the simulated results.

5.5.2 Comparison between Measured and Simulated Energy Losses through the System

In Figure 5.18, the energy flow diagrams from the simulated and measured system performance are presented together to stress the comparison between the expected and the real behavior of the system. As mentioned earlier in this chapter (see section 5.2.1), through this comparison one can 'visualize' better where the deviations occurred, if they occurred, and since the losses mechanisms are clear and quantified, measures for eventual performance improvements can be identified. From the comparison of the absolute values in the diagrams, a good agreement between simulation and measurements in the long-term performance is

again attained, as expected from the results obtained for the daily behavior presented earlier in this chapter.



Fig. 5.18: Comparison between measured and simulated energy flows through the system installed in Cajazeiras, Brazil. The data set utilized in the calculations represents 'normal' operation, i. e., when the system is operating free of external disturbances.

For a more detailed discussion of the system operational behavior along the year, the monthly performance ratios are presented in figure 5.19. A first glance at the curves shows that in general there is a good correlation between the measured and the simulated reference values. At this point, it is important to have in mind that the values of the first 8 months (1-8) are from 1993, while the last 4 months (9-12) are from the year 1992.

The comparison between of the measured and simulated performance ratios in figure 5.18 show that there are periods with operation near the expected (most of the months in the period analyzed) and periods when operation deviates more from expected, as in April and May of 1993 (months 4 and 5 in the graphic). In these months the values of the measured performance deviate by as much as 12.5 % relative to the simulated values. The reasons for these discrepancies are not clear from the measured data, but probable reasons could be accumulation of dust on the modules surfaces (with subsequent less PV-power output) or that the measured data still contain errors which could not be excluded in the filtering process.



Fig. 5.19: Comparison between the simulated and measured monthly Performance Ratios for the PVP-system in Cajazeiras, Brazil.

Figure 5.19 also shows that the performance of the system was slightly higher in the months of 1992 (9 to 12 in the graphic). This fact could be an indication of a decay in the performance of the system in the second year (1 to 8 in the graphic). This might be due to degradation of the pump after more than one year in operation. Similar behavior was showed by Baba in his investigation of PVP-systems in Tunisia [3], who found out that one PVP-system was producing about 10% less water output after 2 years in operation.

The yearly value of the measured performance ratio is about 1% (equivalent to 4% relative) less than the value obtained by simulation (see figure 5.18).

5.5.3 A Reference Simulation for 12 months

The simulation calculations presented in the previous sections were based on data corresponding to about ten and a half months of system operation due to the filtering of operation disturbances, and because of this, the results of the calculations can not exactly be considered as typical values for the long term performance of the plant. In order to estimate the magnitude of the differences in system output, caused by different operation conditions, a simulation run has been performed, using the same plant model, but solar radiation and temperature input data for an entire period of twelve months.

In Figure 5.20 the monthly water output values obtained with this simulation is compared to the original measured values, including the points which were filtered out by the plausibility check mentioned in section 5.2. From the calculations it can be deduced that an average of 7 % more water could be produced in the year if the system was operating according to the rated

values, under the given meteorological conditions. Monthly, however, differences as high as 23 % were found (month 7).



Fig. 5.20: Comparison of simulated and measured monthly water output for the Cajazeiras PVP-system. The input data for the simulation comprises 365 continuous days. The measured values are the measured data during a similar period. The differences between simulated and measured values represent the amount of water which could have been produced if the system was working free of problems.

Figure 5.20 shows that the greater differences in water output happened in months 6,7,and 11. This can be explained by the fact that for these months some data were missing, as detected by the control checks discussed in section 5.2.2. In the other months, the differences reflect the effect of problems with data acquisition and restricted operation of the system (see Figure 5.6).

General evaluation of the plant

A reliable prediction of system performance was obtained through numerical simulation based on a detailed model of a PVP-plant operating in the real world. An annual performance ratio of 19.8 % was estimated by simulation calculations of the system. For the same time period, in which the system was working free of external disturbances, the measured performance ratio attained 18.9 %. This good agreement means that, from the technical point of view the plant is working quite satisfactorily, very close to its rated values. This result also shows that the different steps of energy conversion in the system are understood with the model.

As in the other analysis carried out in the present work, in the case of Cajazeiras the dominating energy losses in the system are due to the limitations of the subsystem, which attained a daily average efficiency of 26.6 % including the hydraulic system power loss. The results in Figure 5.20 inform that in general the system, as it was dimensioned, is working

quite well and that an increase of about 7 % in system output could in principle be attained if some non-technical problems could be avoided.

5.6 Field experience

In the previous sections of this chapter the evaluation of the performance of a PVP-system was done on the basis of operation data that were free from 'external' problems, which could not be reproduced by the modelling of the system, either because of uncertainties in the measured data or due to their non-technical nature. This section will address some of these aspects including the ones which are non-technical in principle, but are sometimes more relevant than the pure technical ones for the judgement of a 'good' or 'bad' PVP-system.

In case of the brazilian PVP-systems, although the implementation programs included important steps such as initial surveys and social work programs, some facts observed by the author during the analysis of field data, as well as during a visit paid to the project sites, are worthwhile to be reported here because they emphasize the need of including a sufficient proportion of time and funds to deal with problems related with management in general, maintenance, water management and collection of money, etc. in projects concerning the dissemination of PVP-technology.

Non-technical problems have not received much attention but they now appear to be the most important causes of failures. In some cases, they even lead to technical problems. This point is well illustrated in Appendix F of this work, which contains the analysis of the operation data excluded by the plausibility tests described in section 5.2.3 for the site Cajazeiras. The analysis presented in Appendix F, revealed that for the majority of the brazilian systems there were constant short time plant standstills, because the water was not being consumed and the inverter would switch off the PV-array every time the storage tank was full. This consequently affects the energetic balance of the systems. If water is not utilized as predicted, the energy which could be made available by the array is not used leading to a drastic reduction of the overall system energy efficiency in the long term, without mentioning the waste of energy itself. This fact is a good example of the influence of the consumer habits on the 'technical' efficiency of a PVP-plant. The reasons why the water was not consumed as planned in some of the pumping stations in Brazil are many, and range from social conflicts to poor water quality, as the author could realize during a stay at the project sites. On that occasion, the following points were mentioned by members of the community:

- Some pumps were installed in pieces of land 'donated' to the community by a big and powerful landlord. Although it was officially donated, the big farmer behaves as the owner of the plant and because in many cases the relations between the community and him are strained, people refuse or are not allowed to pick up the water.
- The amount of salt in the water of some wells where pumps were installed is very high, making it not appropriate for drinking or for washing clothes. The reason why those plants were installed despite of the tests of water quality performed are not so clear, but one can imagine some sort of political prestige which the well gave to the farmer.

- In some places, in spite of good water quality and no apparent social conflict, some people in the community are superstitious and believe for example, that water from a well can not be drank just after being collected. It has to be stored over night (the water has to 'sleep', as they say) before one can drink from it. This may lead to a reduced water consumption.
- During the rain period people normally store the rain water to use it later and the animals can drink from lakes. This is normal practice in those areas, people prefer to drink rain water to any other source, since they think it is 'cleaner' and comes from the 'skies'. This will of course reduce water consumption.

The situations discussed above serve to illustrate that problems of organizational and humane nature can really endanger the lifespan of a project and its cost-effectiveness, if they are not considered during all phases of the implementation of the systems.

Other relevant aspects of the field experience with the brazilian PVP-systems are the reliability and the acceptability of the plants. Those will be discussed in the following:

5.6.1 Reliability of PVP-systems

Concerning operational reliability, a statistic could be realized for the 15 PV-pump systems (including Lagoa das Pedras and Cajazeiras) installed in Brazil, in the frame of the GTZ-program. The basis for the calculations were the analyses of the measured datasets and informations gathered 'in loco' by the author. The time periods considered in the calculations were the number of days passed after the first day of system operation until the 31 of January 1995; but as the systems were installed at different dates, operation times utilized varied from 460 days to 1.200 days of operation among the systems.

The calculations for all 15 systems showed that in average the pumps were available for use 99.7 % of the time. The plants located in Cajazeiras and Lagoa das Pedras, for example,were available 99.5 % and 97.3 % respectively. These numbers are even superior to the results published by GTZ regarding the availability of other PVP-systems in operation in their PVP-program [21], as well as the results of the CILLS project for PVP-systems in Mali [4]. In both projects an average pump availability of 90 % has been reported.

Causes for systems failures could be detected for the following systems:

Cajazeiras:	10 days plant standstill due to an unexpected fall in water table;
Lagoa das Pedras:	30 days plant standstill due to an inverter problem;
Jericoacara:	7 days plant outage due to an inverter problem.

These results demonstrate the increasing maturity of the PVP-technology. Extending the term 'reliability' to the installed equipment, failures of pumps, motors and PV-cells are practically inexistent. The inverter seems to be the most vulnerable component, despite the high efficiencies in operation, even in part load, as it was demonstrated earlier in this chapter.

Pumps running dry, as apparently was the cause of plant shutoff in the example of Cajazeiras,

points out that reliable information on the water resource or well characteristics and also user requirements should continue to be a main issue for PVP-system planners.

5.6.2 Acceptability and Community Participation

In principle it can be said that the PVP-systems in Brazil are well accepted by the target groups. Most of the villagers are proud of the systems and very pleased to have the water. However, in the majority of the plants installed in Brazil in the frame of the GTZ project, the level of participation of the communities in financing and/or managing the operation of the PV-pumps is low or totally lacking. Although the project promoters put much effort towards involving the villagers in those affairs, the results can be said to be poor, especially due to lack of information or even clear delegation of responsibility to the communities. Because of this, even small problems concerning maintenance have to wait to be solved by the utility company personnel who are located in same cases at least 200 Km away, and come only sporadically for supervision visits. The pumping stations may remain stopped for a long time in some occasions.

The problems above mentioned could be partly avoided if the users were 'officially' organized and trained to perform tasks such as cleaning the PV-panels and water tanks, reading the flow meters regularly, repairing leaking water taps and specially collecting money for spare parts and repair services as it happens in other demonstration projects where entities like 'water committees' or similar were created [4,2].

A crucial strategic error that was done in the brazilian project was not charging for the water utilized in the villages since the beginning of systems operation (it was still so at least until January/95, when the author visited the plants). Because of this, people cannot really realize the value of the product and nobody will be willing to pay for repair services in case a problem arises. The results of this are predictable enough concerning future maintenance and continuity aspects of plant operation, since they will be handed over to the communities very soon according to the plans of Coelce, the brazilian counterpart in the frame of the GTZ project.

5.7 General Conclusions and Recommendations for PVP-systems Layout

In this chapter, a procedure was developed for evaluation of PVP-systems by comparing the measured and the simulated performance in a systematic way. The method was applied to systems operating in Brazil with very satisfactory results. The good agreement achieved between the simulated and measured performances also served to validate the modelling of the system. The results demonstrate that the long term energetic balance of such systems can be well predicted by a simulation model that uses as input solar irradiation and ambient temperature time series, the layout data of the site and the characteristics of data sheets from the component's manufacturers. The method permits the most important energy losses in the system to be detected so that the energy production of the PVP-plant can be well understood.

The analysis of the 'non-technical' problems pointed out that the influence of social and organizational aspects on the performance of a PVP-system is considerable.

Regarding improvement of layout methods for PVP-systems, the most important lessons learned from the detailed analysis undertaken in this chapter can be summarized as:

- 1. Accurate PVP-system design can benefit from a digital simulation based on appropriate system component models and characteristics that can be obtained from components manufacturers. However, one of the prerequisites for the accuracy is that the simulation tools have to be derived on the basis of the knowledge acquired from the evaluation of real experiences with such systems;
- 2. The planning of PVP-systems can be enormously improved if the suppliers of the hardware make use of the informations resultant of investigations of real system performance and continue to develop and expand their products to fit the different application needs (the majority of PV-pumps suppliers still offer products within a limited range of hydraulic power potential, so that planners have sometimes to take the 'next' better appropriate pump to their applications);
- 3. The design of a PVP requires very accurate data from site location, especially about the demand and uses of the water and the well dynamic characteristics. Appropriate boreholes testing procedures should be improved and performed carefully before the system can be designed and reliable meteorological data must be available;
- 4. The danger of over dimensioning a PVP-system is high no matter how competent the design is done. This problem is a very sensitive point in the design process, especially concerning system costs. An important aspect in system lay-out is the precise determination of the well peak flow rate in each month, and also the interdependence of head and pumping rate and the variation of both with time. In case the system should be made to meet the demand for the worst case (the times with higher demand), some degree of water surplus should be expected. A way to partially overcome this problem is perhaps to think of possible uses for eventual 'extra' water production, as for instance irrigation of a vegetable garden or similar uses.
- 5. The creation of an infrastructure for the management and operation of a PVP-plant should be a main issue when introducing the technology in remote areas. Lack of financial participation, lack of training for maintenance and lack of a strategy for water payment by the community, can actually lead to complete failures, which will jeopardize the dissemination of PVP-applications.

References

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6 Summary

The supply of drinking water in remote areas of sunny regions is one of the most attractive applications of photovoltaic energy conversion. Field experiences with such systems in the last years have shown that depending on the distance to existing electricity grids, and on the power capacity level, photovoltaic pumping system (PVP) have already established itself, technically and economically, as a real alternative to conventional systems. There is a great potential for PVP-systems applications, especially in dry regions of the world were people do not have access to electricity grid, but in order to exploit this potential it is still necessary to address some issues which can contribute to large scale applications of the technology. This is especially true with regard to design optimization and the evaluation of the performance of the PVP-systems. The research developed in the present work dealt directly with these aspects in an attempt to contribute to the dissemination of PVP-technologies.

In the frame of the present work, the operational behavior of different PVP-system concepts were investigated in great detail experimentally and on the basis of computer simulations. On a PVP test-facility operating outdoors, extensive measurements were carried out during several months in order to provide a comprehensive understanding of the performance of PVP-systems and the interactions between its different components under field conditions to assure a data basis for the modelling of the system components.

A focal point in the present study was the development of mathematical models for the individual components of PVP-systems. Two different concepts of photovoltaic pumping systems have been selected: a system representing the actual standard PVP-system, composed of a centrifugal pump driven by an asynchronous motor; and a novel system concept, made up of a progressive cavity pump (also called screw pump) supplied by a brushless DC-motor (BDC-motor). The characteristics of the individual system components were measured in stationary laboratory tests and precise mathematical models were developed for them, describing their dynamic behavior and interactions within the system.

For each PVP-system investigated, a complete model has been implemented in computer codes and utilized to predict their operational performance through numerical simulation. The comparison of the simulation results and experimental data have shown that the models reproduced the measured system performances with excellent accuracy. Both systems water output were predicted with an accuracy better than 5%.

The long term performance of the experimental plants have been investigated by numerical experiments. The results of the simulation calculations have been used in a detailed energetic analysis, in which the different energy conversion steps and losses mechanisms (conversion losses, threshold energy 'losses', and external losses) for each individual component were separated and quantified, and their influence on the system overall efficiency determined. The annual Performance Ratio (PR), defined as the net energy to overcome the total pumping head normalized to the nominal energy of the PV-generator at standard test conditions, has been utilized as one measure of system performance to compare different systems. For the standard PVP-system (centrifugal pump and asynchronous motor) a PR of 21% has been found for climatic conditions of Northeastern Brazil, while the novel system concept (progressive cavity pump and brushless DC-motor) attained a PR of 48% for the same climate data.

The results of the comparison of the two concepts for PVP-systems has demonstrated that in an energetic point of view, the combination of a progressive cavity pump and a BDC-motor is superior (total daily efficiencies of about 5% were observed), and as such, a very promising alternative to the actual standard system. Although this type of PVP-technology is already available commercially and anterior experiences performed with it have shown its potential, it is still necessary to test this new technology in long-term field conditions before it really can occupy a significant role in PVP-systems applications.

Concerning component efficiencies, the results of the energetic analysis presented in chapters 4 and 5 have shown that the efficiency of the centrifugal pump is far below the rated values given by the manufacturers and that it also is responsible for the largest conversion losses, after the PV-generator, in the system. This fact points out that the search for PVP-system performance improvement should also be concentrated in the subsystem components development, like pumps and motors, whose costs are only a percentage of the system total cost. It is clear that with a more efficient subsystem, the number of expensive PV-modules needed to produce the same power will be smaller, what consequently lowers the cost of the system as a whole.

It has been found that although the very detailed model provides a much more complete understanding of the system behavior, it requires detailed informations about the components characteristics which are not readily available and also may require considerable computation time. This can naturally be a problem for the simulation of the long-term performance or for design calculations of PVP-systems in the practice. Following this consideration, the results obtained with the detailed model have been compared to the results of different simplified simulation methods. The comparisons have shown that for predicting of the plant water output in preliminary design calculations of PVP-systems, or for estimating the potential of a plant at site locations for which only limited data are available, the methods analyzed are adequate enough, especially regarding the easy availability of the models parameters and the reduced computation time. For a more in-depth analysis of system operational behavior however, both methods have limitations.

A comprehensive and systematic method to evaluate measured data from real applications of PVP-systems has been proposed in the present study. The method permits to separate and quantify the technical from the non-technical problems which can influence the performance of the system. This procedure can produce rated energetic values necessary for the interpretation of the measured performance, thus permitting an assessment of the real system behavior and the possibilities to optimize it.

The backbone of the evaluation method is the modelling and simulation of the plant operational behavior as it was done for the experimental plants analyzed in this work, but in order to be applicable to existing PVP-plants, the modelling of the system is based only on informations available in the components manufacturers data sheets, in lay-out values and in measured meteorological data. In this way, an accurate simplified simulation model, which can be applied to most commercially available PVP-systems, has also been developed in the present study. With this simplified model, system performance can be predicted with an accuracy of better than 7 %.

The proposed analytical procedure has been applied, exemplary, to investigate the performance of a PVP-system installed in the Northeast of Brazil in detail. The most significant results of this analysis can be summarized as:

- A reliable prediction of the performance of existing PVP-systems can be obtained through numerical simulation. An annual performance ratio of 19.7 % was estimated by simulation calculations of the brazilian PVP-system, when the system was considered as working free of external disturbances. For the same period the measured performance ratio attained 18.9 %, what means that under 'normal' operation the plant behavior is near its rated values, i.e., with the present lay-out there is few possibilities for performance improvement.
- As with the experimental reference systems, the simulation results in form of energy flow diagrams, showed that the dominating energy losses in the system are due to the limitations of the subsystem, which for the brazilian system, attained an average efficiency of about 28%.

The investigation of the brazilian PVP-system also encompassed the analysis of general aspects which are relevant for a complete appraisal of system performance. Some of these aspects are of technical order, others are non-technical in principle, but most of them can determine the degree of success (or failure) attained in the dissemination of PVP-technology. The following results should be mentioned:

- Two aspects of the monitoring system are important for the evaluation of the long-term performance of a PVP-system: the completeness of the gathered data and the accuracy of these data. Problems with the data acquisition in Brazil reduced considerably the number of plants that could have been investigated and made the interpretation of data a quite difficult affair. This information shows that besides a measurement campaign it is also necessary to have a continuous data check and evaluation mechanism that could detect problems, as early as possible, in order to take the appropriate actions to solve them. A standard method that could be generally accepted is missing, the evaluation method presented in this work can be a starting point in this direction.
- It has been demonstrated how the pattern of water consumption can affect the system performance. The problem could be identified in the analysis of the measured data for various PVP-systems installed in Brazil by the water storage tank being constantly full. Some of the reasons why water was not being picked could be detected by the author during a visit to the project sites, and they range from cultural values or religious believes, to poor water quality. This information has pointed out that independent of how accurate the demand can be calculated, system utilization, will sometimes determine the technical performance of the system. These results confirmed the importance of considering, as far as possible, the social factors involved in the installation and operation of a PV-pump, especially in remote areas of less developed countries.
- The reliability of PVP-systems has been very satisfactory under brazilian conditions. In a total of 15 systems it was found that in average the pumps were available for use 99.7 % of the time. This demonstrates the increasing maturity of the technology. Failures of system components like PV-array, pumps and motors are practically inexistent. Only two inverters showed problems in a period of 4 years, which can be considered remarkable for an equipment that is normally considered the most vulnerable component of the system.

• It has been found that acceptability has not really been a problem in Brazil. The villagers are very pleased to have the water and even proud of their pumps. However, there are clearly social and organizational aspects of the introduction of the technology which remain to be dealt with. One of these problems is certainly the continuity aspects of the operation of systems installed. A more effective involvement of the end users in financing/managing the operation of the plants would have been necessary. A much more transparent delegation of responsibility concerning maintenance, operation and the costs involved, should have been given to the community, and the water consumption should be charged, if only symbolically, to make people value the pumps and become aware of their responsibility to keep them working.

The results obtained with the analysis carried out in the present study have shown that the performance of PVP-systems can be optimized in different ways: by understanding the system behavior better, by improving components efficiency, by utilizing new systems concepts, by improving system lay-out methods, and last but not least, by helping people to use their systems as efficiently as possible. Those are the tasks of researchers, technicians and producers of equipment. Political and legislative support are certainly first requirements for exploiting the recognized potential of PVP-technology in countries like Brazil, but the technological expertise accumulated in research or demonstration projects is still perhaps the essential support required to disseminate PVP and other solar energy technologies.

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Nomenclature

A_{PV}	Photovoltaic Generator Area [m ²]
AM	Air Mass
C_0	Coefficient of light-generated current density $[V^{-1}]$
C_1	Temperature coefficient of light-generate current density [$V^{-1}K^{-1}$]
C ₀₁	Coefficient of saturation current density [Am ⁻² K ⁻³]
C ₀₂	Coefficient of saturation current density $[Am^{-2}K^{-5/2}]$
E _{STC}	Nominal Energy [Wh]
E _{HYD}	Hydraulic Energy [W]
E _{PV}	Photovoltaic Generator Energy [Wh]
E _{out}	Output Energy [Wh]
Ed	Energy in the delivery side of a pump [Wh]
Es	Energy in the suction side of a pump [Wh]
f	frequency [Hz]
\mathbf{f}_1	Inverter input frequency [Hz]
\mathbf{f}_2	Inverter output frequency [Hz]
G	Solar Radiation [Wm ⁻²]
g	Gravitational constant [m/s ²]
Н	Total pumping head [m]
H _{geo}	Geodetic head [m]
H_{pump}	Pump head [m]
H _{sys}	Hydraulic system head [m]
H_{piping}	Head of the loss of pipework [m]
H _{thx}	Theoretical head of a centrifugal pump with finite number of blades [m]
h _{hx}	Hydraulic losses in a centrifugal pump [m]
h _{sx}	Shock losses in a centrifugal pump [m]
Ι	Current [A]
I _{AC}	Alternate current [A]
I _{DC}	Direct current [A]
I _{MPP}	MPP-current [A]
I _{Motor}	Motor current [A]
j	Current density [Am ²]
Jph	Light-generated current density [Am ²]
J 01	Saturation current density [Am ²]
J02	Saturation current density [Am ⁻]
k	Boltzmann Constant , $k = 1.3854 \cdot 10^{-23} \text{JK}^{-1}$
k	Hydraulic conductivity of a well [m/s]
K _c	Temperature Coefficient $[W^{-1}m^2K]$
n	Rotational speed [1/s]
N _p	Number of cells in parallel
N _s	Number of cells in series
Р	Power [W]
p D	Number of of pole-pairs
r _{nom}	Nominal power [w]
P _{AC}	Anternate current power [V]
P _{mech}	Mechanical power [w]

P _{DC}	DC-power [W]
Pag	Power across the airgap of the motor [W]
p	Static pressure [N/m ²]
P _{hyd}	Hydraulic power [W]
P _{fric}	Friction losses in a pump [W]
P _{Fe}	Motor core power loss
¢	Pump flowrate [m ³ /h]
Q _{theo}	Theoretical pump flowrate [m ³ /h]
Q_L	Leakage flowrate [m ³ /h]
R	Ohmic resistance [Ω]
R ₁	Ohmic resistance of motor stator [Ω]
R ₂	Ohmic resistance of motor rotor [Ω]
r _s	Series resistance parameter of the cell [Ωm^2]
r _{sh}	Shunt resistance parameter of the cell [Ωm^2]
S	Storage coefficient of an aquifer
s(t)	Well drawdown [m]
S	Motor slip speed
Т	Aquifer transmitivity of an $[m^2/s]$
Т	Temperature [°C]
T _{amb}	Ambient temperature [°C]
T _c	Cell temperature [K]
T _F	Motor friction torque [Nm.s]
T _{mod}	Modul temperature [°C]
T_{motor}	Motor torque [Nm.s]
T _{pump}	Pump torque [Nm.s]
V	Voltage [V]
V _{Motor}	Motor voltage [V]
V _{DC}	Direct current voltage [V]
V _{OC}	Open circuit voltage [V]
$V_{\rm fix}$	Constant voltage
V_{mpp}	MPP-voltage [V]
\mathbf{V}_0	Geometric volume of displacement
W_u	Wall function
X	Motor Reactance [Ω]
X X1	Motor Reactance [Ω] Leakage reactance of the motor stator [Ω]
X X1 X2	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$
X X1 X2 XM	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$
X X1 X2 XM Y	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$
X X1 X2 XM Y α	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model
X X1 X2 XM Y α β	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model Parameter of the two-diode model
X X1 X2 XM Y α β ρ	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model Parameter of the two-diode model Water density $[Kg/m^3]$
X X1 X2 XM Y α β ρ Φ	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model Parameter of the two-diode model Water density $[Kg/m^3]$ Solar radiation utilizability
	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model Parameter of the two-diode model Water density $[Kg/m^3]$ Solar radiation utilizability Mechanical angular velocity
X X1 X2 XM Y α β ρ Φ ω η_{inv}	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model Parameter of the two-diode model Water density [Kg/m ³] Solar radiation utilizability Mechanical angular velocity Inverter efficiency
X X1 X2 XM Y α β ρ Φ ω $η_{inv}$ $η_{SUB}$	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model Parameter of the two-diode model Water density $[Kg/m^3]$ Solar radiation utilizability Mechanical angular velocity Inverter efficiency Subsystem efficiency
X X1 X2 XM Y α β ρ ϕ ω η_{inv} η_{SUB} η_{PV}	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model Parameter of the two-diode model Water density [Kg/m ³] Solar radiation utilizability Mechanical angular velocity Inverter efficiency Subsystem efficiency PV-array efficiency
X X1 X2 XM Y α β ρ Φ ω $η_{inv}$ $η_{SUB}$ $η_{PV}$ η _{thref}	Motor Reactance $[\Omega]$ Leakage reactance of the motor stator $[\Omega]$ Leakage reactance of the motor rotor $[\Omega]$ Magnetizing reactance of motor $[\Omega]$ Specific energy of a fluid $[m^2/s^2]$ Parameter of the two-diode model Parameter of the two-diode model Water density $[Kg/m^3]$ Solar radiation utilizability Mechanical angular velocity Inverter efficiency Subsystem efficiency PV-array efficiency Threshold efficiency

η_{STC}	STC-efficiency
AC	Alternate Current
BDC	Brushless Direct Current (Motor)
DC	Direct Current
meas.	Measured
MPP	Maximum Power Point
MPPT	MPP-tracker
PR	Performance Ratio
PV	Photovoltaic
STC	Standard Test Conditions
sim.	Simulated
PVP	Photovoltaic pumping systems
PMW	Pulse-width modulation

Appendix

A Laboratory Measurement Set-up for an Asynchronous Motor

Figure A.1 presents a scheme of the set-up utilized for measuring torque and rotational speed of the asynchronous motor installed at the PVP-system of the University of Oldenburg. The tests with this set-up were carried out at the Technical University of Berlin.



Fig.A.1: Scheme of the measuring setup for the determination of the asynchronous motor characteristics and parameters. The numbers stand for: 1 = inverter; 2 = power source for 50 Hz sinusoidal supply; 3 = terminals to switch the supply from the inverter to the power source; 4 = shunt resistances; 5 = voltmeters; 6 = resistances in star connection; 7 = asynchronous motor; 8 = torque measuring device; 9 = DC-generator with variable resistance.

B Fundamentals of Motors

B.1 The Asynchronous Motor

The Equivalent Circuit and the Characteristic Equations

The method chosen for the analysis of the asynchronous motor (ASM) in the present work makes use of the similarity of its operational principle to that of a transformer, in the sense that the induction processes in the motor stator and rotor windings are analysed separately and, by superposition, put together in the form of an equivalent circuit. The equivalent circuit of the polyphase motor is very similar to the usual transformer equivalent circuit, because the asynchronous motor is essentially a transformer with a rotating secondary winding. [5]. The equivalent circuit for a single phase of a triphasic asynchronous motor is shown in Figure B.1. It is important to mention that in deriving the rotor equivalent circuit, the actual cage or phase-wound rotor winding is considered to be replaced by an equivalent short-circuited rotor winding having the same number of turns and the same winding arrangement as the stator.



Fig. B.1: Per phase equivalent circuit of the asynchronous motor. The index 1 designates the stator circuit and the index 2 describes the rotor circuit. The mechanical power is delivered through the rotational speed-dependent resistance $R_2(1-s)/s$.

The ASM is supplied with the voltage V₁ which establishes the stator current I₁. The stator windings (primary) is symbolized in the equivalent circuit by the intern ohmic resistance R1 and by the primary leakage reactance X₁. The correlation between the current and the voltage induced by the magnetic flux is represented by the magnetizing reactance X_m. The rotor is represented by the ohmic resistance R₂, the rotor inductance X₂ and the rotor current I₂. The effect of motor speed is reflected by the presence of an impedance parameter R₂/s, which in the equivalent circuit is divided into two parts R₂ + R₂(1-s)/s, to separate the frequency independent term R₂, representing the heat losses in the rotor conductors [1].

Voltage Equations

Analogous to the approach usually applied to the primary and secondary sides of a transformator, the equations for the voltage of the motor stator and rotor can be derived from the asynchronous machine equivalent circuit in Figure B.1. A detailed derivation of these equations can be found in Fischer [1] and Janssen [3], therefore here only the main equations

which are important to the understanding of the motor characteristics equations used in the simulation model will be presented.

Considering the induced voltage V_m as voltage drop of the mutual magnetizing currents I_1+I_2 on the magnetizing inductance X_m , the voltage equations for the circuit of Figure B.1 can be written as:

$$V_1 = R_1 I_1 + j X_1 I_1 + j X_m (I_1 + I_2) , \qquad (B.1)$$

$$0 = R_2 I_2 + j X_2 + j X_m (I_1 + I_2) + \frac{1 - s}{s} R_2 I_2$$
(B.2)

The above two equations correspond to the simplified standard model for the asynchronous machine, without considering core and friction losses, which were calculated separately through the measurements in chapter 2 of this work.

Torque Equation

At a slip s, the rotor power loss in the equivalent circuit is $I_2^2R_2/s$ watts per phase, whereas, in the actual machine, the rotor copper loss is $I_2^2R_2$ watts per phase. The additional power loss in the equivalent circuit is the electrical equivalent of the mechanical power output of the motor. If P_{mech} denotes the total mechanical power output, including windage and friction losses, then

$$P_{mech} = m_1 \Big[(I_2^2 R_2 / s) - (I_2^2 R_2) \Big]$$

= $m_1 I_2^2 R_2 \Big(\frac{1-s}{s} \Big)$ (B.3)

where m_1 is the number of stator phases.

If ω_m is the mechanical angular velocity of the rotor and T_i is the electromagnetic torque, the total mechanical power output can be written as

$$T_{i}\omega_{m} = m_{1}I_{2}^{2}R_{2}\left(\frac{1-s}{s}\right)$$
(B.4)

or

$$T_{i} = \frac{m_{1}I_{2}^{2}R_{2}}{\omega_{m}} \left(\frac{1-s}{s}\right)$$
(B.5)

Equation (B.5) describes the internal motor torque, which is greater than the useful shaft torque by the amount required to overcome windage and frictions torques.

Since the synchronous angular velocity in radians per second is given by $\omega_s = \omega_m / (1-s) = 2\pi f_1 / p$, where p is the number of pole-pairs, the torque equation can be rewritten as

$$T_{i} = \frac{m_{1}I_{2}^{2}R_{2}}{s\omega_{s}} = \frac{pm_{1}}{2\pi f_{1}} (I_{2})^{2} \frac{R_{2}}{s}$$
(B.6)

Power Division in the Rotor

From the equivalent circuit, the total electrical power input to the rotor across the airgap from the stator can be written as

$$P_{ag} = m_1 I_2^2 R_2 / s$$
 (B.7)

This power is divided between mechanical power output, P_{mech} , and rotor copper loss, P₂. Thus,

$$\mathbf{P}_{ag} = \mathbf{P}_{mech} + \mathbf{P}_2 \tag{B.8}$$

where

$$P_{mech} = T_i \omega_m \tag{B.9}$$

and

$$P_2 = m_1 I_2^2 R_2$$

Combining Equations (B.6) and (B.7) gives:

$$P_{a\sigma} = T_i \omega_s \tag{B.10}$$

This is a classic motor function, describing that the total electrical power input to the rotor is equal to the internal mechanical torque multiplied by the synchronous angular velocity.

So far, the equations for power and torque given above describe the stationary operational behavior of the ASM, now as we are interested in the motor behavior at variable frequency, it is necessary to consider the control strategy applied to the motor. This can be made by utilizing the motor function, which correlates the rotor frequency with the stotor frequency through the slip s.

$$\mathbf{f}_2 = \mathbf{s} \ \mathbf{f}_1 \tag{B.11}$$

In the following, the equations utilized in the motor model for the electrical power demand of the motor and the torque available at the motor shaft will be described.

Power

For the derivation of the power and torque equation it is first necessary to derive the stator and rotor current equations. Utilizing the voltage equations (B.1) and (B.2) and defining

$$X_{11} = X_m + X_1, \qquad X_{22} = X_m + X_2$$
the current equations for both stator and rotor can be given by

$$I_1 = (R_s + jX_2)V_1 / \zeta$$
 , (B.12)

$$\mathbf{I}_2 = \mathbf{j}\mathbf{X}_2\mathbf{V}_1 / \boldsymbol{\zeta} \tag{B.13}$$

with
$$R_s = R_2 / s$$
 and $\zeta = R_1 R_s + X_m^2 - X_{11} X_{22} + j(R_s X_{11} + R_1 X_{22})$

According to [5], the electrical power demand at the motor terminals, considering the core losses, can be given by

$$P_{ele} = m_1 (V_1 I_1 + P_{Fe})$$
(B.14)

Utilizing complex numbers calculation rules, the real part of I_1 can be obtained from equation (B.12). Substituting it into equation (B.14) gives

$$P_{ele} = m_1((R_1R_s^2 + R_sX_m^2 + R_1X_{22}^2)V_1^2 / \zeta^2 + P_{Fe})$$
(B.15)

 P_{Fe} is the core power loss, which can be estimated by

$$P_{Fe}(f, V_1) = P_{Fe, N} \left(\frac{f}{f_N}\right)^{-0.4} \left(\frac{V_1}{V_{1, N}}\right)^2$$
(B.16)

where the index N indicates the values of frequency and stator voltage at open circuit [3].

Torque

Utilizing complex numbers calculations rules and substituting the equations for stator voltage and rotor current in the torque equation (B.6) and redefining the fractional slip as

$$s = \frac{\omega_1 - \omega_m}{\omega_1} \tag{B.17}$$

where ω_1 is the angular synchronous velocity and ω_m is the shaft angular velocity, the motor torque can be expressed in terms of the applied voltage V₁, and the angular frequencies ω_1 and ω_2 .

Considering that the torque available on the motor shaft is smaller than the internal torque because of the friction losses T_F in the bearings, the resulting expression for useful torque, after some transformations can be written as:

$$T_{motor} = pm_i (R_2 X_m^2 V_1^2 / (\omega_1 \zeta^2) - T_F)$$
(B.18)

According to [2] the friction torque T_F for any motor speed can be estimated by

$$T_{F}(n) = T_{F,\lambda} \frac{n}{f_{0,\lambda}}$$
(B.19)

where n is the rotational speed of the rotor, $T_{F,\lambda}$ and $f_{0,\lambda}$ are the values of the torque and rotational speed determined for the open circuit condition.

B.2 The Brushless DC-motor (BDC-motor)

B.2.1 The Circuit Scheme

In a motor with an electronic commutator each of the stator windings is connected by a pair of power semiconductor devices to permit flow in both directions through the stator windings. This arrangement substitutes the mechanical commutator in a conventional DC-motor. Self synchronous operation of the BDC-motor is achieved by the rotor position sensors that control the sequencing of the inverter circuit (commutator). The rotational speed is varied by changing the voltage applied to the stator. This is different for AC-motors where the speed is varied by changing the frequency of the supply voltage.

Figure B.2 shows a typical scheme of a three phase brushless BDC-motor with its electronic controller (inverter). The controller in this case is composed of 6 transistors (T_i) and 6 flyback diodes (D_i). In normal operation the current flows through a pair of transistors. The flyback diodes have two uses: during commutation, to provide an alternative path for the inductive winding current when a transistor is turned off, and also when the motor current increases over a preset maximal value, the current flux is transferred for a short time through a flyback diode

The inverter controls the motor using a defined switching sequence between transistor conducting periods and flyback diodes conducting periods (when the transistor are turned off). The conducting periods for the transistors and the diodes are determined by electrical angular positions. In the figure B.2, the current paths during the non commutation period and the current path through flyback diode at the moment of commutation are shown. The inverter commutation is performed every 60° , so that maximum torque can be continually produced.



Fig. B.2: Scheme of a bidiretional stator connections in a three phase brushless DC-motor. (source: [4]).

B.2.2 The Basic Equations

Torque

 \rightarrow

According to Lenz law, a current flowing through a conductor of length l in a magnetic field of density B produces a tangential force

$$\vec{F} = I \cdot (\vec{1} \times \vec{B})$$
(B.20)

which produces a Torque T in a motor with a rotor diameter d, an average magnetic flux density B and 2N conductors (2 windings with N conductors each):

$$T = \frac{d}{2} \cdot \sum_{i=1}^{2N} F_i$$

= $d \cdot 1 \cdot I \cdot \overline{B} \cdot N$ (B.21)

From (B.21), the Torque equation can be rewritten as

$$\mathbf{T} = \mathbf{c}_{\mathsf{M}} \cdot \mathbf{I} \tag{B.22}$$

where c_M is the motor constant and is given by $c_M = d \cdot l \cdot B \cdot N$ (B.23)

Voltage

The voltage equation of a BDC-motor is similar to that of a permanent magnet DC-motor, and have the following general form:

$$V_{DC} = 2\pi \cdot c_{M} \cdot n - L \cdot \frac{dI_{Motor}}{dt} + R_{Stator} \cdot I_{Motor}$$
(B.24)

where V_{DC} is the motor terminal voltage, I_{Motor} is the motor current, R_{Stator} and L are the resistance and inductance of a phase winding, n is the rotational speed of the rotor, and the term $V_{emf} = 2\pi \cdot c_M \cdot n$ is the usual induced back emf , with c_M given by function (B.23).

B.2.3 Power Division in the Motor

The total electric power (P_{DC}) supplied to the motor is transformed in the motor in the following powers and power losses:

- the mechanical power P_{mech} , resultant from the induced back emf and the motor current

$$\mathbf{P}_{\text{mech}} = \mathbf{V}_{\text{emf}} \cdot \mathbf{I} = 2\pi \cdot \mathbf{c}_{\text{M}} \cdot \mathbf{n} \cdot \frac{1}{\mathbf{c}_{\text{M}}} \cdot \mathbf{T} = 2\pi \cdot \mathbf{n} \cdot \mathbf{T} \quad ;$$

• the sum of the ohmic losses P_{ohm} (copper losses) in the stator, in the connecting cables between motor and inverter and in the inverter itself

$$P_{ohm} = R \cdot I^2 = R \cdot \frac{1}{c_M^2} \cdot T^2 = c_{m_1} \cdot T^2$$
;

- the total losses $P_{volt-loss}$ caused by constant voltage drops in the power conditioning unit

 $\mathbf{P}_{\text{volt}_\text{loss}} = \mathbf{V}_{\text{const}} \cdot \mathbf{I} = \mathbf{V}_{\text{const}} \cdot \frac{1}{c_{\text{M}}} \cdot \mathbf{T} \quad \sim \quad \mathbf{T} \quad ;$

- constant power for the supply of the power conditioning unit $P_{const} = c_{m_2}$;
- the losses caused by eddy currents P_{eddy}

 $P_{eddy} \sim n$;

• the hysterese losses P_{hyst}

 $P_{hyst} \sim n^2$;

• the mechanical losses due to friction in the bearings are proportional to the rotational speed;

While the flyback diodes are in operation, no power is supplied to the motor. During this time the electric energy is stored. The losses connected with this process are already included in the above described losses.

The losses resulting from a constant voltage drop are so small that they can be neglected.

In the literature, the losses due to hysteresis and eddy currents are considered together as core losses (iron losses) P_{iron} . According to Patspour [6] the core losses can be written as

$$\mathbf{P}_{\mathrm{iron}} = \mathbf{a}_1 \cdot \mathbf{n}^2,$$

while, Lawrence [37] calculates them as

$$\mathbf{P}_{\text{iron}} = \mathbf{a}_1 \cdot \left(\frac{1}{3} \cdot \mathbf{n} + \frac{2}{3} \cdot \mathbf{n}^2\right)$$

and according to Fischer [13] they are given as

$$P_{iron} = a_1 \cdot n^A$$
 with $A=1, 6$.

The evaluation of the measurements performed on a BDC-motor in the present work revealed that the iron losses can be well described by the following function:

$$\mathbf{P}_{\rm iron} = \mathbf{c}_{\rm m_3} \cdot \mathbf{n}^2 \tag{B.25}$$

Making the substitutions, the DC-power for the motor model can be described by the following function:

$$P_{DC} = 2\pi \cdot n \cdot T + c_{m_1} \cdot T^2 + c_{m_2} + c_{m_3} \cdot n^2$$
(B.26)

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C Fundamentals of Pumps

C.1 The Centrifugal Pump

In a centrifugal pump, the energy, or the specific ability to produce work possessed by the particles of a fluid in a flow, can be given by the Bernoulli Constant 'E', that for incompressible fluids can be calculated as [2]:

$$E = \frac{p}{\rho} + \frac{c^2}{2} + g.h$$
 (C.1)

with

Denominating E_d and E_s as the specific ability to produce work by a fluid in the delivery and suction sides of a pump, the specific energy (Y) will be given by

or,

$$Y = \frac{p_d - p_s}{\rho} + \frac{c_d^2 - c_s^2}{2} + (h_d - h_s)g$$
(C.2)

In pump literature [2,3] the term head (H) is more commonly used, instead of the specific energy (Y). The relationship between H e Y is given by:

$$\mathbf{H} = \frac{Y}{g}, \qquad ([\mathbf{H}] = \mathbf{m})$$

 $Y = E_d - E_s$

The actual flow patterns through an impeller are very complex and simplifying assumptions are necessary to describe it. When considering the flow through a passage between the blades of a rotating impeller, a distinction should be made between the absolute flow (velocities and paths with respect to the stationary walls of the pump casing) and the relative flow, considered with respect to the rotating impeller. The so called velocity triangle and the blade diagram, showed in Figure C.1, are used to describe the actual flow.



Fig. C.1: Velocity triangles and blade diagram utilized to describe the motion of the fluid particles through the impeller blades of a centrifugal pump. The suffixes 1 and 2 distinguish impeller blade inlet and outlet respectively. The velocity components appearing in the diagram are described in the text. (source: [2])

In Figure C.1 the blade diagram and the velocity triangle constructed for a centrifugal pump are shown. The water enters the impeller in an axial direction and immediately turns so as to flow outwards in the plane of rotation. The water approaches the impeller vane with the absolute velocity c_1 , which is determined by the continuity equation

$$c_1 = \frac{Q}{A_1}$$
 with $A_1 = 2\pi \cdot \mathbf{r}_1 \cdot \mathbf{b}_1$ (C.3)

where Q is the nominal discharge of the pump, A_1 is the cross-sectional area of the impeller inlet passage, b_1 is the width of this passage and r_1 is the impeller inner radius.

If the impeller, in Figure C.1, rotates, the tangencial velocity ω at the inner radius is

$$\mathbf{u}_1 = \boldsymbol{\omega} \cdot \mathbf{r}_1 \tag{C.4}$$

The relative velocity w_1 , i.e., the speed of the water relative to the impeller (impeller considered as being at rest, or if an observer would 'sit' on the impeller) is found by completing the vector triangle as shown in Figure C.1. According to [2], for the best flow pattern, the relative velocity w_1 should align with the vane angle β_1 .

The water flows outwards in the passages between the vanes with its relative fluid path following the curvature of the vanes. It is discharged from the outer periphery of the impeller at the relative velocity w_2 and at the vane blade angle β_2 . From this velocity, only its radial component, equal to c_{m2} can be immediately determined. Applying the continuity equation gives

$$c_{m2} = \frac{Q}{A_2}$$
 with $A_2 = 2\pi \cdot \mathbf{r}_2 \cdot \mathbf{b}_2$ (C.5)

The absolute tangential velocity of the impeller at the outer periphery is

$$\mathbf{u}_2 = \boldsymbol{\omega} \cdot \mathbf{r}_2 \tag{C.6}$$

Using β_2, c_{m2} and u_2 , the velocity triangle for the outlet can be completed. The absolute velocity of the water is obtained by vectorially adding w_2 and u_2 . Comparing c_2 with c_1 shows that the absolute velocity of the water has increased which is obviously the effect of the rotating impeller.

The Euler Equation (Conservation of Momentum law) is used to describe the torque at the pump shaft. Momentum of a body is the product of its mass and velocity. The resultant external force acting on this body is equal the rate of change of momentum of the body. Thus, for fluid flow

$$\vec{F} = \rho \cdot Q \cdot (\vec{dv_1} - \vec{dv_2})$$
(C.7)

The tangential components of the inlet and outlet water velocites (Figure C.1) are the only ones able to produce torque, which is the product of the tangential momentum by the radius of the point where it is being applied. Thus, the expression for the total torque at the pump shaft is

$$\mathbf{T} = \boldsymbol{\rho} \cdot \mathbf{Q} \cdot (\mathbf{c}_{u2} \cdot \mathbf{r}_2 - \mathbf{c}_{u1} \cdot \mathbf{r}_1) \quad [N.m]$$
(C.8)

For rotating systems, power is the torque multiplied by the angular velocity

 $\mathbf{P} = \boldsymbol{\omega} \cdot \mathbf{T}$

so that,

$$\mathbf{P} = \boldsymbol{\rho} \cdot \mathbf{Q} \cdot (\mathbf{c}_{u2} \cdot \mathbf{u}_2 - \mathbf{c}_{u1} \cdot \mathbf{u}_1) \quad [W]$$
(C.9)

since $u = \omega \cdot r$

Another expression for power is work done per second, which leads to

$$\mathbf{P} = \boldsymbol{\rho} \cdot \mathbf{g} \cdot \mathbf{Q} \cdot \mathbf{H} \tag{C.10}$$

Inserting equation (C.10) into expression (C.9) leads then to Euler equation:

$$H_{thoo} = \frac{1}{g} (c_{u2} \cdot u_2 - c_{u1} \cdot u_1)$$
(C.11)

 $H_{th\infty}$ represents the ideal increase in total head (in meters) of the fluid due to the action of the impeller, i.e., increase of head when all losses are ignored. The index th ∞ stands for theoretical value at infinite number of blades.

For a real pump these ideal characteristics and the losses have to considered and subtracted from the original Euler equation.

First, one must consider the transition from the idealized pump, with infinite number of blades, to a still theoretical pump, but with a finite number of blades.

Considering that at the inlet of the impeller the water enters radially and has little or no tangential velocity and, therefore, no initial angular momentum equation (C.11) is simplified to:

$$H_{\text{those}} = \frac{u_2}{g} c_{u2} \tag{C.12}$$

Utilizing the velocity triangle relationships in Figure C.1, equation (C.12), after some transformations, becomes:

$$H_{thoox} = \frac{u_2}{g} (u_2 - \frac{Q_x}{Q} c_{2m} \cot \beta_2)$$
(C.13)

where the index x means deviation from the nominal values. Equation (C.13) represents the theoretical total head for an impeller with infinite number of blades $(n=\infty)$ and under homogeneous flow.

By a finite number of blades $(n < \infty)$ the flow in the blade channels is not homogeneous anymore. Due to the complexity of flow there, this effect can not be completely described qualitatively. A satisfactory approximation according to Pfleiderer [3] is,

$$H_{thx} = \frac{1}{1+p} H_{th\infty x} \tag{C.14}$$

with p ='minderleistungzahl' of a pump (p > 0).

Both characteristics $H_{theox}(Q_x)$ and $H_{thx}(Q_x)$ as given by equations (C.13) and (C.14) are presented graphically in Figure C.2, to illustrate the transition to a finite number of blades. The dashed line shows the deviations to equation (C.14) which still can occur for small flowrates Q_x .



Fig. C.2: Transition from the theoretical head of a pump with infinite number of blades H_{thex} *to a finite number of blades* H_{th} (source:[2]).

Until this point the friction losses and the losses due to change of velocity patterns within a pump were not considered. These losses are commonly known as hydraulic loss and shock loss in centrifugal pump terminology, and have already discussed been in section 3.5.1.2 of the present work. Figure C.3 illustrates how the final throttling curve of a centrifugal pump is obtained from the ideal characteristic.



Fig. C.3: Illustration of how the throttling curve of a real centrifugal pump H=f(Q) is obtained from the theoretical pumping head (equations C.13 and C.14), considering also the hydraulic and shock losses, which are given by the equations $(h_{hx} = \alpha_h Q_x^2)$ and $(h_{sx} = \alpha_s n_x^2 - \beta_s n_x Q_x + \gamma_s Q_x^2)$ respectively.

C.2 The Progressive Cavity Pump

C.2.1 Characteristics Equations

Flowrate Q

The pump flowrate \dot{Q}_{Pump} is composed of the theoretical flowrate \dot{Q}_{theo} and the leakage flowrate \dot{Q}_{L} , that is,

$$Q_{\text{Pump}} = Q_{\text{theo}} - Q_{\text{L}} \tag{C.15}$$

The theoretical flowrate \hat{Q}_{theo} is proportional to the rotational speed *n* and the goemetric volume of displacement V₀, and is given by

$$\mathbf{Q}_{\text{theo}} = \mathbf{V}_0 \cdot \mathbf{n} \,, \tag{C.16}$$

where V_0 is determined by

$$V_0 = 4 \cdot d_R \cdot h_{ST} \cdot e$$

with d_R being the rotor diameter (see Figure 3.5.4)

According to Genthner [1] the leakage flowrate can be estimated for a pump from the following expression which is based on the Navier-Stokes-equation:

$$\dot{\mathbf{Q}}_{\mathrm{L}} = \frac{\mathbf{U}}{12 \cdot 1 \cdot \eta} \cdot \Delta \mathbf{p} \cdot \mathbf{S}^{3} \tag{C.17}$$

where S is the constant width of a gap between two parallel walls having the length l in the direction of the flow and the width U across it, Δp is a pressure difference acting on the length l of the walls on the occasion, and η is the viscosity of the fluid.

The expression (C.17) is in principle only valid for pumps with a metallic stator. In the case of a pump with an elastometer stator, the expression (C.15) has to be adapted, since the width S of the gap between the two walls is not constant in a pump, but dependent on the pressure acting on the walls and eventually also dependent on the rotational speed. Therefore, for an elastometer stator, the following correction is proposed by Genthner in [17]:

$$\mathbf{S} = \mathbf{S}_0 + \mathbf{c}_{\mathbf{S}} \cdot \mathbf{p} \quad , \tag{C.18}$$

where S_0 represents the overlap between rotor and stator (for sealing proposes the rotor diameter is bigger than the internal diameter of the stator) and is negative. The pressure p is the pressure acting on the contact area between two cavities (see fig 3.5.7). Making the substitutions in equation (C.15) the flowrate of the pump becomes:

$$\dot{\mathbf{Q}}_{\text{pump}} = \mathbf{V}_0 \cdot \mathbf{n} - \mathbf{a}_1 \cdot \Delta \mathbf{p} \cdot \left(\mathbf{a}_2 + \mathbf{a}_3 \cdot \Delta \mathbf{p}\right)^3 \tag{C.19}$$

To minimize the number of parameters the following empirical estimation has be made

$$Q_{pump} = V_0 \cdot n - a_1 \cdot (\Delta p)^Z$$
, with 0.5 $\leq Z \leq 4.0$ (C.20)

The evaluation of the laboratory measurements demonstrated that with the value Z=2.0 in equation (C.20) the best result could be found. Thus, the model for the pump flow rate can finally be determined by:

$$Q_{pump} = V_0 \cdot n - c_{Q_1} \cdot (\Delta p)^2$$
(C.21)

Torque

The torque developed in a progressive cavity pump has two causes: first due to the transfer of hydraulic power to the fluid, and second due to the power losses caused by friction. The hydraulic torque of the pump is given by

$$T_{hyd} = \frac{Q_{theo} \cdot \Delta p}{2\pi} = \frac{V_0 \cdot n \cdot \Delta p}{2\pi \cdot n}$$
$$= \frac{V_0}{2\pi} \cdot \Delta p \tag{C.22}$$

The friction torque is a function of the rotational speed n and the viscosity of the fluid. In a progressive cavity pump the friction losses are caused by different types of friction:

- friction between rotor and stator: constant
- friction through laminar flow: proportional to speed
- friction through turbulent flow: proportional to the square of the speed

For varying speeds there happens not only a change between these types of friction, but additionally there is a change in the area where the friction acts [4]. Therefore, the transition from one form of friction to the other should also be considered and can be empirically determined as a function of the rotational speed n.

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D Groundwater Deposit

Types and characteristics of Aquifer Systems

According to the water conductivity of the earth layers, three different types of layers are distinguished: The Aquifer, as the water conducting layer, the Aquitard as the layer with a relatively low conductivity and the Aquiclude as an impermeable layer. A sequence of these different layers forms the Aquifer system.

Three basic types of Aquifer systems are classified in the literature. Figures D.1, D.2 and D.3 below represent the different types. A confined aquifer (Figure D.1) is bounded above and below by aquicludes and its pressure head is usually higher than its watertable. On the other hand, an unconfined aquifer (Figure D.2) is only bounded below and its pressure head matches with its watertable. A leaky aquifer (Figure D.3) can be considered as a transition form, where at least one bounding layer is an aquitard which allows vertical flow (leakage) to the next aquifer, if there is a pressure gradient.

ground surface	pressure head	watertable
aqu aquirer	icude	
	aquiclude	

Fig. D.1: Scheme of a confined aquifer.



Fig.D.2: Scheme of an unconfined aquifer.



Fig.D. 3: Scheme of a leaky aquifer.

E Flow-chart of the Simulation Algorithm for a PVP-system Composed of a Progressive Cavity Pump and a Brushless DC-motor



Fig.E.1: The Scheme of the simulation algorithm of a PVP-system composed of a BDC-motor and progressive cavity pump.

According to the flow-chart in Figure E.1, the model is fed with the solar radiation and the ambient temperature which are used to calculate the I-V-characteristics of the PV-generator. In the PV-loop, the working point of the generator is calculated. Then the rotational speed-torque characteristic of the motor is calculated using the electrical power as parameter. In the same way the pump torque-rotational speed characteristic is calculated with the flowrate, calculated in the flowrate-loop, serving as parameter. The working point is then the crossing point of both characteristics. For its turn the flowrate is determined in the head-loop, in which the working point is obtained through the crossing points of the H(Q)-curve of the pump (parameter: rotational speed) and the hydraulic system characteristic. The presented algorithm works with 3 loops, from which 2 are interconnected.

F Analysis of the Main Operational Problems at PVP-plants installed in Brazil

Utilization of a System: The Consumer Influence

A relevant information which could be detected by the analysis of the measured data points filtered out by the plausibility checks (section 5.2), concerns the utilization of PVP-plants. This information involves the question of the use of water and its technical implications; therefore deserves to be closer examined since it reveals important details that have to be considered in the planning and implementation phases of such systems, besides being essential if a correct assessment of plant performance is to be made.

To illustrate the impact of the consumer behavior on the performance of a PVP-system, figure F.1 shows a plot of the water flow rate over the irradiation, for a period of five months operation for the system at Cajazeiras. The data presented here include the data points which were filtered out by the plausibility check, discussed in section 5.2.3 of the present work. As it can be seen in figure F.1 below, the performance of the system is often away from the expected. The plot shows a great deal of scattering for the water flowrate at all levels of irradiation, similar to that already shown in Figure 5.7 in chapter 5 (where the DC-power was plotted against irradiation). It can be seen in the plot, that by irradiation values as high as 1000 W/m² the water output varies from zero to about 3.5 m^3 /h, assuming all possible intermediary values in this interval.



Figure F.1: Measured flow rate versus irradiation (Q(G)) plot from five months operation (August-December of 1992) for the PVP-system installed in Cajazeiras. The plot illustrates deviations from expected system performance (the scatterings) which are explained in the text.

The reasons for these scatterings were analyzed in detail. In principle, several reasons could be the cause of the deviations. Some of these are:

- 1. PV-generator failures;
- 2. Inverter failures;
- 3. Pump failures;
- 4. excessive well drawdown (pump running dry);
- 5. water storage tank full.
- 6. failure of water flow measurements

In the information gathered by the system operator there was no reference of system or components failures in the period from which the data is evaluated in this work. This fact excludes the three first items listed above (1,2,3) as the causes for the deviations from normal operation.

A close analysis of the measured data shows that in the analyzed period there was no excessive drawdown which could cause the pump running dry. The average drawdown in the period was about 2 meters at maximum irradiation and is in the range considered in the dimensioning of the plant.

From the above facts, the most probable motives for the extreme deviations from the expected system performance was the situation of the water storage tank and/or failures in the water flow sensors. The problems coming from the storage tank were closely analyzed.

In order to provide a better understanding of the problem concerning the storage tank it is necessary here to be mentioned that in all systems installed in Brazil, the inverter controls, among a variety of other control tasks, the maximum level of water in the tank. A remote switch connected to its control board will signalize to the inverter when the water table in the tank attains its maximum, causing the inverter to enter in stand-by modus, until enough water is taken out of the tank. The details of the functioning of the remote switch are illustrated in Figure F.2 below.



Fig. F.2: The principle of the water level switch. While there is enough room in the tank the level switch stays in the horizontal position. When the tank is full, the switch stays in the vertical position, until enough water is taken out and it returns to the horizontal position again. According to the inverter operation manual the time necessary for the switch to return to the horizontal position depends on the quantity of water which taken out of the tank, which was estimated to be about 1/5 of the tank total volume.

The problem of the water tank being full and how that influences the performance of the system is well demonstrated in Figures F.3a and F.3b.

In Figure F.3a, plots of irradiation, array output power and pump water flow rate for two different days with clear sky conditions are shown. The plot on the left side is for the site of Cajazeiras, while that on the right hand side is for the plant in Lagoa das Pedras. In the first day (graphic on the left), the system is operating as expected. It can be seen that the generator output power and the flow rate curves follow the irradiation pattern. In the second day (graphic on the right), although under excellent irradiation conditions, the operation is critical, with the DC-power output as well as the water flow rate going often to zero while the irradiation is pretty high. This means that the tank is always full, or almost full, causing the inverter to switch off the PV-array several times.

The change in the system load caused by the storage tank being full can be better understood if one looks at the water pumped and water co

shows these curves for the same days of figu consumption fluctuates but the pump continue sufficient PV-power levels. The water consumpt



Fig. F.3a Influence of the storage tank on system load. Solar radiation, PV-array power output and pump flow rate are plotted for two different days with clear sky conditions. The graphic on the left (Cajazeiras) shows the system working normally, and the graphic on the right (Lagoa das Pedras) shows the repeated reduction in DC-power and water flow rate caused by the tank being full or almost full during the day.



Fig. F.3b Effect of the water consumption on system output. The dotted curves are the water pumped and the solid lines represent the water consumed for the same days presented in figure 5.22a above. The graphic on the left shows (Cajazeiras) that the pumped water flow rate is not interrupted, the day apparently started with an almost empty tank. While in the graphic on the right (Lagoa das Pedras) the water flow rate is constantly interrupted, suggesting that the tank was full in the morning.

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I hereby declare that the work presented in this thesis is solely my work and that to the best of my knowledge the work is original except where indicated by reference to other authors.

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