AN EFFICIENT PHOTOVOLTAIC PUMP SYSTEM USING A PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE

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ABSTRACT : In PV pumping systems the cost for PV array accounts for a substantial fraction (25-50%) of the total cost. A higher overall system efficiency results in a lower cost for the PV array. This efficiency is determined by the energy conversion efficiency of each of the components and by the matching of the components to each other. Based on synthetically generated hourly meteorological data for the site of Bamako (Mali) in a normalised 1kWp PV array is simulated using a thermal model for free-standing modules and a one-diode electrical model. The water yield is evaluated to optimise different system configurations. The development of a new highly efficient 3.5 kW permanent magnet synchronous motor (PMSM) is presented. It is chosen to implement a nominal PV array voltage of 270 V DC which corresponds to a nominal motor voltage of 190 V DC. Since no commercially available inverters fulfilled the combined requirements of the envisaged system, a standard inverter (IGBT power modules) is modified and adapted, adding a control algorithm and specific protection measures. Through means of overall system simulation the different system components are optimally matched and different control algorithms are compared.

Keywords : PV pumping - 1: Water-pumping - 2: Developing Countries - 3

1. INTRODUCTION

Photovoltaic (PV) pumping systems are used for satisfying drinking water and irrigation needs. Several systems have been developed in the recent past [1,2]. Surface applications for irrigation systems are driven by permanent magnet DC machines while for submerged motor-pump units induction machines are used. However, small induction motors have, when compared with permanent magnet motors, a lower efficiency, whereas DC machines are not applicable for submerged installations.

Most of the currently operating photovoltaic systems offer a mechanical output power in the range of 0.85 kW up to 2.2 kW [3]. For higher system power ratings the cost of the photovoltaic array increases substantially, however, these larger systems offer major opportunities for increasing overall system efficiencies. Due to the fact that the cost of the photovoltaic array accounts for a substantial fraction (25-50%) [1] of the overall installed pumping system cost, an increase in system efficiency can induce an important cost reduction. The optimised overall system efficiency is determined by the matching of all system components (Fig. 1) and the energy conversion efficiency of each of the components itself. Within this project a new 3.8 kW permanent magnet synchronous motor (PMSM) is developed for higher efficiency. The motor is controlled by a semi-standard inverter with selectable operation modes.

This paper presents experimental results from the drive compared to the standard induction motor performance. The optimisation of the overall system is performed for the typical site of Bamako in Mali taking cost-considerations into account. Different inverter algorithms are evaluated.

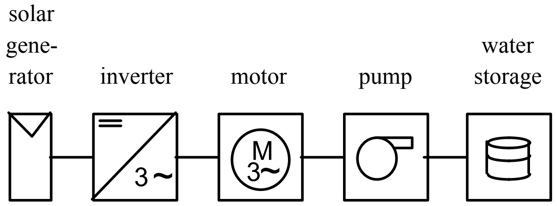

Figure 1 : General lay-out of the photovoltaic pumping system.

2. PHOTOVOLTAIC ARRAY

The installed power and configuration of the photovoltaic array is designed as such that it is matched with the inverter, motor and pump to obtain a maximum water output for the given meteorological conditions (Bamako, Mali, 12° N, 8.4° E). Hourly meteorological data are generated based on monthly values. A normalised 1 kWp PV array (10° tilt angle, South oriented) is simulated using a thermal model for free-standing modules and a one-diode electrical model. The histogram of figure 2 represents a distribution of the time in a year a certain in-plane irradiance and module temperature occur at the PV array. Based on this graph water output calculations are performed and optimised for different system configurations. For the motor with a nominal power of 3.8 kW the optimal photovoltaic array has a peak power of 5.5 up to 6 kWp.

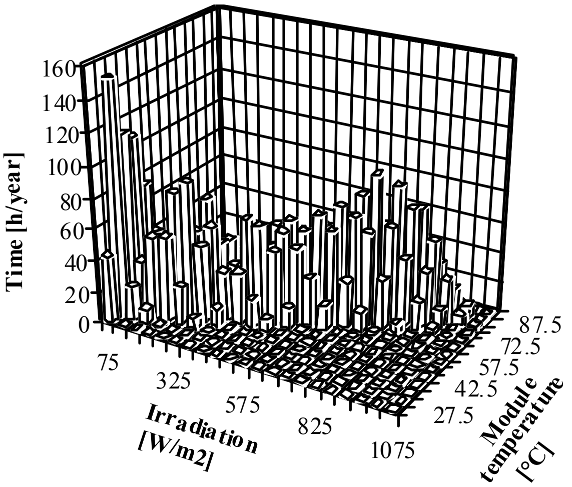

Figure 2 : The distribution of the time of the year a certain irradiation and module temperature occur for a normalised PV-system in Bamako (Mali).

It is chosen to implement a nominal PV array voltage of 270 V DC which corresponds to a nominal motor voltage of 190 V DC. The higher voltage is chosen in order to limit the current, reducing not only the motor size and the cost of the semi-conductor components for the inverter but also the inverter losses and the conduction losses in the PV array. Special safety precautions are to be taken to apply these voltages without inducing higher personal risk.

3. INVERTER

3.1 Inverter type and specifications

No commercially available PV inverter fulfils the combined requirements of the envisaged system, because of limited input voltage range, inverter standardization for induction motors and limited output frequency. However, the development and assembly of a completely new inverter would increase substantially the cost of the overall photovoltaic pump system. Therefore, a standard inverter (with IGBT power modules) is modified and adapted, adding a dedicated control algorithm and specific protection measures to ensure reliable operation under severe conditions. It is mounted on a water cooled backplane body and can be placed in an IP55 enclosure. Because of the use in rural environments, only a few relevant functions can be altered externally of the inverter after properly installing the system.

A wide DC voltage input range, 100 V - 340 V, enables the use of the inverter in a variety of PV array configurations. During laboratory tests, the inverter was tested at different input voltages and under various load conditions. Rated power of the inverter is 4kW/5.5 kVA.

A full inverter efficiency curve is not yet available but preliminary measurements show a conversion efficiency of around 87 % at 5% of nominal power and at least 95% efficiency from 10% of nominal invertor power on. Stand-by power consumption is rated at 4 to 5 Watts with a maximum of 10 (LCD display).

3.2 Input power control algorithm

The inverter used for laboratory tests can operate in three modes:

- constant voltage operation ;
- constant voltage operation with feedback of PV array temperature ;
- maximum power point tracking operation.

The first two control algorithms are implemented by the manufacturer of the inverter. However during laboratory tests on a real pump system, their performance was not satisfactory. In order to maximise the overall system performance it is considered essential to work in the MPP as much as possible. Because this MPP algorithm was not available from the inverter manufacturer it is developed in the frame of this project. The set-up used for the development and the testing comprised the standard invertor which was computer- controlled with direct access to the firing circuits of the IGBT's. After satisfying testing, the algorithm is programmed in an EPROM inside the invertor.

The implemented maximum power point tracking algorithm is based on simple decision rules. DC power available at the invertor input is measured every three seconds (other interval length can be easily implemented) and compared to the previous measured value. When an increase in frequency entails an increase in power, the frequency is further increased at the next sample instance. In case an increase in frequency leads to a decrease in power, the frequency will be decreased again at the subsequent sample moment. By the same token, when the frequency is decreased and this leads to an increase in available DC-power, the frequency will be further decreased.

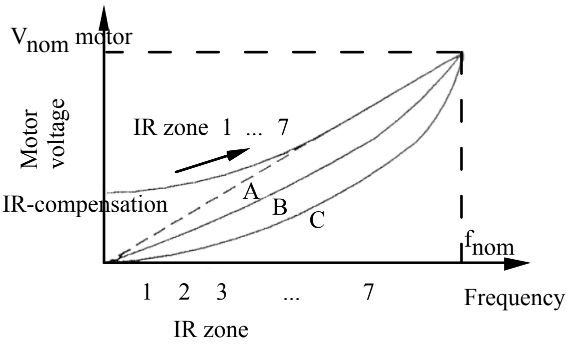

Figure 3 : The resulting voltage/frequency characteristic for the modified inverter. Characteristics A,B,C are preprogrammed standard curves which are modified by introducing the compensation measures, typical for the PMSM motor/pump combination, in the low frequency range.

The inverter is conceived in such a way that it allows for programming of the voltage/frequency relationship by which the motor is controlled in the MPP tracking sequence. This V/f-function is adapted specifically to the permanent magnet motor developed in this project thus optimising the interaction between the two system components. The V/f characteristic is given in figure 3. It shows three preprogrammed standard characteristics (A,B,C) and the resulting curve including the compensation in the low frequency (starting) range which is typical for this motor/pump combination.

Table 1 gives the results of a comparative simulation of the efficiency of the 3 input power control algorithms for a normalised PV system under the given meteorological conditions. For the difference of around 1.5 % in energy yield a trade-off counts between the increased system complexity and the additional PV module cost.

Table 1: Simulation results of yield of normalised PV system for the three different control algorithms.

Control algorithm	**Yield [kWh/kWp]**
MPP tracking	1603
Constant voltage	1582
Module temperature dependent voltage	1597

4. MOTOR DESIGN

To optimise the PV pumping yield, it is important to reach high conversion efficiencies at medium and low irradiation levels. This corresponds to the requirement that the motor operates with low losses in a large power range, at least from about 50 % to 100 % of its rated power.

NdFeB permanent magnet material offers a high energy density as well as a high remanence flux density. A high remanent flux density is needed, while a high coercivity is less important as overloads do not occur. Besides the permanent magnets (NdFeB), the rotor has to carry a rotor cage in order to enable the motor to operate in “open loop” mode. Therefore, the angular magnet width is restricted to give way for the rotor bars [4,5].

In order to compare the performance of an induction motor to that of a PMSM, a 3.2 kW standard induction motor is modified by applying a new stator winding and a new rotor containing permanent magnets and a symmetrical rotor cage. The higher efficiency of the permanent magnet motor at partial load can be demonstrated distinctly if the newly assembled rotor is compared to the original standard rotor of the induction machine, both having the same stator. The measurements show that due to the new stator winding the maximum efficiency point for the induction motor has shifted to the lower load region (Fig. 4). However the efficiency of the motor with the permanent magnet rotor is distinctly higher than the efficiency with the squirrel cage rotor.

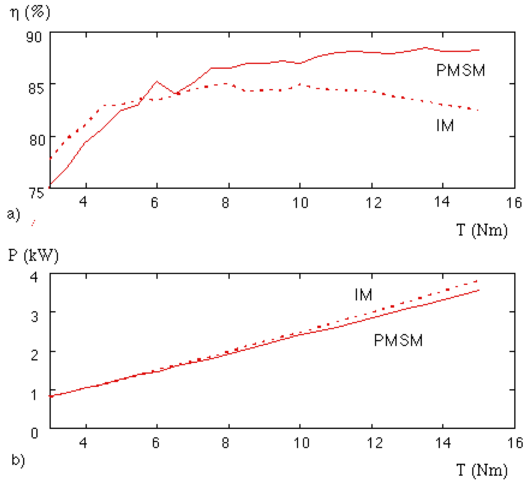

Figure 4 : a) Efficiency and b) mechanical output power versus torque, for the two rotor types using the same stator at 2000 rpm. The plain line corresponds to the permanent magnet rotor while the dotted line represents the results for the induction rotor cage.

5. PUMP

According to the envisaged installed power range, a centrifugal pump is chosen. Considering the constraints set by the PMSM, the pump has the highest efficiency in the range of 1500 to 2200 rpm and a maximum mechanical power of 4 kW (Fig. 5, next page). The optimum working conditions of this pump are found at a total manometric head between 12 and 18 m. However, this can be adapted by adjusting the impeller.

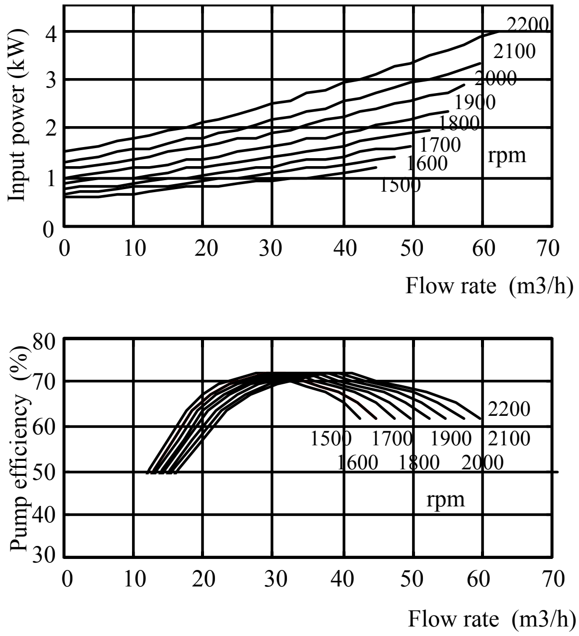

Figure 5 : Required input power and pump efficiency as a function of flow rate.

6. CONCLUSION

Due to increased component efficiency on one hand and optimal matching of the different system components on the other, a major cost reduction is obtained. This reduction is caused by lower PV array costs which account for a substantial fraction of the total cost for the size of pumping system under consideration.

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REFERENCES

[1] Ph. Malbranche, J.M. Servant, A. Hänel, P. Helm Recent, Developments in PV Pumping Applications and Research in the European Community, 12th European Photovoltaic Solar Energy Conference, April 1994, pp. 476-481

[2] R. Barlow, B. McNelis, A. Derrick, Status and experience of solar PV pumping in developing countries, Proceedings of the 10th European Photovoltaic Solar Energy Conference, Lisbon, April 1991, pp. 1143-1146

[3] S. Makukatin, Water from the African sun, IEEE Spectrum, October 1994, pp.40-43

[4] Nasar, S. A.; Boldea, I.; Unnewehr, L.E.: "Permanent Magnet, Reluctance, and Self-Synchronous Motors", CRC Press, London Tokyo, 1993.

[5] Sebastian T., Slemon, G. R., Rahman, M. A.; Design Considerations for Variable Speed Permanent Magnet Motors, Proc. ICEM'86, Sept. 1986, part 3 , pp. 1099-1102.