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A Review on the Diversity of Photovoltaic Water Pumping Systems

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ABSTRACT

Three aspects of the photovoltaic water pump, namely: i) technical and commercial viability; ii) design versality; and iii) matching analysis and optimization are thoroughly reviewed using a number of published articles. These articles reflect the importance, around the world, of this technology from the socio-economic and environmental points of view.

INTRODUCTION

Photovoltaics (PV) is one of the most popular choices for renewable energy sources. The basic characteristics of a PV system which make it an attractive choice are: i) direct conversion process; ii) little or no maintenance problems of the system; iii) applicability in remote and isolated areas; iv) pollution free system; v) availability of abundant solar energy; and vi) simple to operate by lay users. PV power has found applications in all corners of the earth – from villages in Polynesia to Ethiopia, to large-scale utility projects in California. PV is used in water pumping, lighting, consumer electronics, refrigeration in third world village pharmacies, utility-scale projects and space applications. Even though PV found its first application in space, the magnitude of its terrestrial applications at this time overshadows the extra-terrestrial uses. Of these terrestrial applications, water pumping is particular important with uses ranging from the simple provision of drinking water to household, agricultural and industrial uses.

Since the first installations in 1978, PV pumps have gained enormous acceptance. It is now estimated that over 10,000 PV pumps have been installed around the world [1], of which over 1000 pumps have been installed for water supply in Indian villages, mostly pumping water from shallow wells. A report [2] of the Department of Non-Conventional Energy Source (DNES), Ministry of Energy of India shows that 852 PV water pumping systems have been supplied through DNES to various agencies for installation at numerous places in India. The ASVIN programme of CNRS (France) and the WORLD ENERGY FOUNDATION [3] have installed twelve French solar PV pumping systems in various climatological and sociological regions in India. Ten deepwell PV pumps have been installed at various sites of India by COWI Consult (Denmark) [4] and Central Electronics Limited (India) plans to set up 200 deepwell pumps powered by PV generators at remote and isolated Indian villages [5].

The installation of PV water pumping systems in India has a very promising future, because of the need to replace the 4-5 million 3.5 kW diesel powered water pumps, which are currently operating in remote and isolated areas. This market alone could support annual PV sales of perhaps 1000 peak megawatt, 25 times the current global sales [6]. The potential of the PV water pumping system applies not only to India. It is also estimated [7] that there are over one million remote rural villages in the world (with populations of over 200 people) that need to pump water to sustain their existence. Most of them are located in hot, dry and sunny areas where the PV water pump is an ideal solution.

PV pumping programs are also flourishing in other developing countries [1,8]. In Mali, there are approximately 160 working installations. As part of the CEC (Commission of the European Communities) solar electric pumping project in the Sahel region [9], 226 pumps are being installed in Mali, and 814 systems in other areas of the Sahel. In Morocco about 100 PV installations were provided by the Ministry of the Interior and there 100 other systems have been installed privately, with an average capacity of around 1 kWp. In Brazil, approximately 53 systems had been installed by September 1990, with an array rating of 500 Wp. There are plans to install 8 PV pumps under a German-Brazilian co-operation programme. Thailand has installed around 15 PV pump systems.

Some higher power PV water pumping systems with high water heads applications have been installed (or have been commissioned) to study its commercial and technical viability in the field around the world. The details of these installations are shown in Table 1.

Although PV water pumps are widely accepted, there is generally a gap between the conception of a technological or scientific innovation and its actual implementation in the field. This review article, therefore, is an attempt to stimulate interest in PV water pumps and help to reduce this implementation gap.

Table 1. Description of different installations of large size PV pumps.

Place	Power in kW	Motor Type	Pump Type	Head in m	Power Conditioner	Back-up Power	Purpose	Date of Instal.	Reference
Zambelli (Italy)	70	AC	Submersible Centrifugal	350	Com., Inv., Battery Charger	Battery	Drinking Water Supply	1984	10,11
Karpathos (Greece)	10	AC	Submersible Centrifugal	70	Inverter, MPPT	Diesel	Irrigation	1987	12
Mugombwa (Rwanda)	7	DC	Centrifugal	80	Battery Charger	Battery	Drinking Water Supply	1986	13
Gua-Gilap-Gunug (Indonesia)	6.3	AC	Submersible Centrifugal	150	Inverter	Battery	Village Water Supply	1986	14
Corsica (France)	3.83	AC	Submersible Centrifugal	80	Inverter, MPPT	NO	Watering Cattle	1987	12
Freiburg (Germany)	1.71	DC	Aquasol KSB 50L	–	NO	Battery, Wind	Pavilion Water Supply	1987	12

VIABILITY OF PV WATER PUMPS

The viability of the PV water pumping system can be studied under two headings: i) technical viability and ii) commercial viability.

Technical Viability

The technical viability of this technology is determined by the reliability of its field performance. Therefore, a number of reported field performance studies of the PV water pumping system are discussed in this section.

Barlow et al. [1] reviewed the field performances of more than 5000 PV pumps which are installed all over the world. This study concludes that the technical problems are now largely resolved and that reports of poor performances from some of the systems are mainly due to the incorrectly specified solar, water resources and water demand data.

The field performances of about 3000 PV water pumping systems, installed in different parts of the world under a project sponsored by UNDP and the World Bank from 1978-83 are reported [15,16] to be good and well accepted by local people. These systems are of three types: (a) low water head (2-7 m); (ii) medium water head (7-20 m); and (iii) high water head (more than 20 meters).

The largest number of PV pumps installed in one country is in India. The field performances of more than 500 PV pumps in India are reported to be quite acceptable [17]. It is also reported that nearly 58 irrigation PV pumps out of 60 installations had been working satisfactorily for more than 4 years.

Ten years of continuous operational experiences [9,18] with low power PV water pumping systems in Mali with a failure rate of less than 1% has proved the reliability of the PV water pump system in the field. The detailed monitoring of 66 pumps from 1983 to mid-1989 found 37 failures, equivalent to a mean-time between failure (MTBF) in excess of 30,000 hours. The typical time taken to respond and repair a pump was 4 to 10 days with a few cases over 3 months. Given the average repair times encountered in Mali, the average pump availability is more than 99%. It is also reported that of the 126 pumps observed in mid 1988, nine were inoperative due to the age of the model and five pumps were abandoned because the wells had dried up. The remaining 112 pumps were working well.

Sorokin et al. [11] writing about the field performance analysis of the Zambelli PV pumping station reported that the daily pumping utilization factor of this plant frequently exceeds 60%, which is an extremely high value hardly reached by other PV pumping systems. The pumping utilization factor defined here as the ratio of the hydraulic power transferred to pumped water volume and the maximum capability of the PV array.

The causes of failure of different PV pumps under different climatic conditions have also been studied [12,19]. Jl Barret [19] noticed from the field performance of 5 micro PV pumps with an average power of 200 watts in the regional parks of Marais Poitevin, France that some controllers and house meters had failed and that choking of the pipe sometimes created a problem of water flow. This study also reported on the field performance of irrigation PV pumps of 1.5 kW and stated that sometimes the inverter is the cause of failure of the systems.

The field performances study of irrigation PV pumps [12] at Bourriot Bergonce, France showed that the pumps had worked perfectly since 1979, apart from a breakdown in one pump in 1980, caused by faulty adjustment and a failure of the shaft extension in 1981.

With reference to two PV pumps which began operating in the public garden, Freiburg, Germany in April 1986, it was reported that after two years both pumps had to be replaced: in one case due to electrical problems and in other one due to sealing problems [12]. After replacement these pumps were still working, without problems, in 1992.

The PV pumps for watering cattle and washing operations in a slaughterhouse in Corsica, France have been satisfactorily operating since March 1987 [12]. No repairs of PV parts have been necessary, only the submersible pump had to be cleaned sometimes and some motors had to be replaced in the summer of 1988.

The field performances of more than ten irrigation PV pumps with water heads of 3 m and 40 m during the period of 1985-90 at a rural site in the Aures mountains, Algeria have been reported by Hamouda et al. [20]. The systems adaptability to the realities of water influx and water supply in the local well was sometimes problematic due to the incorrect design of these pumps. In this design the pumping capacity was too high. The training of local staff for maintenance reduced the problem of having to completely stop the system. One of the main reasons for system failure here was the unauthorized intervention of local people. At first the rural people objected to PV modules being installed right next to the local well where the land is most fertile, however, the attitude of the local people completely changed when they received the benefit of increased irrigated land. The technical failures of these systems have been estimated as: i) cells, 5%; ii) AC motors, 7%; iii) DC motors, 14.2%; iv) glass of modules cracked, 15%; v) electronics, 21.1%; and vi) inverters, 27.7%. Sometimes the system was stopped due to outside vandalism, 10%.

Technical Barrier

The most obvious ingredient to successful PV projects is the appropriateness of the technology – it must be matched to customer needs, cost effective and simple to install and maintain [21]. The PV industry is rightly focused on reducing costs and developing user-friendly designs. But developing a simple, reliable and low cost PV system is only part of the equation. Much more needs to be done on the worldwide PV consumer market. It will depend on incorporating consumer feedback on product quality and service, removal of import barriers and encouragement of joint foreign/domestic manufacture and assembly of equipment. Information programs and other supporting infrastructure are usually lacking in the developing world. There is also a need to counter misconceptions about alternative energy performance, applications and cost competitiveness.

Commercial Viability

PV is already competitive on the basis of overall costs with alternatives such as small diesel generators. For example, a cubic meter of solar pumped water is 20% cheaper than diesel pumped water [22] in the Sarwal and Gopalpur regions, India. This calculation has been made with a failure rate of 10% based on 10 years of operation, whereas a diesel pump does not usually last more than five years.

The costs of PV pumps and diesel pumps were compared using the market price of 1989 for variable power ratings [23, 24]. This showed that the cost of PV pumps for the size of less than or equal to 1 kW is always less than the diesel pumps.

A comparative cost analysis of DC PV pumps and diesel water pumps installed in the Aures mountain, Algeria has been made under variables of time span by Hamouda et al. [20]. The study shows that the water costs of a PV powered pump and a diesel powered pump will be equal in the seventh year of installation but the cost of the PV powered pump will be lower thereafter. A similar cost comparative study [9] for Mali PV water pumping station shows that PV pumping systems have comparable or lower water costs than hand, animal or diesel pumping for water table depths greater than 15 meters, and for villages with more than 250 people.

Experiences with about 3000 PV pumps around the world show that the array cost can compare with the cost of the rest of the hardware [15,16] for PV water pumping of relatively low power at medium water head applications (less than 1 kW). Therefore, low power PV water pumping systems in remote locations can compete with diesel or hand pump systems. Amado et al. [22] reported that a directly coupled small scale PV water pump in the tribal villages of India is an appropriate technology.

PV is not yet cost competitive with grid electricity. However, the cost of PV largely depends on government policies and the availability and demand for energy from other sources in a particular place. It is estimated [12] that PV systems with power of 400 Wp are cheaper than grid extension when their distance from the grid is greater than 600 meters, and that systems of 1200 Wp are cheaper when their distance is greater than about 1500 meters in France. Of course, these will vary with the nature of the countryside. In India, 1.5 kW PV panels do not cost more than the cost of an electric line of 1 km [22]. Therefore, it can be concluded that the cost of installing 1.5 kW PV systems is cheaper than grid extensions to places 1 km away from the grid. The experience with installations of different size PV pumps in India also reveals that the PV pumps are economically interesting at locations more than 5-7 km from the public grid [4].

A comparative cost analysis on DC and AC PV pumps installed in the Aures mountain, Algeria has been made by Hamouda et al. [20]. This study shows that the AC PV pumps will be economic as compared to DC PV pumps when the value of a parameter (flow rate * water head) is more than 600 m^4/day.

Commercial Barriers

Power and utility preferences for large, centrally managed energy projects, emphasis on capital rather than life cycle costs and limited accessibility to affordable credit [21,25] are serious barriers to the widespread adoption of PV systems. Macroeconomic pricing policy distortions are also significant barrier, for example, subsidized kerosene and electric prices, especially for the rural and agricultural sectors, are the rule, rather than the exception, largely because of political considerations.

Another financial barrier is the high capital investment required for PV pumps compared to traditional technologies. Rural people have barely enough money for subsistence living, paying cash for relatively expensive home systems is simply out of the question. However, PV pumps incur no fuel costs, and have very low operation and maintenance costs, compared to kerosene, diesel or grid connected systems.

Conclusions

From this survey, it can be concluded that PV water pumping systems are technically viable all over the world. In the field performances studies, some problems have been identified. These problems are now largely resolved. However, problems may still arise due to unexpected weathering conditions and incomplete/incorrect system design.

From the survey of the commercial viability of PV pumps, it can be easily concluded that PV pumps have commercial viability in rural areas. The conclusion is further strengthened when environmental costs are factored into the equation. The keys to the popularisation of this technology are: i) government commitment to energy pricing reforms, in particular, tariff reforms in the power sector; ii) widespread training and workshops for lay users on operation and maintainance, and for designers on new and innovative technological advancements; and iii) bold and innovative financing and leasing schemes related to PV technology for the rural people.

SYSTEM DESIGN

System design means the selection of efficient, technically reliable, and appropriate system components. A PV water pumping system can be designed in a number of ways as shown in Fig. 1. Improved system designs could mean substantial savings in the initial investment cost. A large number of interdependent factors which have been identified by different investigators, are involved in the design of PV water pumping systems. In the following section, the versatility of PV water pump system designs and the comparative performances of different categories of these are discussed.

Baltas et al. [26] examine, theoretically, the various design philosophies of PV water pump systems including the battery and tracking array. Jansen [27] discusses an effective design procedure based on a simulation program and the effect of alterations in the design. The problem that these design procedures face is that, in practice, only a limited number of types of components are offered.

Rosati et al. [28] illustrate the technical features of a project concerning development of a motor-pump unit for remote zones, having some innovative concepts with high efficiency and reliability. This system is composed of a mixed flow centrifugal pump, a permanent magnet DC motor and an electronic control system. The innovative concepts in this design are: i) high adaptability of the pump for high speed motors; ii) minimisation of moving parts in pump; iii) proper grease lubrication of motor; and iv) use of an Al-Ni-Co permanent magnet instead of a rare earth material permanent magnet in motor design.

Studies on system designing of small power (0.5 kW) PV water pumps under equivalent field conditions are reported by Fett et al. [29] and Koner et al. [30]. One of the pumps was designed and developed [29] by the Institute of Energy Technology, University of Siegen, Germany. The energy balance study shows that the total efficiency of the investigated system is 3.6% for a standard day. Another pump was designed and developed [30] by the Centre for Energy Studies, Indian Institute of Technology, Delhi, India. The system consists of a PV generator, a brushless DC motor and a centrifugal pump. This study investigates different losses: a) voltage/current mismatch between PV array and DC motor-pump for its maximum efficiency; b) array loss due to the change of configuration of solar cells; and c) non-optimal power extraction from the array to the motor-pump. The results show that the maximum total efficiency of 2.74% can be achieved under outdoor conditions after proper designing.

Design characteristics of water pumps with PV generator for different locations and requirements are addressed by various researchers [31-34]. Kulunk [31] designed a water pumping system at Urfa [latitude 37°N, longitude 39°E and altitude 54 meters] in Turkey. The system consists of a solar array, a piston pump and a DC motor and a water tank. Characteristic parameters of the system are determined by using daily solar radiation and sunshine data. A PV pumping

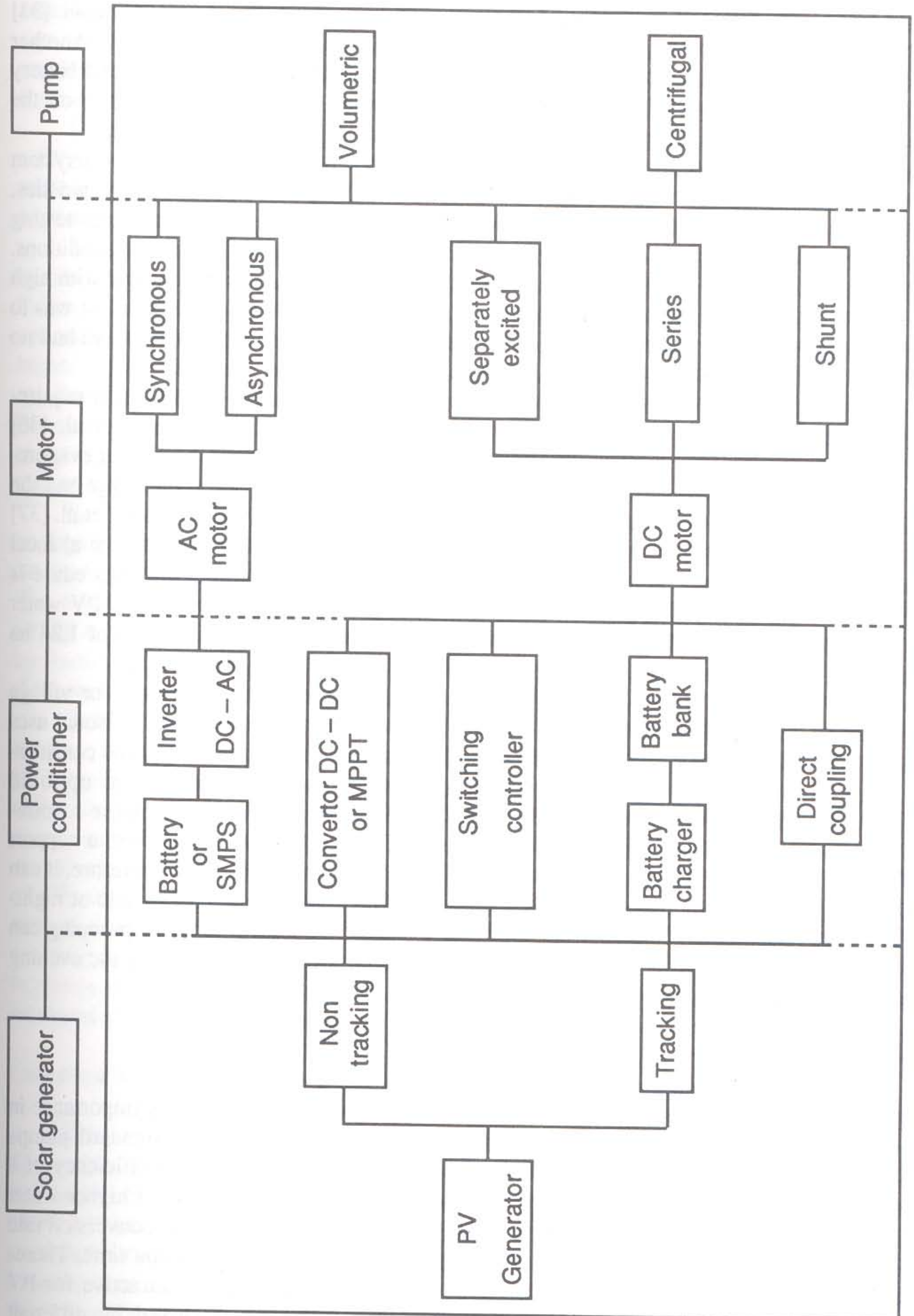

Fig. 1. Block diagram of different options for a photovoltaic water pump.

system based on a computer program is described by Hasson et al. [32] where the basic parameters are: solar insolation, temperature, water consumption, the power of the pump. Al-Rawi [33] describes a water pump installed to supply drinking water to 20 residential units in Iraq. Another study of low concentration PV water pumping system with a microprocessor control and battery back-up subsystem is presented by Teoh et al. [34]. The design of this system is based on the statistical results of the solar radiation in Penang, Malaysia from 1975 to 1980.

Cass and Hulse [35] present a design of the PV powered pumping as an irrigation system which was constructed in San Luis Valley, Colorado,USA. They present the site characteristics, design requirements and system description. Following the installation, an extensive site testing and evaluation were performed. The testing was performed during extreme weather conditions. The conditions included 45°C, heavy snows, frost on the lens on most mornings, coupled with high speed winds in excess of 30 miles/hour. The authors concluded that the effect of the frost was to reduce the operating time by approximately 0.75 hour per day assuming 50% of the days had no frost. The number of days analyzed was 75.

The design of PV water pumps for irrigation including the parameters of crop water requirement and local climatic data has been reported in the literature [36-37]. Al-sagir et al. [36] designed an irrigation system based on the irrigation discharges, leaching discharge and evaporation factors. The Peman's formulae is used to calculate the amount of irrigation discharge and the leaching discharge is based on the electrical conductivity of water and soil. Fraidenraich et al. [37] analyse an integrated PV irrigation system by considering the interaction of four factors: a) local climate; b) irrigated crops; c) soil conditions; and d) PV pumping equipment. This procedure is used for the cultivation of grapes in the area of Petrolina PE, Brasil. It shows that a PV water pump of 450 watts can irrigate an area of 1.57 ha using a storage system and an area of 1.24 ha without storage system.

A novel pumping system (PULSA Solar oscillation pumps) has been designed for village hydraulics which will supply from 4 m^3 to 7 m^3 of water for drinking purposes and personal uses [38,39]. This design is based on the parameters of inhabitants in a village of 200 people considering the minimum prescribed by the WHO (25 liters/person/day) and bore-holes heads up to 50 meters deep. It shows that a PV array of only 160 Wp to 240 Wp is sufficient for these requirements. The system is composed of a solar kit comprising an upper element chamber, a support structure, a DC motor, a fly-wheel, a PV array and a PULSA hand pump system. Therefore, it can be operated by PV energy as well as by hand. Manual operation is, therefore, possible at nighttime and when instantaneous sun power is not available due to cloud cover. Manual pumping can also help to enhance the capacity of pumped water early in the morning and towards the evening when sun power is not sufficient.

Subsystem Designing

The designing of subsystems (pump, motor and storage system) are also of key importance in improving the matching performance and efficiency of the system. Generally, standard pumps suffer at low insolation levels and high water head in the field. For example, the efficiency of a conventional multistage centrifugal pumps decreases at part load conditions and at higher water head (more than 100 meters) applications [40], because under these conditions the conversion rate from electric to hydraulic energy is rather low during a significant part of operation time. Therefore, the progressive cavity pump which is the improved design of pumps, is attractive for PV water pumping applications. Such pumps have been designed and are discussed by different investigators [42-46]. The initial investigations show that this pump is superior to the conventional centrifugal pumps for PV applications because it has better operating characteristics at low insolation levels and higher efficiencies at low hydraulic loads. The reliability of this pump has been verified by Hermann et al. [43] who ran this pump by PV array under equivalent field conditions for 8 months. The primary results are quite satisfactory.

Lasnier et al. [44] present a study of a new type of positive displacement pump connected to a PV generator through an impedance adapter. The performance of positive displacement pumps without impedance adapter is very poor. However, the study by Koner et al. [45] reveals that the high speed centrifugal pump can be a competitor for high water head PV applications.

The properties of the hydraulic system play a significant role in the performance of the system, especially in the case of small capacity wells with long recovery times, as discussed by Baltas et al. [46,47]. In these studies, the overall system performance of small water wells is optimized by a computer simulated program. This method can be used for different applications of higher volumes of water because the well is allowed to recover, hence, the average draw down is smaller. The viability of each pumping option will depend on the dynamics of the hydraulic part of the system. Computer simulation programs can help the designer to choose pump models and to size the components of particular pumping applications. Analytical results can be obtained in the case of linear wells and centrifugal pumps by this simple model.

Reliability problems of DC motors with brushes make the development of brushless motors in submersible pumps attractive. A model of a permanent magnet AC machine and DC to AC inverter which consists of a single phase brushless DC motor, is discussed by Mayer et al. [48]. The computer simulation is used to illustrate steady-state operation and dynamic performance during starting. The high efficiency brushless motor was also characterised and tested in the field by Barth [49]. The design of this motor is based on rare earth magnets. The field performances of these motors are quite promising.

Better designed storage systems for PV pumping applications are very important. In general, there are two types of conventional storage systems in this application: i) electrō-chemical storage (Battery) and ii) hydraulic storage (Water Tank). The battery storage system has its own disadvantages: shorter life, heavy maintenance and poor recovery energy. Moreover, the water storage system cannot help to match the load and source. Therefore, a new short term electro-mechanical storage system was designed and is discussed by Landau et al. [50]. This storage system consists of a flywheel and a sturdy permanently excited synchronous machine. The basic principle of this storage system is that the energy is stored in the electromechanical device when the pump is not working due to poor insolation levels. This energy will be released to the pump when the pump begins to operate at its optimum level. The advantages of this system are: i) low maintenance; ii) increased system preformances; and iii) overload protection.

Comparative Performance of PV Water Pumps

Comparative studies on the impact of the choice of PV pumping technology are discussed in this section. A comparison of the different options of PV generators in pumping systems has been studied [32, 51]. Hori et al. [51] compared a prototype PV water pump system for different types of PV modules. It shows that the pumping water flow quantity achieved 91% of the theoretical maximum flow with cz-Si solar cells, and 86% of theoretical maximum flow with a-Si solar cells by using a particular optimized water pump system. It indicates that the type of solar cell affects the pumping performance. Hasson et al. [32] compared the performance of fully tracking and fixed

PV water pumping systems. This study shows that the tracking PV water pumping systems are more efficient, however, they seem to be very expensive compared to fixed systems.

The same comparison has been made under the options of power conditioners and storage systems [52-54]. Hanitsch et al. [52] report on a comparison study of stand-alone PV pumping systems with and without battery storage. This study indicates that the system performances do not suffer significantly without battery storage. In fact, no battery is needed to supply the electronic control circuit and microcomputer. The performance of 3 kWp pumping station in Zaire (PV-generator-battery-DC motor-volumetric pump) has been compared by Geldof [53] with battery and with electronic impedance adapter. The efficiencies of both systems are found nearly the same whereas a battery system has its specific battery related disadvantages: cost, weight, maintenance, place and shorter lifetime. Semmola et al. [54] compared the performances of PV water pumps in the range 0.3 to 1 kWp with and without a maximum power controller. This investigation shows that in an optimized system the loss of energy is negligible in comparison to a system incorporating a maximum power controller.

The system performances of different types of motors have been compared by several investigators [55-57]. Redi [55] presents the results of a comparative study of the use of asynchronous, synchronous and brushes DC motors in a 300 watts submersible pump using a variable frequency converter. Synchronous motor with permanent magnet offers the best efficiency whereas AC generation from PV generator is more complex. A similar study on a directly coupled PV generator with two different types of motors has been made by Koner et al. [56, 57]. These systems are i) PV-generator-DC series motor-centrifugal pump and ii) PV-generator-brushless DC motor-centrifugal pump. The results of the study indicate that the brushless DC motor PV water pump without power conditioner is superior.

Lastly, a detailed study has been carried out to compare a system's suitability for a pumping chain using photovoltaic generator by CIPEL and SOFRETES, France [58]. The performance results for different chains and components for a PV water pumping system are shown in Fig. 2. The conclusions of this study are that the directly coupled PV generator connected to a separately excited DC motor and a volumetric pump, with an electronic adapter is placed between motor and pump, gives the best efficiency.

Conclusions

There is no unique choice for the design of a PV water pumping system. It strongly depends on a number of parameters, site selections and applications [59]. The major field variables in the design are: i) seasonal variation of water depth of a site; ii) variation of solar insolation level and temperature (during a day and season); iii) extreme weather conditions (snow, frost, dust and high wind, etc.); and iv) long term degradation of PV modules in the field. Other variables are: i) type of solar cells or modules; ii) mode of tracking or fixed PV generator; iii) with or without power conditioners; iv) type of storage system; v) water requirement for different applications; and vi) control system (microprocessor/computer/manual). Site selection is important apart from considerations of the site's climatic conditions because the design must take into account the felt needs and priorities of the local population.

From the survey of comparative performances, it can be concluded that for rural areas driving a pump using only a PV array, without any intermediate battery storage unit, is desirable from the socio-economic and maintenance points of view. It is extremely feasible in the dry

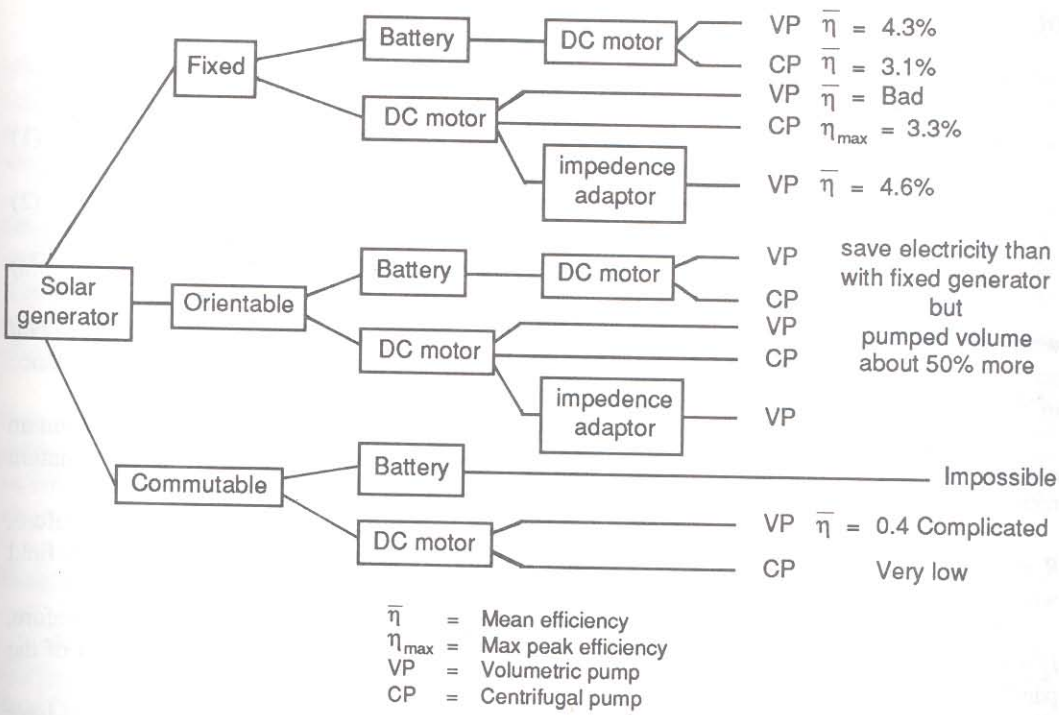

Fig. 2. Comparison performance of different configured photovoltaic water pumps.

tropics such as India on account of the very short duration of periods of no direct sunshine. In addition, power conditioners or electronic equipment are not advisable for lay users and in remote and isolated areas where a maintenance service is hard to get.

SYSTEM ANALYSIS AND OPTIMIZATON

Low powered directly coupled photovoltaic water pumps make an important contribution to the socio-economic life of rural regions [16,22,53 and as also discussed in the previous section]. However, the losses in small PV pumping systems in the field are considerably high. These losses can be minimised by careful design of the system based on detailed mathematical analysis [60]. Analysis by means of mathematical models improves the system performances and helps to achieve further reduction in system cost. Therefore, a number of research articles on the analysis of DC PV water pumping systems using such models are reviewed in this section.

A directly coupled PV water pumping system consists of a PV generator, a DC motor and a pump. There are three main types of DC motors: a) series; b) shunt; and c) separately excited motors, and two types of mechanical loads: a) centrifugal pump or ventilator load; and b) volumetric pump or constant load pumps.

DC Motors

The I-V characteristics of DC motors can be approximated as:

$$V_L = I_L . R_t + V_e \tag{1}$$

$$V_e = K . F . w_L \tag{2}$$

$$T_m = K . F . I_a \tag{3}$$

where K is the dimensionless constant, F is magnetic flux in Weber, w_L is the speed of shaft in rad/sec, T_m is the torque in Nm, V_e is the internal generated voltage in volts, R_t is the internal resistance in ohms and I_a is the armature current in amps.

For a separately excited motor, the magnetic flux is supplied by a winding powered from an auxiliary source. Therefore, $R_t = R_a$ and flux is fixed (K . F = C), where R_a is the armature resistance and C is the motor field constant of the separately excited motor.

For a series motor, the magnetic flux is generated by a series connected winding. Therefore, $R_t = R_a + R_f$, $I_L = I_a = I_f$ and K . F = M . I_a, where R_f and I_f are the resistance and current of the field winding respectively, and M is the motor field constant of the series motor.

For a shunt motor, the magnetic flux is generated by a parallel connected winding. Therefore, $I_L = I_a + I_f$, $R_t = R_a . R_f/(R_a + R_f)$ and K . F = M . V_L / R_f, where M is the field constant of the parallel motor.

Preliminary analyses of the characteristics of three types of motors for PV applications have been made [61,62]. These analyses show that, because of their good reliability and ability to operate over a wide range of input voltage, separately excited or permanent DC motors are generally regarded as the most suitable motors for use in PV systems without power conditioners.

The PV generator is a non-linear and time-dependent power supply. Its output varies with the insolation levels (hourly and daily), therefore, the steady and transient performance characteristics of the DC motors will be different. Therefore, the steady and transient motor characteristics powered by a PV generator were analysed by Appelbaum [63] with the help of the computer program "Super Sceptre". It was found that the shortest starting time was taken for the separately excited motor, and the longest time for the shunt motor.

DC shunt motors are not recommended (according to the above studies) for use in PV pumping systems. However, a detailed analysis on their matching efficiency has been made [64, 65]. A graphic analytical method has been proposed [64] for the analysis of a shunt motor directly coupled to a PV generator. It allows determination of the behaviour and the characteristics of the system on the basis of a correspondence between the point of the electrical plane (voltage to current) and the points of the mechanical plane (speed to torque). The dynamic performance of this system was also studied by Fam [65]. However, the DC shunt motors have not yet been forwarded to the PV water pump applications.

PUMPS

The working point of a pump is determined by the intersection of the curves of the torque as a function of the speed for a constant water head of the pump. This relation can be approximated as:

$$T_l = T_s + To \,.\, w^x \tag{4}$$

where T_l and T_s are the load torque and static torque of a pump, T_o is load constant and x is the load-torque constant or load factor. The load factor categorises the pump class such that x = 0 corresponds to a constant load pump or volumetric pump or positive displacement, x = 1 to a viscous friction pump and x = 2 to a ventilator load or centrifugal or rotodynamic pump.

The characteristics of centrifugal and volumetric pumps were experimentally determined for identical conditions by Follea [66]. Using these relations in the analysis of a direct coupled PV water pumping system, he concluded that the ventilator load pump is the best choice for PV applications. Khater [67] presented a study on the matching analysis of a directly coupled PV pump under variable load factors. He concluded that load factor changes the operating conditions of the system and that the maximum efficiency is found for a load factor of two.

A comparative analysis of complete directly coupled DC PV water pumping systems with three different motors and two different pumps, has been conducted by using a graphical analytical method [63, 68-70]. These studies suggest that a separately excited or permanent magnet DC motor coupled with a ventilator load is the most suitable system for directly coupled PV applications.

Separately Excited Motor

Detailed analyses of different aspects of matching on different pumps driven by separately excited motors have been carried out by various researchers [71-78]. The relative position of the load line to the maximum output line of the PV generator indicates its utility in pumping. The analysis of pumping utility under variation of the pump speed [71] shows that the characteristic performance variations of a directly coupled system with a separately excited motor and a centrifugal pump are within reasonable limits during a standard day. It is also pointed out in the same study that the array utilization is strongly dependent on the load line but the load line does not necessarily coincide with the maximum power line for good array utilization.

The matching condition of a separately excited motor connected with two pumps (centrifugal and volumetric) with a PV generator has been analyzed theoretically by Appelbaum [72]. This study contributes to an understanding of the system performance for both load types and both steady and transient characteristics of a motor when operated by a PV source. A three dimensional graphical presentation of the parameters (motor terminal voltage and current, speed, solar cell generator voltage and current, and output power of the generator), has shown that all of these are affected by solar insolation levels and temperatures. The conclusion of this study is that a centrifugal pump is the best choice for this application. This study also suggests that it might not be necessary to use a motor starter since the starting armature current is limited by the size of the PV generator.

A theoretical analysis under three different load conditions has been made by Khouzam et al. [73]. The load conditions are: i) constant load (when load-torque constant is zero); ii) viscous friction load (when load-torque constant is one); and iii) ventilator load (when load-torque constant is two). The conclusion of the study is that ventilator loads offer good matching performance. This study also shows that a viscous friction load is more sensitive to the choice of the field constant and rated current of the motor than the ventilator load.

Hsiao et al. [74] analysed a pumping system based on the simulated performance. The basic units of this system were a centrifugal pump and a permanent magnet DC motor with selected characteristics. This study shows that motor-pump speed-ratio matching can greatly improve the average daily efficiency of a pump. Another study by Khouzam et al. [75] on the same configuration of the system shows that the most suitable choice of PV water pumping system will not be affected by variation of rated torque and the temperature has little effect on the matching factor in this system.

Although the volumetric pump is not preferred for pumping water from shallow wells due to poor matching performance with a PV generator, its use is recommended for reverse osmosis. Therefore, detailed analyses of this system have been made [76,77] to improve the matching efficiency. A simplified model [76] was used to compute the optimum size and to compare the system performances with a battery bank and without a battery system. The simulation results of this study indicate that the efficiency is improved from 63% to 92% when a battery bank is used between generator and motor. Another investigation [77] has been made on the same system replacing the battery with a DC-DC converter. It shows that a good matching performance of the system can be achieved by using a DC-DC converter instead of a battery.

In a PV water pumping system, the PV array is usually designed to power a single motor-load-pump. Several water pumping systems of the same or different types that are in close proximity to each other may each be powered by separate arrays (sources), or alternatively, by a common PV source for all the water pumping systems. However, Appelbaum [78] has analyzed the operation of a permanent magnet DC motor connected with two different types of pumps which are powered by a common source of solar cells. One motor-pump system consists of a permanent magnet DC motor and a volumetric pump, and the other of a permanent magnet DC motor and a centrifugal pump. A similar comparison exercise has been carried out for the same system when a maximum-power-point-tracker (MPPT) is included for both the separate and the common PV source. The study shows, for example, that in system without MPPT, the total performance of two motor-pumps in a common PV source system is improved compared to the performance of the two motor-pumps when they are powered separately by individual sources.

Series Motor

A centrifugal pump connected DC series motor is a very close competitor to the same pump connected to a separately excited motor with regard to the matching performance in the direct coupled PV applications [61-63,66,69,79]. DC series motors are also widely used in various applications other than water pumping due to the high starting torque Appelbaum [62] discusses the electrical matching performance, i.e. the percentage of electrical energy used by a motor with respect to the available maximum power of a PV generator in a day, of the directly coupled DC series motor-centrifugal pump PV generator. It is a fact that sometimes the motor can exploit maximum available PV energy whereas the motor efficiency may fall due to under- and over-voltage problems. Therefore, a study on the matching analysis in terms of motor mechanical energy under a variation of the motor constant for a particular load constant has been reported by Saied [69]. However, the ultimate aim of the system is to get the maximum hydraulic output. Therefore, a detailed matching analysis of the hydraulic output has been made by Koner et al. [79].

A detailed analysis on the matching of DC series motor-centrifugal pump connected PV generator has been made by Braunstein et al. [80]. The relations of flow rate vs. water head, pump factor vs. speed, speed vs. voltage of solar cell generator and current of solar cell generator vs. solar insolation levels have been individually derived. This study also presents a method for the determination of the rate of volume flow and the variations in speed as a function of insolation level. It is not possible using this model to analyze the speed-torque relations of a motor-pump system for different water heads under various motor-terminal voltages, and speed-water head relations under the same variables, even although these are the most important relations for optimizing the system.

Most of the matching studies between the PV generator and DC motors, for a given input characteristic of mechanical load, have been done by considering both analytical and graphical methods to handle a large number of interdependent variables [61,69,78]. In this procedure, generalisation and prediction conditions are limited. Therefore, to give a comprehensive solution to the above problems, a pure analytical method of matching has been developed [81] with the help of i) generalised speed-torque relation of a conjugate DC series motor and centrifugal pump, ii) the relation of motor terminal voltage vs. motor-pump speed and iii) the flow rate dependence water head relation. This method can calculate different matching conditions under variations of any of the parameters of the total system.

Optimization

From previous studies on the matching analysis of a directly coupled PV water pumping system, it can be concluded that perfect matching is nearly impossible for any configuration of subsystems. Therefore, a number of optimum matching studies on directly coupled PV water pump systems have been carried out and are reported in the literature.

There are three possibilities to optimise a directly coupled PV water pumping system: i) proper choice of the constants of motor and pump; ii) reconfiguration of PV modules; and iii) changing water heads.

The optimum matching studies under the proper choice of constants of the system have been made by different investigators [63,69,73,75,79]. The results of optimum values of field constants are shown in Table 2.

From the data in Table 2, it can be concluded that the optimised values of field constant of a motor strongly depend on the values of load constants, load factors and other environmental parameters. The load constants and load factors generally depend on the applications. The environmental parameters depend on the site. By putting the correct values of these parameters in the analysis, one can calculate the optimised value of motor constant to optimize the system performance. However, most analyses have been made under a particular condition. Therefore, generalised optimised values can not be calculated for different load factors, load constants and environmental parameters. However, the generalised analytical method of Koner et al. [79] can be used to calculate the different optimised values under different conditions for the series motor.

Appelbaum [63] calculated that the optimum value of motor constant of series motor is 0.0675 Nm/A^2 for a load constant of 1.54×10^{-3} WS^{-3} and a load factor of two. However, the same optimum value of motor constant is 0.12Nm/A^2 under the same conditions as have been calculated by Saied [69]. The optimised motor constants referred to by Appelbaum and Saied are not equal whereas load constant and load factor are fixed. By using Koner et al.'s method [79], this value has been verified. It is found that the optimum value of motor constant for a series motor is 0.12 Nm/A^2 for a load constant of 1.54×10^{-3} WS^{-3} and a load factor of two. The optimum value of motor constant referred to by Appelbaum is not correct because in his analysis the matching has been made on the output characteristics of a PV generator and input characteristics of a motor whereas Saied made the same analysis with the output characteristics of a motor and a PV generator.

The principle of the optimization of the system with different configurations of PV modules is that the operating characteristics of pumping load are forced to be kept near to the maximum

Table 2. Optimised values of constants of motor and pump.

Motor Type	Pump Type	Load Factor	Load Constant (WS^{-3})	Field Constant	Temperature (°C)	Reference
Separately excited	Centrifugal	2	100	50 V-sec	–	73
do	do	2	$1x10^{-3}$	2 V-sec	–	73
do	do	2	$15x10^{-3}$	0.571 V-sec	25	75
do	do	2	$15x10^{-3}$	0.389 V-sec	100	75
do	do	2	$15.4x10^{-3}$	0.621 V-sec	–	63
do	do	2	$15.4x10^{-3}$	0.6626 V-sec	–	69
do	Viscous Friction	1	100	35 V-sec	–	73
do	do	1	$1x10^{-3}$	0.1 V-sec	–	73
Series	Centrifugal	2	$15x10^{-3}$	0.271 H	25	75
do	do	2	$15x10^{-3}$	0.181 H	100	75
do	do	2	$15.4x10^{-3}$	0.0675 H	–	63
do	do	2	$15.4x10^{-3}$	0.12 H	–	69
do	do	2	$2.83x10^{-7}$	0.22 H	30	79

power point of a PV generator by changing the number of series and parallel connected PV modules, where the total number of PV modules are constant. The current at maximum power point of a fixed combination of PV modules sharply rises with the increase of solar insolation levels whereas the variation of voltage at maximum power point of the same generator is insignificant under the same conditions. Therefore, the operating points of a fixed pumping load go down from the maximum power points of the PV generator at higher insolation levels if these are matched at low solar insolation level. This mismatch can be controlled by reducing the number of parallel connected PV modules and increasing the number of series connected PV modules according to the I-V characteristics of the pumping load.

The different aspects of this optimization technique have been studied by different investigators [82-85]. Naaijer studied the optimum operating conditions of a DC motor and a PV generator by proper matching of the motors to the solar cell array using a switching device [82]. Salmeh et al. [83] present the quality of load matching (pump load) in a PV system by using a multistage electric array reconfiguration controller. The analysis of the optimum switching point is based on the simulated performance of each component. The electrical coupling has been studied for a pump load by changing the configurations of PV modules [84]. This study deals with the design of the switching controller. Koner et al. [85] have attempted to find the 'cut-off solar insolation' of any centrifugal pump connected DC series motor using an analytical solution of PV generator-motor-pump system. The authors describe the design of a portable switching controller for reconfiguration of PV modules which has been developed and tested in the field.

A new approach to optimize the direct coupled PV pumping system has been developed by Saied et al. [86,87] by the combination of the properly selected constants of motor and pump and reconfiguration of PV modules. Several possible combinations of PV modules and field constants of motors, yielding maximum values for annual output of gross mechanical energy, or equivalent, resulting in the minimum values for the annual area mismatch integral have been examined [86]. In another paper, Saied et al. [87] present a study on the optimal parameters of a PV water pump system in terms of maximum total annual gross mechanical energy. The analysis and design procedure include a variable DC-DC matching transformer placed between the array and the motor. The DC-DC matching transformer produces different levels of voltage and current, equivalent to the reconfiguration of PV modules. The model takes into consideration the effect of different temperatures as well as insolation profiles throughout the year. The study revealed the dramatic effect when the change in the ambient temperature increases the ratio load variation of DC transformer.

For a fixed combination pattern of PV modules, the supply voltage to a motor changes with solar insolation levels. The motor-pump efficiency, as analyzed by Koner et al. [81], is maximised at different water heads for different motor terminal voltages. Therefore, if water head is varied according to the change of solar insolation levels in the field, the system can give greater daily average hydraulic output. The change of water head can be done in real cases, such as the supply of water to different floors of multi-storey buildings at different times of the day.

The possibilities of maximum utilization of PV energy in a pumping system, comprising a monoblock DC series motor and a centrifugal pump, have been studied [88] by changing the water head of the pump according to the variation of insolation profiles. The system performance can be improved by changing water heads for a particular case, but not for all cases.

CONCLUSION

The separately excited motor connected with a centrifugal pump is the best choice for the PV pumping system. The series motor connected centrifugal pump is close to the first choice in matching the performance of direct coupled PV pumping systems. However, shunt motor and displacement pump are not recommended for direct coupled PV applications. It can be concluded from this review that all matching analyses of PV pumping system are restricted by their application conditions. However, a generalised and simple analysis for PV pumping system is very essential to optimize the system under different conditions. Koner et al. have made an attempt to generalise the matching analysis of series motor connected centrifugal pumps for PV applications.

There are three types of optimization techniques, however, all systems may not be optimized by a particular technique due to the wide variation of climatic data in different places in the world and the requirements for various applications. At the same time, all optimization techniques are not equally applicable for a particular pumping system. The best optimization technique is the reconfiguration of PV modules. However, this technique is restricted by the power rating of PV modules and motor. As an example, this technique gives better results for the higher wattage pump and the lower power PV modules connected system, or both.

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