Photovoltaic Water Pumping System: Part I - Principal Characteristics of Different Components

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ABSTRACT

The main objectives of this paper are (1) to review the various photovoltaic water pumping systems to be used at low to medium pumping head and (2) to present the characteristics of their principal components such as photovoltaic generator, the electrical motor (d.c./a.c.), the inverter, maximum power point tracker, the pump (centrifugal/volumetric), energy storage, water storage and its distribution.

1. INTRODUCTION

Adequate quality and reliability of potable water supply are required not only for human life but also for industries and agriculture. A variety of pumping techniques are available to meet the water demand. In terms of mechanical pumps (i.e. non-hand operated pumps) the most common type of the pump is either the A.C. pump (run by using main electricity) or the diesel pump. It is true that such pumps are technologically well understood, able to be transported at modest cost, relatively easy to install, etc., but the main problem associated with such units is their use in the far remote villages where there is little surface water and no electricity or fuel available for pumping water from boreholes. It is therefore in this context that to meet the growing world-wide water supply demand, especially in the remote areas, efforts should be made to design pumping systems run by power, available locally, such as solar energy, wind energy, biogas, etc.

In developing areas of the world, renewable energies have been used for many centuries, and are still being used in the production and preservation of food, and, the supply of water for human consumption and irrigation of crops, etc. However, amongst potential new energy sources, solar energy, especially the direct photovoltaic (PV) conversion of sunlight into electricity, is extremely promising. Photovoltaic power has found applications in all corners of the earth. PV technology is used in consumer electronics, refrigeration in the third world village pharmacies, utility scale projects, space applications, lighting and water pumping. Amongst different terrestrial applications of photovoltaic technology, PV water pumping is particularly important.

The basic characteristics of a PV water pumping system which make it an attractive choice are: (1) direct conversion process; (2) availability of abundant solar energy; (3) pollution free system; (4) applicability in remote and isolated areas, etc. Presently, PV is mainly used for potable water pumping from wells, but the delivery of water from superficial sources to elevated settlements is also an issue

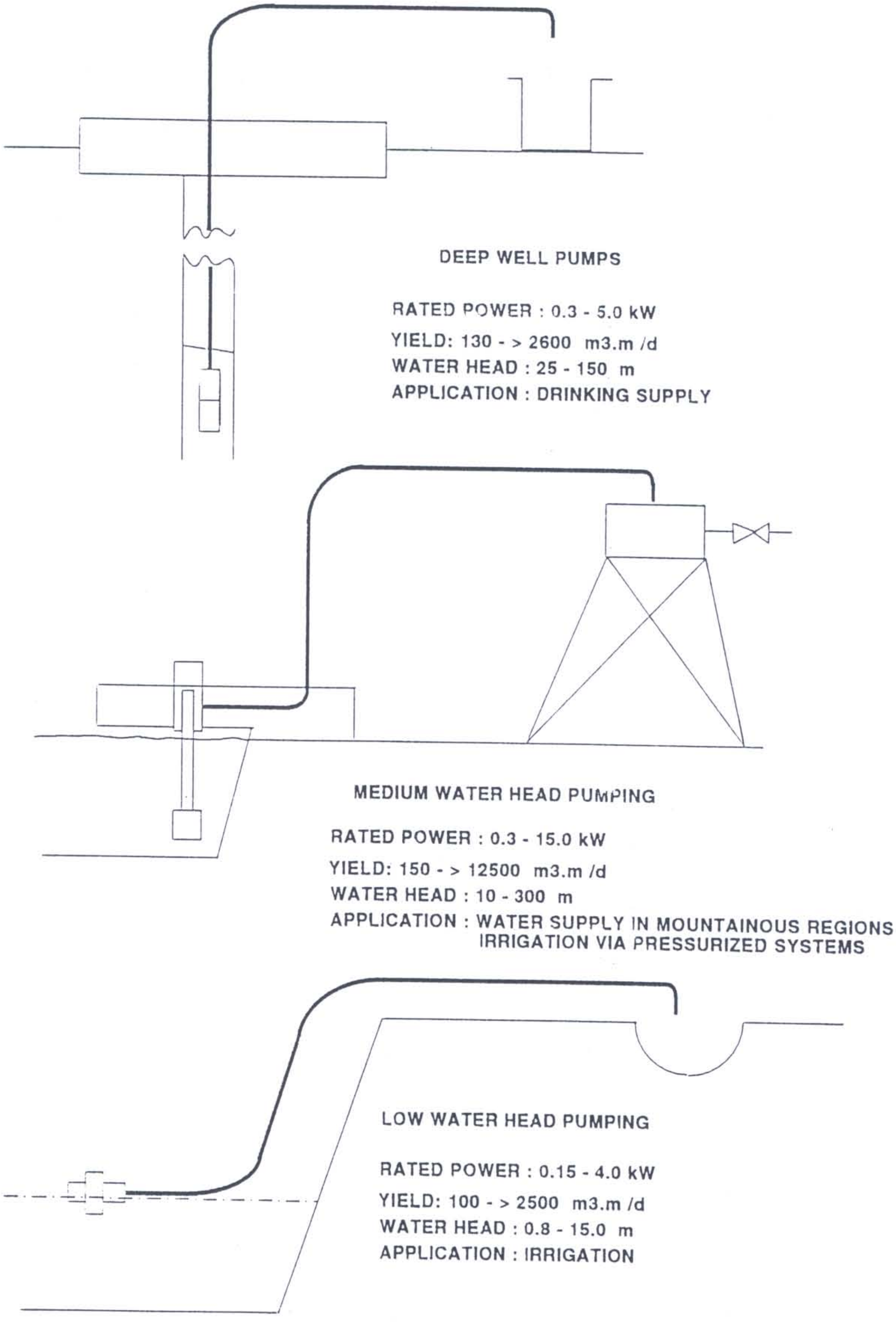

Fig. 1. Applications of photovoltaic pumping systems.

for PV pumping. Irrigation is feasible, where shallow water pumping is applicable. Fig. 1 depicts typical examples of a photovoltaic water pumping system.

Studies on solar photovoltaic pumps have continued for a long time. Indeed, thousands of systems are currently being used for water pumping around the world [1-10]. Despite the relative maturity of this technology and its cost competitiveness, especially for low power applications (< 5 kW) in the remote and isolated areas, the photovoltaic power operated water pumping system is a very under-utilized resource. While this mainly stems from a lack of awareness of the cost competitiveness of this technology, there are many other factors that must be considered [1].

No doubt, PV water pumping systems are now technically viable all over the world but the fact remains that there is generally a gap between the conception of a technological or scientific innovation and its actual implementation in the field. Therefore, it is felt that there is a need to further understand the characteristics of various types of PV water pumping systems, i.e. the selection of efficient, technically reliable, and appropriate system components.

This paper presents the characteristics of various photovoltaic water pumping systems and their components such as the photovoltaic array, the electrical motor, the pump and the water storage and distribution system. Once this job is completed successfully, the next important step is to provide necessary guidelines concerning system sizing to be discussed in the second part of this communication.

2. PHOTOVOLTAIC WATER PUMPING SYSTEM

A photovoltaic water pumping system (Fig. 2) is an assembly of different components such as PV modules, the electrical motor, the inverter, the pump, storage and distribution of water, etc. The basic system can be varied to suit particular requirements. For example, a storage battery with charge regulator may be used to provide overnight load or to carry the load during periods of low irradiance.

However, considering the facts that batteries inherently (1) mean energy losses; (2) are very sensitive to maintenance and operation (load and recharge) and (3) are comparable in annual costs to those of the PV array itself, there are good reasons to leave the battery out of the system. Also, an inverter, besides being an expensive piece of equipment, is based on high technology and introduces power losses [11].

For reasons mentioned above, in the author's opinion, it is worthwhile to avoid complexity and so a simple system could be designed as shown in Fig. 3.

However, because of the importance of these configurations, each and every component of photovoltaic water pumping system has been discussed, separately, in the following sections.

2.1 Photovoltaic Power Generator

A photovoltaic power generator is an integrated assembly of modules and other ("balance of system" (BOS)) components, designed to convert solar energy into electricity to provide a particular service, either alone or in conjunction with a back- up supply (Figs. 4 and 5). A module is the basic building block of a photovoltaic generator. It is defined as the smallest complete environmentally protected assembly of interconnected solar cells. For the purpose of having a reliable photovoltaic generator, it is essential that the module must be capable of a reliable, low maintenance operation for many years in the environment for which it is intended [12].

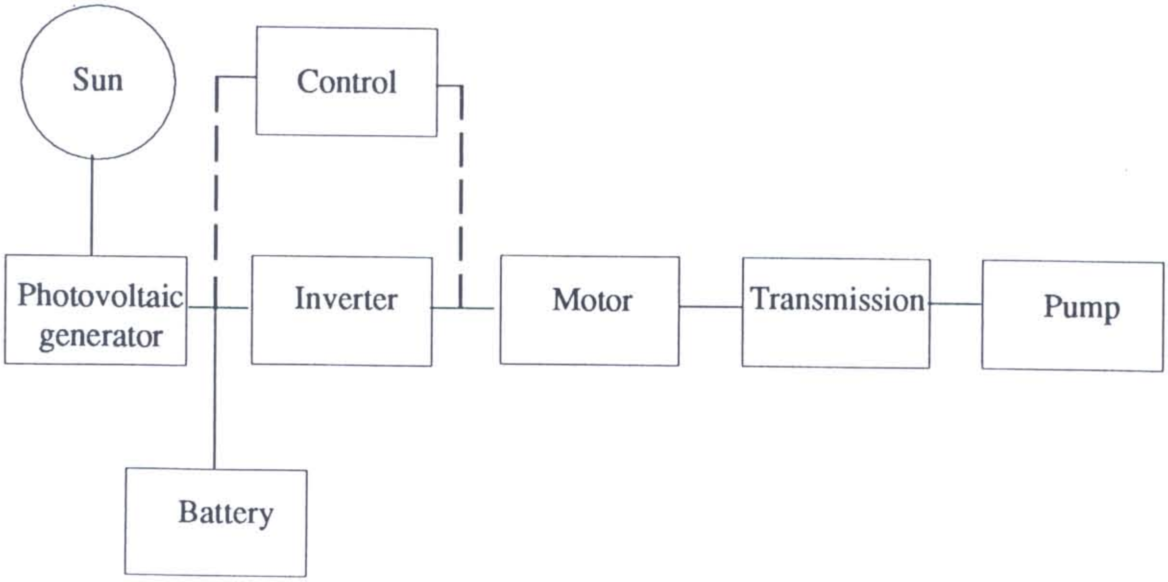

Fig. 2. Components of a solar pump.

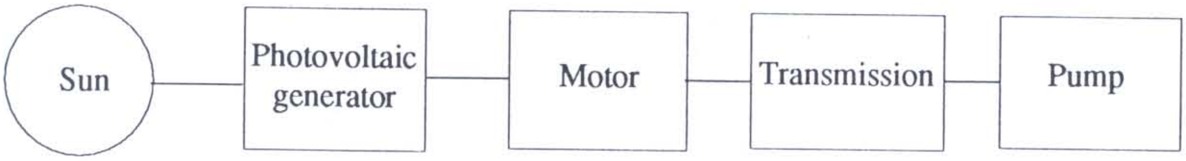

Fig. 3. Simple solar pump.

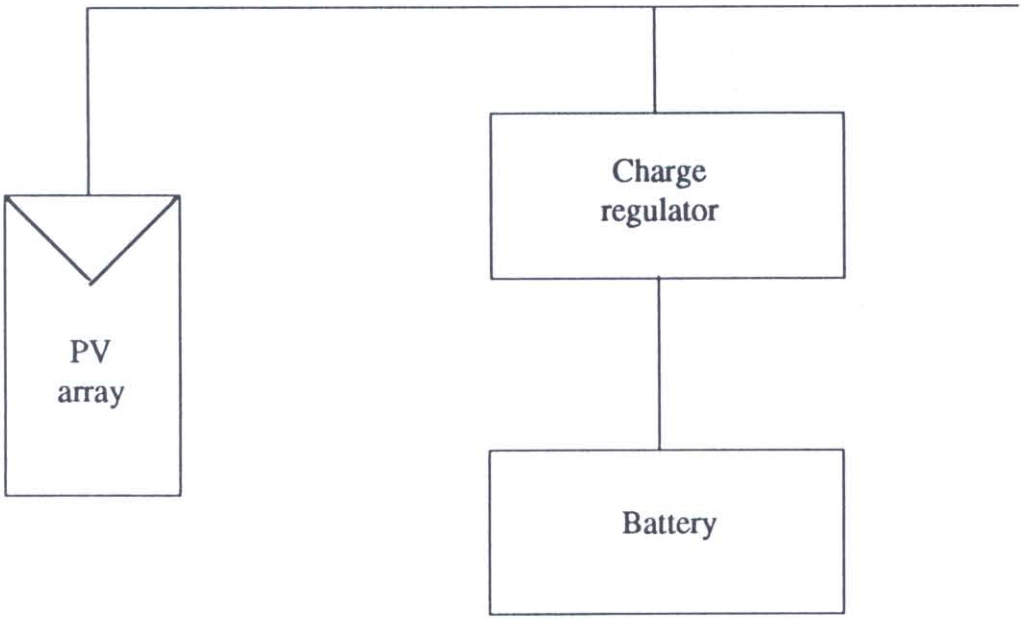

Fig. 4. Stand alone DC system with battery.

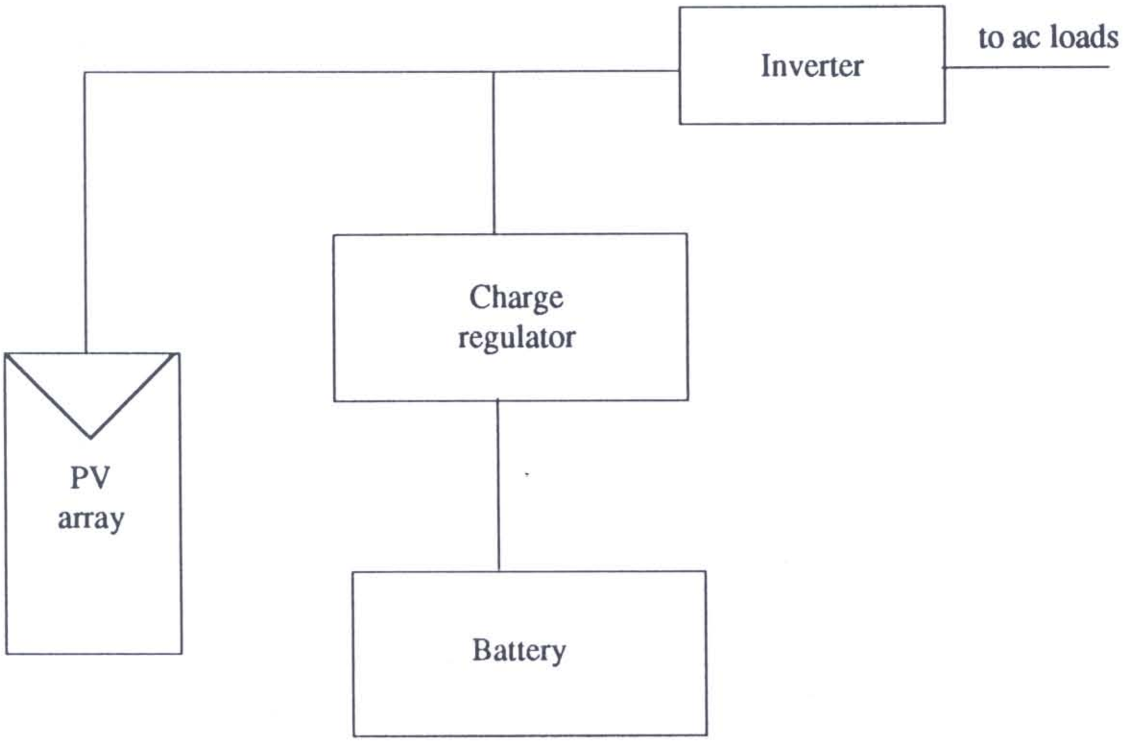

Fig. 5. Stand alone AC system with battery.

Although PV modules have been manufactured in different configurations, for most of the applications, modules with 36 series connected monocrystalline silicon cells measuring 982 mm x 436 mm x 38.5 mm, are used to meet the electricity requirements of a direct coupled photovoltaic system. The solar cell module with its rated power as 45 "Peak" watts (Wp) at 16.5 V, is suitable for charging a 12 V battery.

After the module selection, it is necessary that the modules intended for the PV generator should be subjected to performance measurement, before assembly. As shown in Fig. 6, the photovoltaic performance of a module is measured by exposing it at a known temperature to simulated or natural sunlight and tracing its current-voltage (I-V) characteristics while at the same time measuring the irradiance. The irradiance is to be monitored, not with a Pyranometer, but with a specially calibrated reference cell or a module. This automatically relates the measurement to a reference solar spectral irradiance distribution. For rating purposes, the I-V characteristics is transposed to standard test conditions (STC), which are

Irradiance= 1000 W/m^2, with the reference spectral irradiance distribution

Cell junction temperature= 25 ± 2°C

The rated power is defined as the power output at STC when the module is loaded at voltage at or near the maximum power point (the "rated voltage"). This can be read off from the transposed

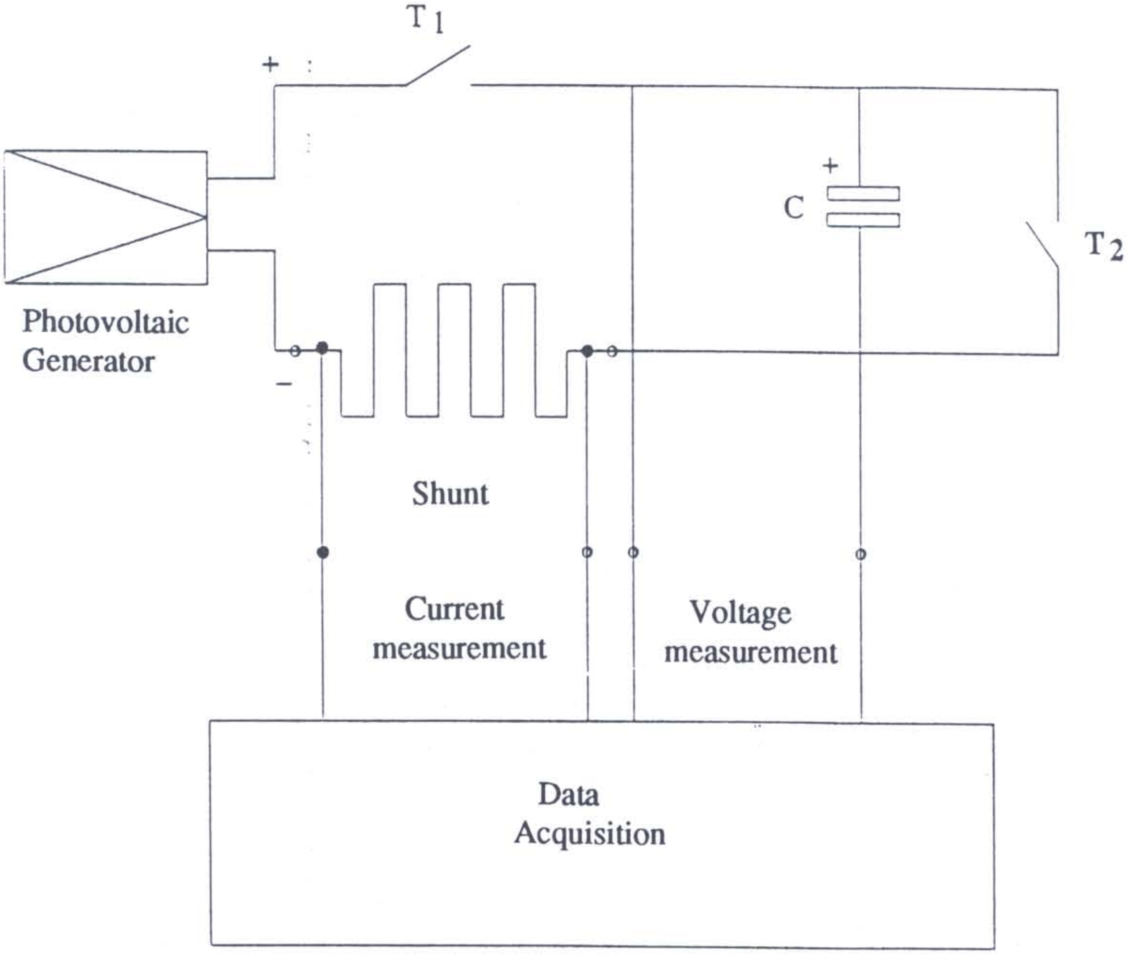

Fig. 6. Measurement of I-V characteristics using capacitive load (Source: G. Noviello, 1993).

characteristics. It is commonly expressed in terms of "Peak" watts (Wp).

In its simplest form, a photovoltaic system consists of an array of one or more modules supplying the load directly. Such a system can be used for battery charging (with a simple charge regulator) or for water pumping where the storage medium is water. The modules in a photovoltaic array are connected in series strings to provide the required voltage. If one string is not enough to provide the required power, two or more strings are connected in parallel.

As with series-connected cells in a module, the modules in a series string must all pass the same current. It is therefore important to match them in terms of their current at the maximum power point. Otherwise the modules with the poorest performance will limit the output of the whole string and may, under certain load conditions, be forced into reverse bias.

To protect the array from hot spots in the event of shadowing or damage, a by-pass diode is usually connected across each module. A diode is also inserted between each series string and the DC bus to prevent leaking from the battery during the hours of darkness. These blocking diodes also protect the battery, should one of the module strings develop a short-circuit. Furthermore, they prevent the reverse currents which might otherwise flow under some load conditions in strings which are not well matched in terms of voltage.

Some PV generators may consist of more than one array, in which case the installation is called an "array field". An array field may be divided into sub-fields and arrays into subarrays. In most flat-plate arrays, the modules are supported at a fixed tilt facing the equator.

In an ideal situation, with prevailing clear, sunny weather, fixed tilt modules will produce the highest annual output at an inclination equal to the angle of latitude. But a smaller inclination will be better for sites with a high proportion of diffuse radiation and a steeper angle will increase output on sunny winter days and thus helps to reduce storage requirements.

By mounting arrays on 2-axis trackers, upto 40% more energy can be collected over the year [13]. Single-axis tracking is less complex but yields a smaller gain. As a general rule, the complication of automatic sun tracking can only be justified for large (MW) installation. But with small, manually adjustable arrays, useful gains can be obtained by changing the tilt every three months and moving the array in azimuth to face the sun twice a day (mid morning and mid afternoon).

The area occupied by an array field can be minimized by mounting all the modules in one plane. This is a common practice with arrays mounted on the roofs or walls of a building. For other installations, however, it can increase the cost of the supporting structure and can make access to the modules difficult.

The more usual approach is to arrange the arrays in easily accessible rows, spaced so as to prevent too much shadowing of one row by its neighbor at the beginning and end of the day. The land area required for array fields of this type can be from 1.5 to 4 times the total module area depending on the tilt angle. For array fields with 2-axis tracking, even more land is required, typically 8 times the total module area [13].

Finally, the array must be well earthed and surge protectors fitted to conduct any lightning - or fault - induced current surges to ground.

2.2 Pump Technology

In order to understand the problems encountered in powering a water pumping system by using a PV generator, it is instructive to first compare the differences between different kinds of pumps available in the market, which differ in several different ways. There are two main types of pumps used in solar pumping system:

1. Centrifugal pump, and
2. Volumetric pump.

Both types of pumps are characterized in terms of water head, water flow rate, speed etc. These pumps can be operated using both DC and AC electric power. In the following, analyses of both kinds of pumps is covered so that the characteristics of each pump are easily understood.

2.2.1 Centrifugal Pump

Centrifugal pumps are reliable, have no dynamic loading, and are easily obtainable. Such pumps are ideally suited for conditions of high flow in tube wells, cisterns, or other reservoirs. These pumps are designed for a fixed head (viz. the distance from the top of the water to the surface) and their water output increases with rated speed. Such pumps have been installed with capacities as high as 1200 m^3/day and can be used for flow rates as low as 10 m^3/day - 15 m^3/day.

The most important operating characteristics of a regular centrifugal pump are the pump capacity, `$Q$' ($m^3/s$), the pumping head, `H' (m) and the shaft power,'T' (watt), which are the function of the impeller speed, 'n' (rev/s). A centrifugal pump has an impeller which consists of a large number of vanes where the water flows almost parallel to such vane surfaces. When the impeller is rotated by a motor at a certain speed, a displacement,'D'(m^3), of the water occurs in every single rotation of the pump. Therefore, the amount of water displaced by the pump at a certain impeller, or so - called pump capacity, is defined as the volume of water displaced per unit time [14], and is formulated as

$$Q = Dn \tag{1}$$

The second parameter is the head of the pumping system (H) which represents the net work done on a unit of water in passing from the inlet to the discharge flange. Referring to Euler's pump equation, as the impeller rotates, and so do the particles of water, the head is proportional to the square of the speed. Consequently, the shaft power of the pump, which is defined as the required work to move a certain pump capacity at a certain pumping head (QH), is directly proportional to the third power of the speed.

The characteristics of centrifugal pump when operating at a constant head (H) are shown in Fig. 7. That means that for a given head there is only one operating point at which the pump operates at maximum efficiency and these maximum efficiencies of small centrifugal pumps vary from 40% to 60%, depending on size, pumping head, etc. To this maximum efficiency operating point of the pump corresponds to one value of power input of the pump. This means that, whether a MPPT is used or not, there is only one value of solar radiation where the total system operates at maximum efficiency[11].

In fact, if the pump is connected via a DC motor to the photovoltaic array, the pump torque - speed requirement can be transformed into I-V loads on the array by considering that in first approximation the motor characteristics are such that current, I, is proportional to torque, T, and voltage is proportional to pump speed, n.

Considering the fact that DC motor directly connected to a photovoltaic generator is cheaper and moreover, it simplifies the system design as compared to the use of an AC motor, it is genera]]y preferred to have a direct coupling between a photovoltaic array and the motor using DC-motor centrifugal pump [15 - 20].

Combination of a centrifugal pump and an electric motor yields a load line. Fig. 8 shows the

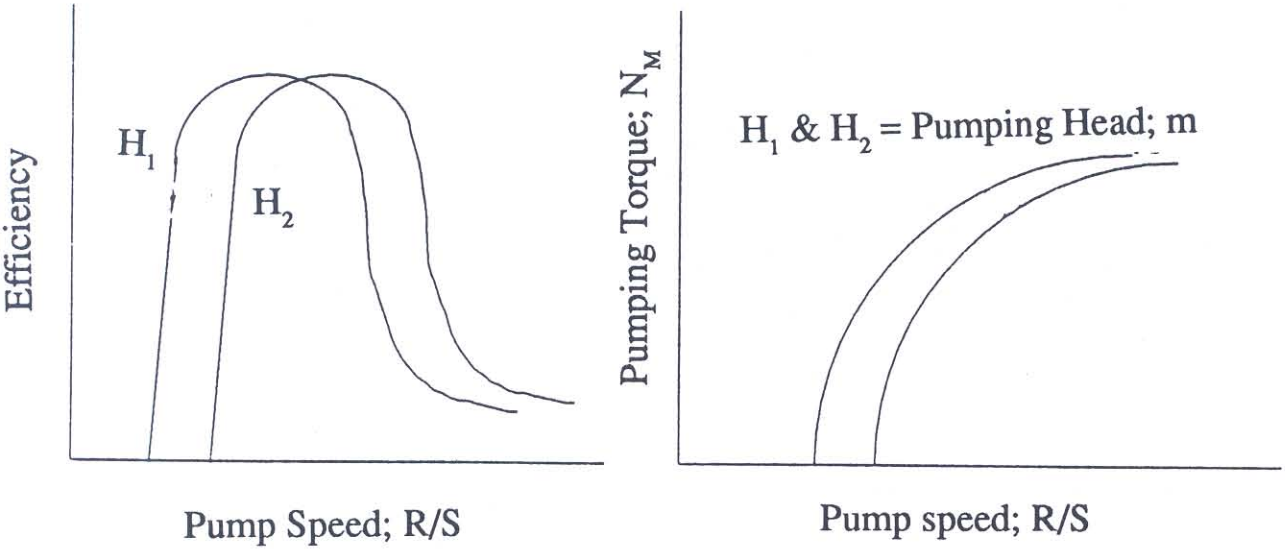

Fig. 7. Characteristics of centrifugal pump when operating at constant head, '*H*' (Source: Smulders and Burton, 1993).

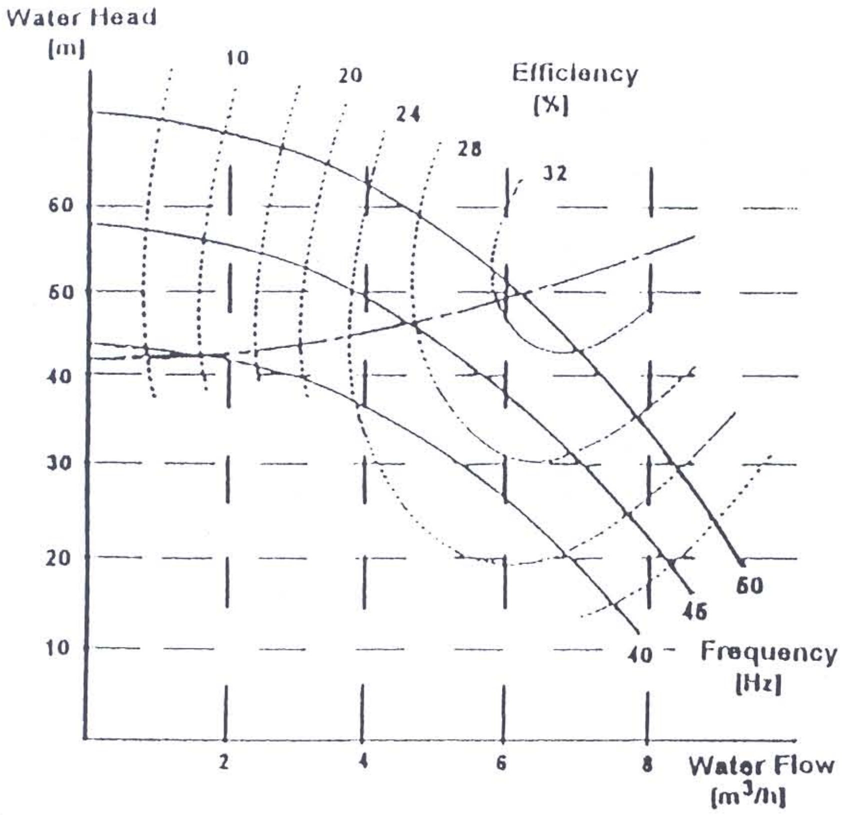

Fig. 8. Centrifugal pump characteristics (Pump Type: KSB UPA 100/10).

I-V plane in which the characteristics of the PV array, including the optimum power point line and the load line corresponding to the DC-motor /centrifugal pump, are represented.

Comparing the load line of such a centrifugal pump/motor combination with the optimum power point line shows that the curve yields a much better matching. However, maximum efficiency is only found for a well defined rotation speed and decreases rather sharply if the speed deviates from its optimum value. That means that at best there is only one point at which all components operate at maximum efficiency, if the point coincides with that of maximum pump efficiency.

So it is in this reference that due consideration should be given to this concept while selecting an operating point for the system.

Pump performance is based on the water flow Q(m^3/hr) that an electric pump can deliver at a given pumping head H(m). Manufacturers provide pump performance data in graphical or tabular form. From these H-Q curves suitable pump size able to deliver water at a desired flow rate from a specified pumping head can be selected.

Fig. 9 represents the hydraulic performance curves for a centrifugal pump of type KSB UPA 100/10, tested experimentally by Dr. W. Bucher from DLR Germany.

2.2.2 Volumetric Pump

As mentioned above, low power threshold and an insufficient partial load efficiency affect the energetic performances in many PV pumping systems. In order to solve these problems, the idea of using volumetric pump has been investigated by a number of researchers [21 - 27]. From the test data, it has been confirmed that rotating displacement pumps present a viable solution, performing efficiently in a wide range, starting pumping water at nearly zero speed, and last but not least - fitting into the frequently used "submerged" configurations. The essential advantage of displacement pump lies in a better partial load performance.

Positive displacement pumps come in many different types and styles. They fall into two main categories: reciprocating (plunger, piston, and diaphragm) and rotary (gear, screw, etc.).

A piston pump can in principle be matched to a solar cell, as the power demand is proportional to the piston rotational speed, which could in principle be varied in accordance with the incoming radiation. But the torque characteristics as shown in Fig. 10 being flat in nature, does not match to the characteristics of the cell. In a piston pump with a normal valve, the piston motion is generated by a crank mechanism. If the pump rod is sufficiently large, the piston motion is sinusoidal and likewise is the torque in the upstroke. In the down stroke the torque is zero i.e. if friction forces are neglected [11].

In the case of the matching valve, the situation depends on the pump speed. At stand still and very low pump speeds the valve remains open in the upstroke due to the buoyancy of the valve. In moving upwards through the stagnant water, the hydrodynamic drag forces on the valve are directed downwards. At a certain critical piston speed, $V_{critical}$ the hydrodynamic forces (proportional to V^2_{piston}) become equal to the buoyancy force and the valve closes. For detail information, readers are advised to go through the final research report prepared by Douve and Smulders [11].

In rotary category, a single screw pump is a special type of rotary positive displacement pump in which the water flow through the pumping element is truly axial [24]. The water is carried between screw threads on a rotor and displaced axially as the screw rotates.

The rotor thread is eccentric to the axis of rotation and meshes with internal threads of the state (rotor housing or body). The rotary action and the positive - displacement characteristics makes this pump operate very differently from the centrifugal units.

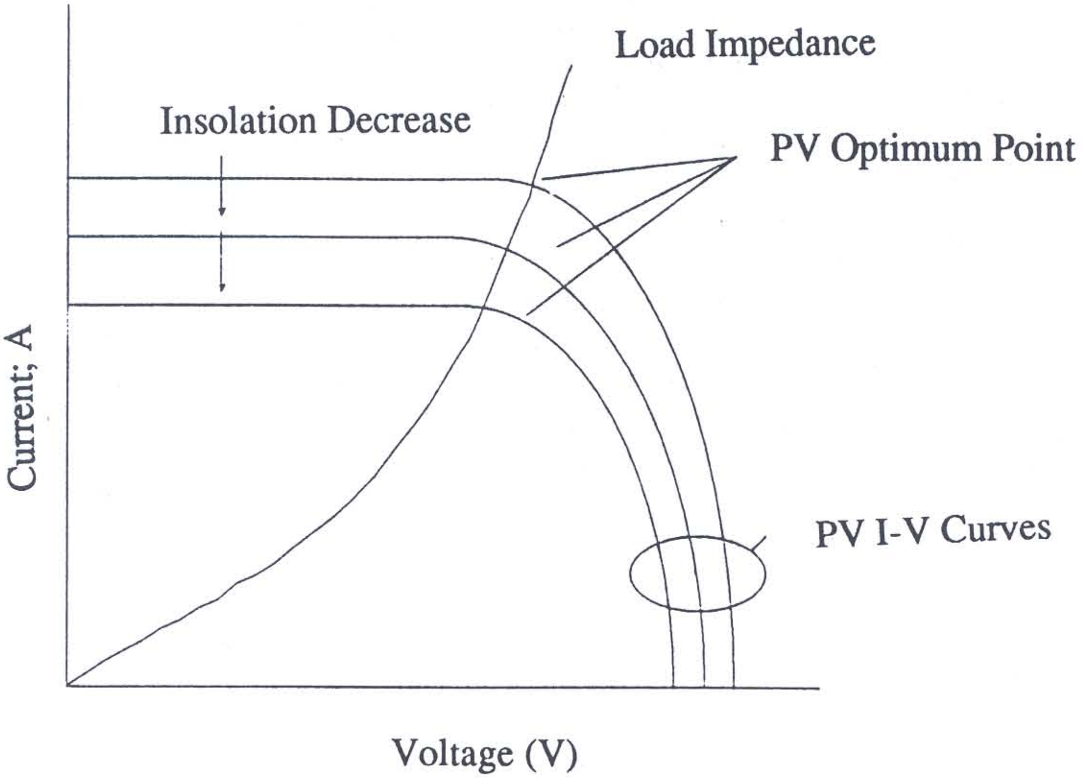

Fig. 9. Load impedance curves of centrifugal pump on I-V characteristics of PV generator [14].

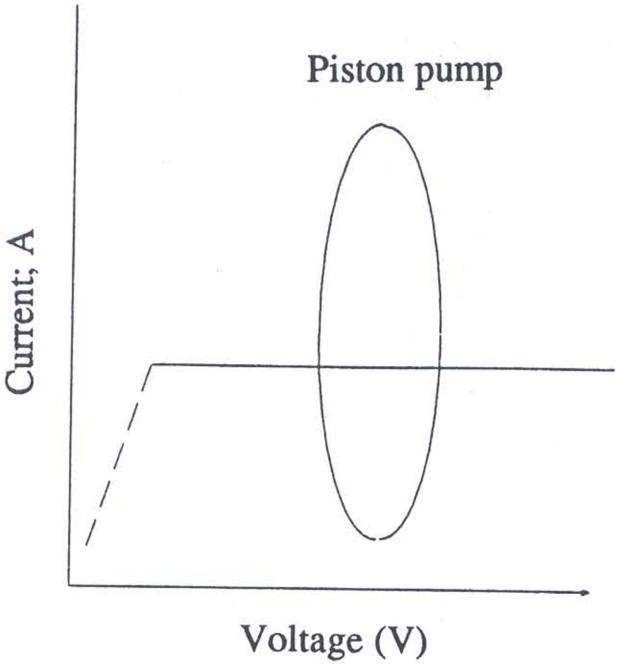

Fig. 10. Coupling a piston pump to PV generator [11].

A single screw pump operates in a relatively simple manner. The intermeshing of the threads on the rotor and the close fit of the surrounding housing creates a set of moving seals in series between pump inlet and outlet. This set of seals acts as a labyrinth and provides the screw pump with its positive pressure capability. The successive set of seals from fully enclosed cavities moves continuously from inlet to outlet. These cavities trap the liquid at the inlet and carry it along to the outlet, providing a smooth flow.

Similar to the centrifugal pump, the screw pump will deliver a quantity of water with every revolution of the rotor, so that its theoretical capacity, `Q_t' (m^3/s) can be defined in the same way as for the centrifugal pump [23].

The internal clearances, however, do exist, with the result that whenever a differential pressure occurs, there will always be internal leakage from outlet to inlet, called slip (S). This leakage, for any condition, is unaffected by the pump speed. Therefore, the actual delivery, `Q' (m^3/s) of this pump is defined as

$$Q = Q_t - S \tag{2}$$

The typical characteristics of a volumetric pump are shown in Fig. 11. When the power is directly supplied by a photovoltaic system i.e. a DC power source, the volumetric pump is driven by a DC motor. The current drawn by such a motor is directly proportional to the output shaft demand, while the motor speed is directly proportional to the input voltage.

As a volumetric pump has relatively low inertia of its rotating parts, it will draw less current from the photovoltaic power supply, and consequently, the system voltage is higher and so is the motor speed. As the pump is coupled to the motor through a lengthy breakable flexi-shaft, the maximum motor speed needs to be set. As a result, however high the level of insolation, the pump never rotates beyond its maximum set speed.

Fig. 12 presents the performance curves for DC - motor/progressive cavity pump system. The experimental curves presented above were observed experimentally by Dr. W. Bucher from DLR Germany [11]. The rotary displacement pump used for testing was of type Netzsch NQ 14.

The other problem on this kind of the pump is its stall speed. For a given head condition and differential pressure, the motor must draw at least a minimum amount of current from photovoltaic power supply in order to operate. If less current is available to the motor, as the insolation level is lower than the minimum required level, the pump will stall. Thus, motor stalling under degraded solar conditions is a real problem with a directly coupled photovoltaic rotary volumetric pumping system.

So from the above discussion it is clear that in the case of a volumetric pump, the efficiency is roughly constant over a wide range of rotation speeds. The volumetric pumps have a water output that is almost independent of head but direct]y proportional to speed. Therefore in many cases, volumetric pumps are preferred.

The poor matching efficiency, however, eliminates a direct connection and it is generally necessary to insert a DC-DC converter or maximum power point tracker (MPPT) between the modules and the motor. There are many different types of volumetric pumps available in the market but the most interesting for inclusion in the PV - powered systems are the Jack pumps and progressive cavity pumps. These pumps, and in particular the Jack pump, are ideally suited to conditions of low flow and high heads.

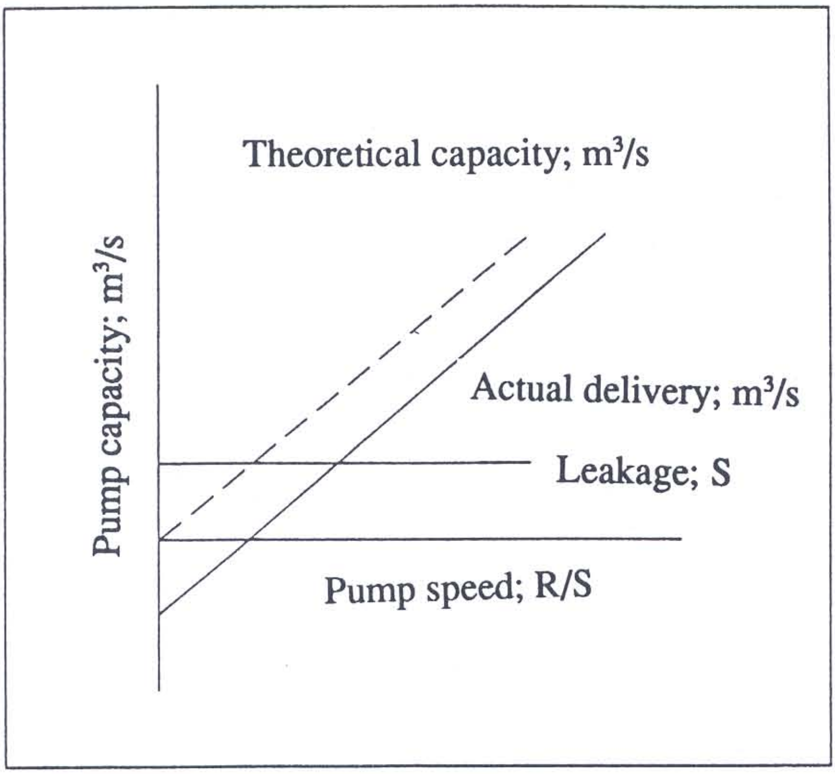

Fig. 11. Characteristics of the rotary volumetric pump [14]

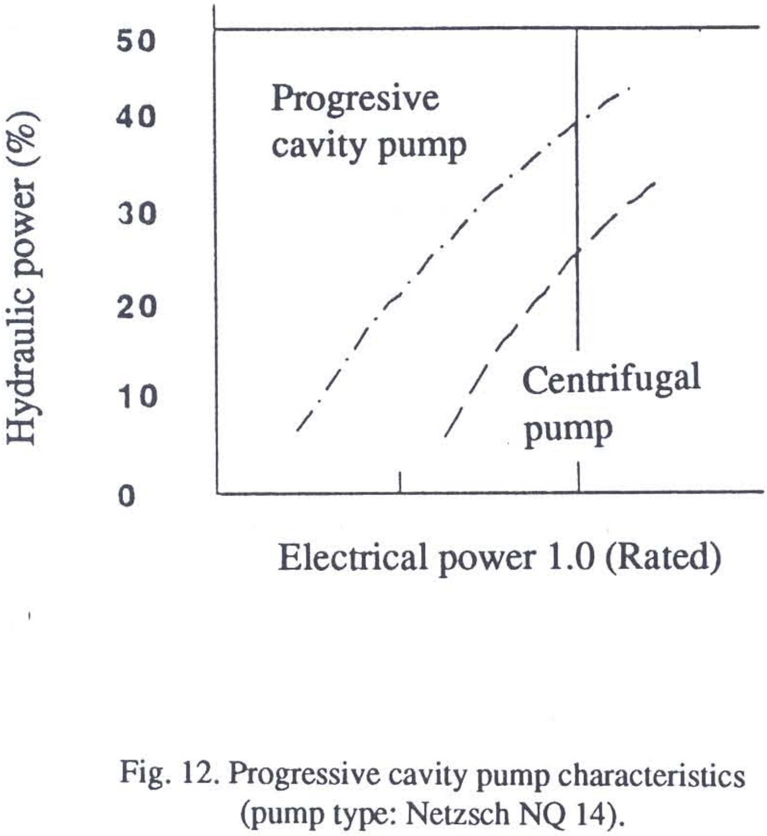

Fig. 12. Progressive cavity pump characteristics (pump type: Netzsch NQ 14).

2.2.3 Pump Selection

Comparing the performance curves for both types of pumps available in the market and commonly used in most pumping applications, it can be stated that for favorable sunshine conditions, the difference is negligible. But at unfavorable days, the system's performance are remarkably different. Threshold limits do not allow the centrifugal pump to start. Therefore, the energy delivered from the photovoltaic panels is not used.

Standard pumping equipment for photovoltaic applications uses multistage centrifugal pumps. In the wide field of applications, where low pressure levels prevail, multistage centrifugal pumps are the best choice, if some disadvantages can be overcome.

There is a reliable and efficient technique for low head pumping, but when used in deep well applications, impeller pumps with submerged AC motors do not perfectly match the needs for PV pumping. Centrifugal pumps show best performance at (or near to) rated power. However. the multistage technology has disadvantages at partial load, which is the most probable operation condition for any solar system. The decrease in power conversion factors at partial load can significantly reduce daily output values at low insolation levels/day.

Considering the performance data for such pumps, it can be stated that higher speeds could increase pump efficiency. Frequencies going beyond 50 (60) HZ yield higher water heads per impeller stage, and thus a higher power density of the system. Furthermore, redesigning hydraulic properties seems to be promising. A design with an optimal efficiency at partial load conditions could influence the utilization by augmenting the energy output at low insolation levels.

Displacement concepts offer an alternative. Displacement pumps are best suited for high water

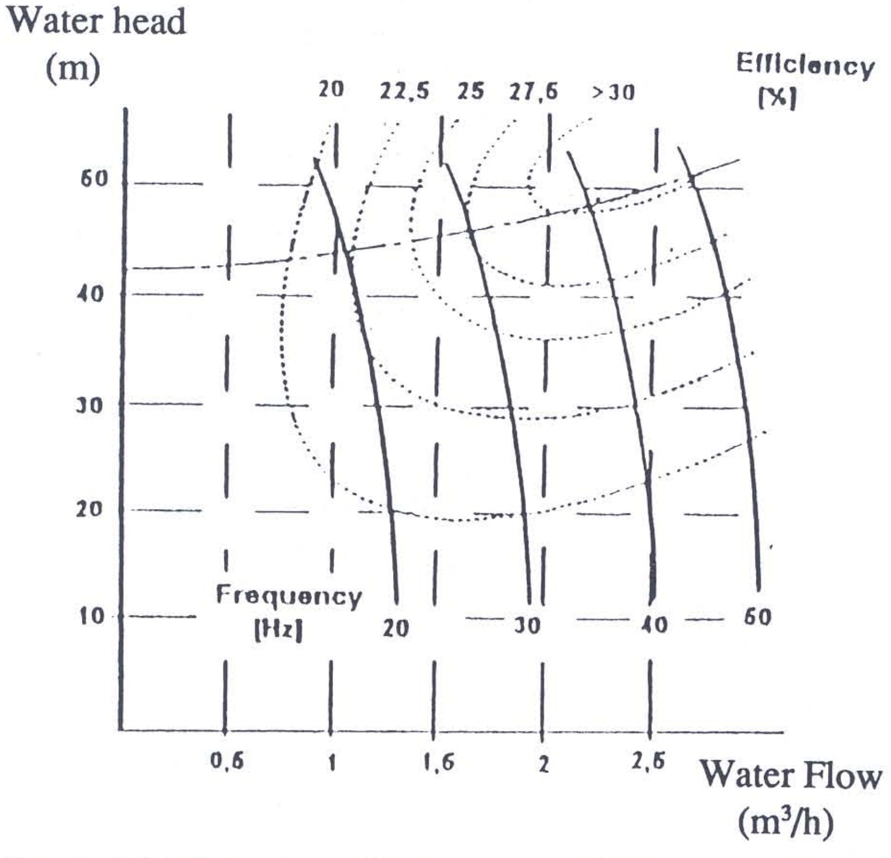

Fig. 13. DC input vs hydraulic power output for different well pumps [11].

heads and low flow regimes. Thus piston pump, which could easily be powered by DC- motors, seems to be a promising alternative too. Due to good partial load efficiency of the pump, the hydraulic energy output is quite good even at very bad weather conditions.

As mentioned above, there is no doubt that the technique is well established and efficiency is excellent but there are some difficulties as well. The problems of non-steady operation, severe start-up conditions, and torque should be treated carefully, if photovoltaic operation is envisaged. It is hoped that by combining a rotating displacement pump with a conventional submerged AC - motor, the system performance at medium water head can be increased.

A comparative plot (hydraulic output) of systems with centrifugal and progressive cavity pumps is presented in Fig. 13. A 20% - 25% better partial load performance of the displacement concept compared to the submerged centrifugal pump has already been reported experimentally. The daily yield could be increased between 15% and 25% [20].

2.2.4 Solar Pumps Developed Recently

- SHURflo Submersible Solar Pump

New solar submersible pump (Volumetric type; model 9325) for operation in standard 100 mm diameter boreholes over a wide range of depths down to 70 m has been developed by SHURflo Ltd. U.K. The pump is run by thermally protected permanent magnet motor (model P/N 11-126-10) and is best suited for the potable water well pump. Powered by two 48 watt solar panels, the pump produces a flow of 220liters/hr - 320 liters/hr.

The pump has an internal bypass which prevents hydraulic overload if the pump is too deeply submerged or the output line is blocked. The unit has an impact - resistant outer case molded in high strength engineering plastics for corrosion resistance and protection against mechanical damage.

- Suntron Submersible Solar Pump

Suntron power products, Melbourne based company, has despatched the first of its new generation of submersible solar water pumping systems known as the Suntron Sunpump™. According to Suntron, tests before despatch revealed an instantaneous system efficiency of 7.1% which is well in excess of that achieved by any other commercial solar water pumping system in the world.

The system has been tested under four standard Solarex 58 Wp solar modules; the new high efficiency Suntron submersible motor and Suntron Solar Motor Controller (SMC), and a standard exstock Mono SM041 submersible pump. The new motor and the controller utilize the latest technologies in both the motor design and electronics, resulting in a brushless motor whose efficiency is in the order of 90% over a wide load range. All the systems from the first pilot production run are being tested under field conditions by selected Suntron distributors.

3. DC ELECTRIC MOTOR

As mentioned earlier, a photovoltaic water pumping system can be operated using either an AC motor or a DC motor. For operation directly supplied by a photovoltaic power system, which is a DC power source, the pump is driven by a DC motor. The current drawn by such a motor is directly proportional to the output shaft demand while the motor speed is proportional to the input voltage. Looking at the typical characteristics curves for a DC motor, it can be stated that the efficiency does not vary a lot for the direct current motor at least when the value is not too far away from the design point. The maximum power point of the PV system (power = current(I) multiplied by voltage (V)) at standard conditions determines the normalization of motor speed and torque.

There are three main types of DC motors:

1. series type
2. shunt type, and
3. separately excited motor.

If the current is proportional to the armature current, the winding is referred to as a series winding or series field. So in a series motor, the magnetic flux is generated by a series connected winding.

If the current is proportional to the voltage of supply, the field winding is said to be a shunt field. So for a shunt motor, the magnetic flux is generated by a parallel connected winding.

The typical characteristics of an electromotor are shown in Fig. 14. From the preliminary analysis of the characteristics of the three types of motors for photovoltaic applications, it has been shown that due to 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 photovoltaic systems without power conditioners [28 - 30].

From the results of the different studies undertaken by various researchers [31 - 32], it can be concluded that DC shunt motors are not suitable for the photovoltaic pumping systems.

Detailed analyses of different aspects of matching on different pumps driven by separately excited motors have been carried out by various researchers [33 - 38]. The relative position of the load line to the maximum output line of the photovoltaic generator indicates its utility in pumping.

The analysis of pumping utility under variation of the pump speed showed that the characteristic performance variations of a directly coupled system with a separately excited motor and a centrifugal pump were within reasonable limits during a standard day [33].

The results obtained by Hsiao [36] from the analysis of a pumping system with basic units of a centrifugal pump and a permanent magnet DC motor with selected characteristics, showed that motor/pump speed -ratio matching can greatly improve the average daily efficiency of a pump. It was also shown that the most suitable choice of photovoltaic water pumping system will not be affected by variation of rated torque and that the temperature has little effect on the matching factor.

A centrifugal pump connected DC series motor is a very close competitor to the same pump connected to a separately excited motor with regards to the matching performance in the direct coupled photovoltaic applications [28-30,39, 40,41]. Most of the matching studies between the photovoltaic generator and DC motors, for a given input characteristics of mechanical load, have been done by considering both analytical and graphical methods to handle a large number of interdependent variables.

From the above analysis, it can be concluded that a separately excited motor connected with a centrifugal pump is the best choice for the photovoltaic water pumping system. The series- motor connected to a centrifugal pump is close to the first choice in matching the performance of direct coupled photovoltaic pumping systems. However, shunt motor and displacement pump are not recommended for direct coupled photovoltaic applications [42].

Reliability problems of DC - brush motors make the development of brushless motors (for their possible use with submersible pump) an attractive choice. The design of such a motor is based on rare earth magnets. The high efficiency brushless motor has already been tested by a few researchers [43 - 44]. The field performance of these motors are quite promising.

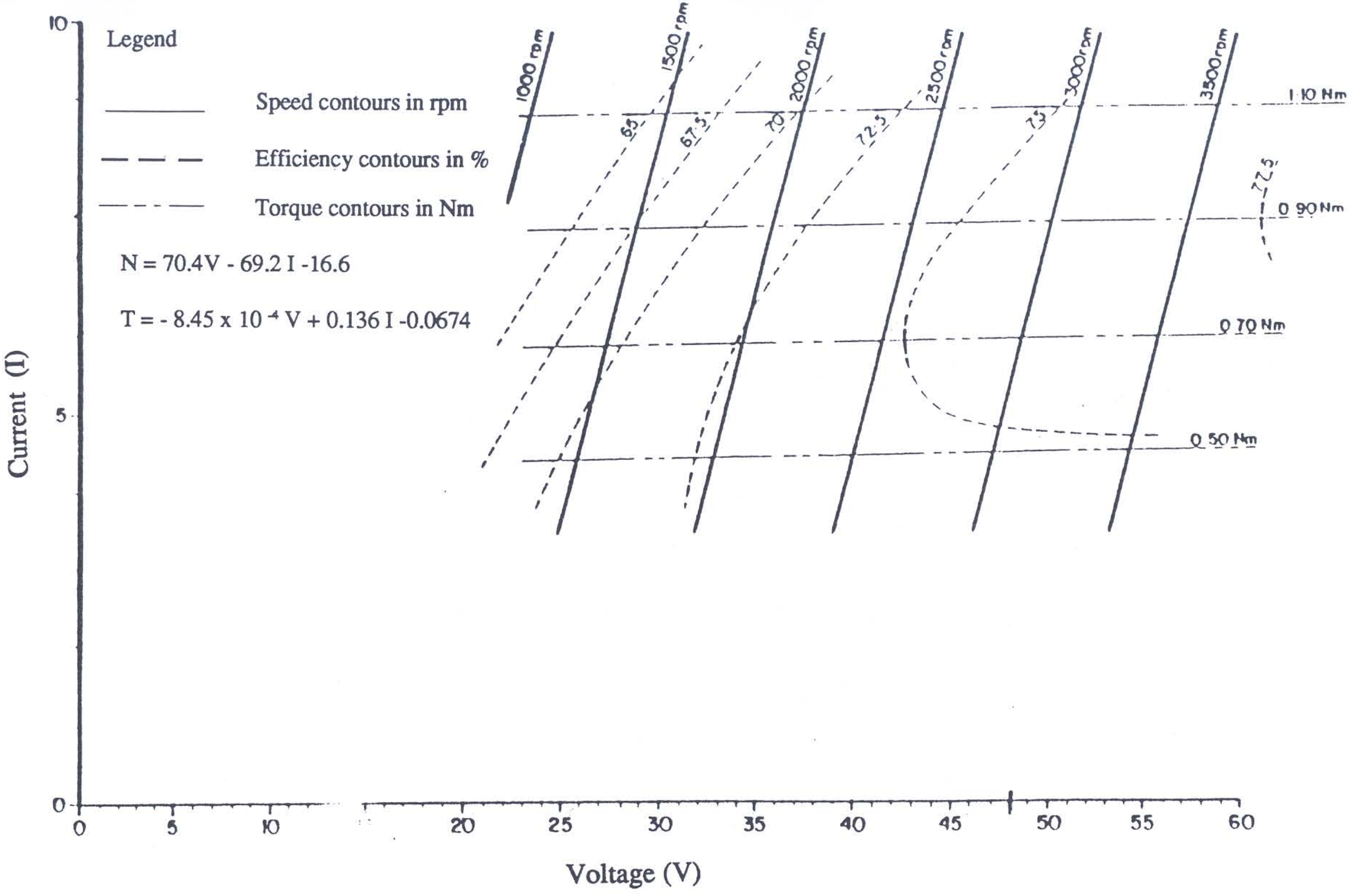

Fig. 14. Typical characteristics of an electromotor
(The Arco Solar Mavilor MO 300, World Bank Report 7).

4. AC ELECTRIC MOTOR

The first alternating - current (AC) generator was built by Warner Siemens in Berlin in 1856. Because there was no demand for AC at that time, no further work was done on it until 10 years later, when Henry Wilde of Birmingham, built a similar machine, first with permanent magnets and then with an electromagnet. Although it was known quite early that DC machines could be used either as motors or as generators, the fact that alternators could be used as motors was not pointed out until 1884, and the first recorded installation was not made in US until 1890.

All the early machines were single-phase machines. The advantages of more than one phase machines become apparent with the disclosure of Tesla's and Ferrari's work on induction motors, both of them having based their original designs on two phases. Within a few years, however, the economic advantages of three -phase distribution became obvious, and both alternators and synchronous motors were then designed and built for three phase service.

Single phase induction motors are simple machines except for the additional components required for the second winding to provide a revolving field in one direction larger than in the other, at least for starting. They have the advantage of requiring only a single phase supply, and therefore are commonly used in domestic and many commercial applications.

They suffer from the disadvantages of having lower efficiencies than three-phase motor of equal output power rating and from the fact that pulsating torque are inherent in the mode of operation. A further disadvantage is that the starting torque is usually not very high.

Despite the disadvantages, their fundamental simplicity and low cost of construction, together with nearly constant speed in the running range, made them very popular for many domestic applications. As with three - phase induction motor, the speed is not readily adjustable.

The three phase induction motor is the most elegant of AC machines. It has the characteristics of being self-starting with high but acceptable line currents at start, and with torque above rated values, and of running at nearly constant speed in its normal running range.

Efficiencies are high if the load is greater than 50% of the full load. Construction is the simplest of any machine, resulting in lower cost. The characteristics are under the control of the designer and not of the user, and hence it has the disadvantage of being incapable of having its major characteristics changed in the field.

Multiple induction motors, especially those with squirrel cage rotors, are the simplest and least expensive electrical motors. The fundamental principle on which induction motor is based is the revolving field concept.

Synchronous motors are sometimes used because of their constant speed characteristics, but more generally because they can be forced to draw leading current and therefore to offset highly inductive loads elsewhere in the installation. They are not inherently self-starting, but depend on the induction motor action of their damper winding to provide starting torque.

Under a given load, there is a minimum value of field current necessary to cause the motor to remain synchronized; for that field current, the motor has its most lagging power factor. As field current is increased, armature currents fall and power factor becomes progressively less lagging until minimum armature current is reached at unity power factor. Further increase in field current causes armature current to increase and to lead the applied voltage.

As stated earlier, in a direct coupled AC water pumping system, the main components are 1) photovoltaic generator: 2) inverter: 3) pump and 4) AC motor.

The idea of running photovoltaic water pumping systems in the AC mode was considered in order to overcome the different problems faced during the experimentation with DC pumping systems.

Just to mention, DC system requires more maintenance, since the reliability of the DC motor is not as high as expected. This type of motor is more difficult to obtain and more expensive compared to an AC induction motor. On the other hand, the good reliability, less maintenance problems, availability of AC system spare parts in the open market, etc. make it convenient in supplying the system spare parts for the maintenance and repair schedules for the AC motor system. Also, due to its speed limitation, DC motor system efficiency is lower than that of the AC motor.

However, an AC system needs an inverter, an additional cost, and overall system losses. It is therefore essential that this should be considered in the design of a direct coupled AC pumping system.

While conducting a market survey, it has been observed that there is absolutely no problem in selecting and having a suitable AC motor from the market best suited to one's own requirements.

5. INVERTER

The inverters is necessary to transform the DC power, from photovoltaic power source or a battery, into single- or three-phase AC power to suit load requirements. In grid interactive systems, the output must meet the often stringent requirements of the electricity authority in terms of voltage, frequency and the harmonic purity of the waveform.

The utility grid normally provides a pure sine wave. Not all inverter do; their output wave form can be a square wave, a step wave or, of course, a sine wave, depending on the type of the inverter, the load and the load condition. If the waveform is not a sine wave, many key AC devices such as the motor for example, will work at lower efficiency and hence dissipate more heat. This increased heat dissipation could destroy the apparatus if no precautions are taken.

Considering the fact that the overall efficiency of commercially available photovoltaic cell is as low as 12% to 14 %, it is essential to use the auxiliary equipment such as a charger, DC to AC inverter, etc., with highest possible efficiency. In the case of an inverter system, the amount of DC power required per day to supply an AC load is determined by the efficiency of the inverter as

$$DC\ (Wh/day) = AC\ load\ (Wh)\ /\ Invertor\ Efficiency \qquad (3)$$

Hence, if a system is operating with a low efficiency inverter, then the amount of DC (Wh) required will be quite high as compared to a system using high efficiency inverter. It is therefore necessary that to improve the overall efficiency of a photovoltaic system for AC load as well as to bring down the overall system cost (due to reduced battery storage/PV module requirement), the inverter should not only be reliable but also highly efficient, with minimum THD [45].

Fig. 15, presents the typical efficiency curves for an inverter that can be used in photovoltaic applications.

The most straightforward approach to achieve DC to AC conversion is simply to mechanically couple a DC motor to an AC alternator. The combined efficiency of such a motor/generator group is generally low, especially at low power levels. Therefore, this technique is not very suitable for photovoltaic applications, where the power requirements are of the order of a few kW. Modern solid -state inverters usually employ one of the following two techniques to construct a sinusoidal output:

1. Waveform Synthesis
2. Pulse Width Modulation (PWM)\

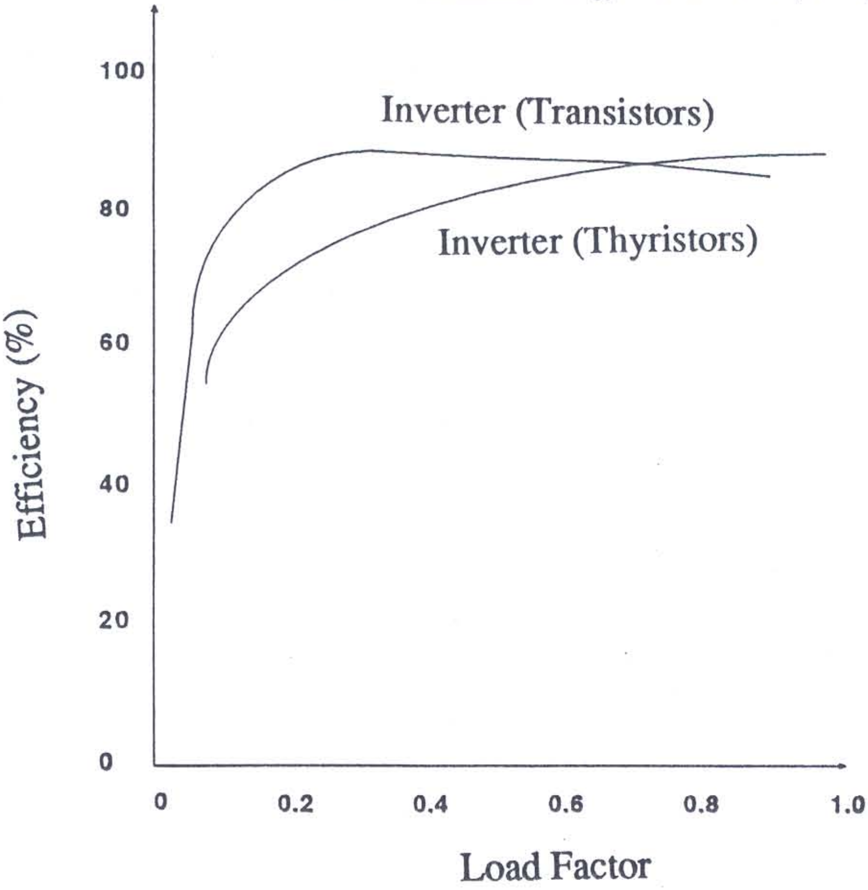

Fig. 15. Typical efficiency curve of an inverter as a function of load factor.

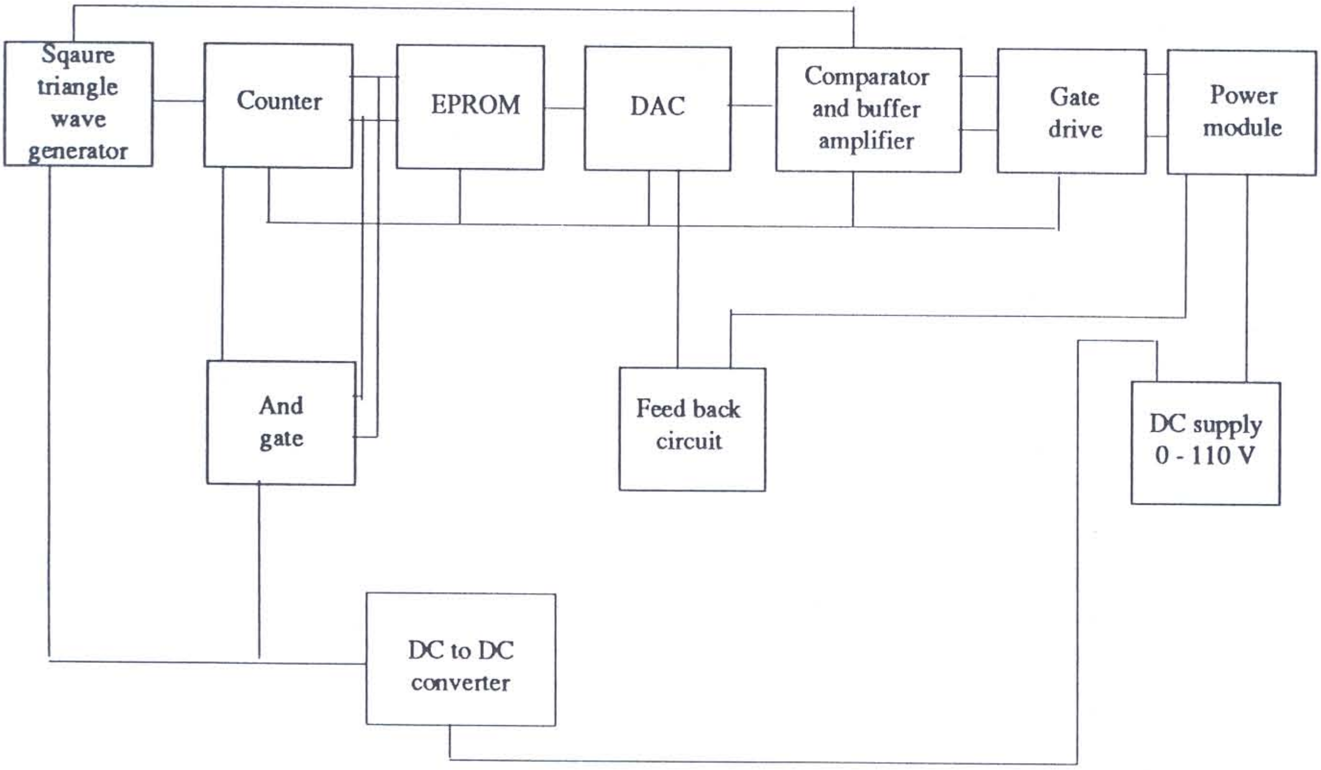

Fig. 16. Block diagram of an high efficiency inverter [45].

5.1 Waveform Synthesis

The phased outputs of several inverter stages, each producing a square wave by chopping the DC input, are combined by switching at the fundamental frequency to construct a stepped output waveform approximating a sinewave. The more inverter stages are used, the better is the approximation and lower is the harmonic distortion.

5.2 Pulse Width Modulation:

Another new technique to generate a sine wave from a DC source is Pulse Width Modulation (PWM), Fig. 16 [45]. An approximate sine wave, free from the main harmonics is generated by switching square- wave inverter stages at a rate higher than the fundamental frequency. The output voltage at any instant is controlled by varying the conduction time of the power switches, i.e. the pulse width. The total harmonic distortion is inversely proportional to the switching rate.

The process by which the forward current is interrupted or transferred from one switching device to another is called "commutation". A "self commuted" inverter, the type commonly used in stand alone AC systems, is one in which the switching is performed wholly within the unit, using power from DC input. A "line commuted" inverter, as used in grid interactive systems, is one in which the switching is triggered by the AC system to which the power is being supplied or by reactive elements connected to the output side of the unit.

The efficiency of a solid-state inverter on full load is usually better than 95% but it falls when the load is reduced beyond a certain point. As the inverter in a photovoltaic system will be operating for most of the time at load which is less than the full load, it is very important to choose an inverter of appropriate size with a good partial load efficiency.

In some large systems, the DC/AC conversion efficiency is improved by using multiple inverters, which are automatically switched 'ON' and 'OFF', to suit the load demand.

Japan Storage Battery Co., Ltd. has developed and started marketing a three - phase Lineback Series of newly developed three phase (200 V) network inverters available in 7 modes (rated capacities of 10kW - 60 kW) for use in photovoltaic power generation by electronic utilities.

These inverters convert the DC electricity generated by solar cells into three phase AC electricity. When the electricity generated by solar cells is inadequate, the shortage is supplemented with commercial power, and when there is surplus electricity, it is fed to the commercial power generation network.

This has been made possible by introducing the high frequency switching technique and micro-computed technology developed through the UPS system, such as the capacity enlargement and three phase conversion techniques, as well as the introduction of a linkage protection system.

The photovoltaic power generation system incorporates linkage protection systems such as voltage and frequency protection relays, and a function for terminating PV power generation and preventing independent plant operation to achieve safety whenever the commercial power system is interrupted.

In general, while selecting an inverter for a photovoltaic system for AC load, it is very important to consider the following points

1. Automatic switch-off if the DC input voltage is too high or too low.
2. Automatic re-start when the DC input voltage rises above a set minimum.
3. Protection against short circuits and overloading.
4. Appropriate size with a good partial load efficiency.

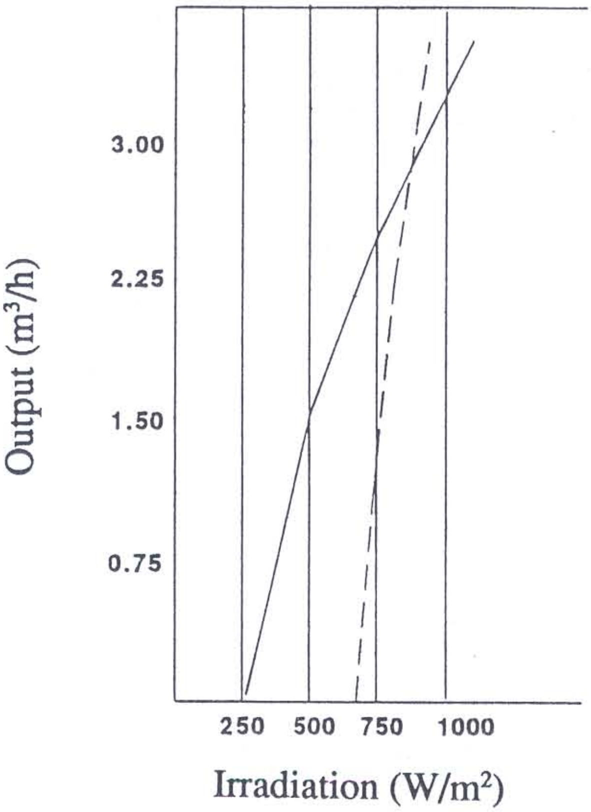

Fig. 17 Effect of MPP- tracking (DC system) [4].

6. MAXIMUM POWER POINT TRACKER (MPPT)

The matching of the load to the photovoltaic array is accomplished by incorporating an electronic control device; a MPPT for maximum utilization of photovoltaic energy into the system [45]. MPP-Tracking, common with AC applications, is essential also, if DC systems are applied. Fig. 17 highlights the effects of voltage tracking in a DC pump, for example.

The maximum power point tracker may be viewed as a time variable transformer (TVT), in which the transformation ratio is changed electronically, corresponding to the variations of the load operating point due to the variations of the solar insolation. The basic principle of a MPPT is that it forces the pump to track electronically the maximum power of a photovoltaic array at the given load.

It is reported that a single stage centrifugal pump, for an application of a static water head of less than 10 m, connected with a DC motor, can be designed in such a way that it can track near the maximum power point of the photovoltaic array output from morning to evening without an MPPT. However, a multistage centrifugal pump or a piston displacement pump, for a static water head of more than 10 m, connected to a DC motor cannot track the maximum power of a photovoltaic array for a whole day without a maximum power point tracker [20].

7. STORAGE SYSTEMS FOR PV WATER PUMPING SYSTEMS

Better designed storage systems for photovoltaic pumping applications are very important. In general, there are two types of conventional storage systems in this application:

1. Electrochemical storage (battery)

2. Hydraulic storage (in the form of mechanical energy of water in a water reservoir)

7.1 Electrochemical Storage

Electro-chemical storage technique is based on an electrochemical cell which enables the direct conversion of chemical energy into electricity. The topic of electro-chemical storage is not a new one. There is a large volume of literature available on the subject. The author summarizes the most relevant aspects involved in such operation. Also the main idea is to facilitate the discussion about the main principal concepts that characterize the improvement in the efficiency of battery storage systems.

The batteries in most photovoltaic systems are of lead-acid type. The life, cost and performance of storage battery in photovoltaic applications is affected by the Depth of Discharge (DOD) i.e. inverse of state of charge. Depth of discharge and the period after discharge before charge commencement are critical in photovoltaic applications for system reliability. The battery life is severely affected by the depth of discharge.

The energy efficiency is dependent upon the rate of discharge charge and depth of discharge of the battery. Values are on a decline mode with the increase of depth of discharge at a particular temperature and rate of discharge/charge. The results have been confirmed experimentally by Sayigh et al. [46] for three types of batteries acquired from different manufacturers i.e. 12V, 85 Ah BP Lucas; 6V, 75 Ah Varta; and 2V, 75 Ah chloride battery.

Keeping the depth of discharge and environment temperature constant, the rate of discharge/charge is varied. In this particular case as the rate of discharge/charge is decreased, the efficiencies are increased. The experiments were conducted at three different temperatures i.e. 25°C, 35 °C and 55 °C. It has been observed that batteries should be recharged as quick as possible after the discharge and in case of problem, it should be rectified, immediately [47].

It is therefore very important that the depth of discharge should in no circumstance exceed 80%, and the battery should never be left uncharged in this state for a long period. Overcharging, also results in corrosion, plate growth and loss of active material from the plates, leading to reduced life.

Another important factor concerning cycle life and battery operating efficiency is the temperature. It has been demonstrated, experimentally, by Sayigh et at. [47] that the cycle life and battery operating efficiencies significantly reduces at higher temperatures (> 35 °C). Also, the processes contributing to battery degradation are greatly enhanced at these temperatures. So providing cooling system to battery room to bring down the temperatures within the optimum, can improve the battery efficiency significantly. It has been reported that an improvement of 23.4% in energy efficiency is possible while lowering the temperature from 55 °C down to 25 °C. The tests results correspond to an 12 V, 85 Ah battery manufactured by BP Lucas company, for photovoltaic applications.

It has recently been seen that nickel-cadmium pocket plate batteries are in many ways more suited to operation in photovoltaic systems than the lead-acid types. Such batteries do not suffer from the problem of electrolyte depletion and stratification which afflict lead-acid batteries. Also, the capacity of the battery is not influenced much by the rate of discharge and temperature rise. The batteries can be fully discharged and are not damaged by a long period in this condition.

As seen above, nickel-cadmium batteries are more suited to operation in photovoltaic applications as compared to the lead - acid types but so far these are not diffused into the market. Apart from the high cost involved, the growing concern on the cadmium toxicity raises some questions on the opportunity of keeping the production at the actual levels.

To conclude, it can be stated that electrochemical storage technique is used in most photovoltaic systems but its disadvantages are: 1) shorter life; 2) heavy maintenance; 3) poor recovery energy and costly etc.

7.2 Hydrostorage

On the other hand, hydrostorage is a well known example of a mechanical technique. In large photovoltaic systems, water is pumped from a low level to a reservoir at higher level during the periods of high solar insolation and low energy demand. During the period of high energy demand, the energy can be recovered using turbines. However, for the systems such as photovoltaic water pumping, the energy is stored as mechanical potential energy in a water reservoir and is used without reconverting into electricity. The idea, no doubt, has been put into practice by some research group but it has its own disadvantages.

However, recently a new short term electro-mechanical storage concept has been suggested by Landau et al. [48]. 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 electro-mechanical device when the pump is not working due to poor insolation levels. This energy is released to the pump when the pump begins to operate as its optimum level. The advantages of this system are 1) low maintenance ; 2) increased system performance; and 3) overload protection.

8. CONCLUSION

From the discussions made so far concerning a photovoltaic water pumping system, it can be concluded that to lift a specified quantity of water through a given water head, at a given site, the overall sizing of the system depends upon a number of important considerations such as:

- Type of the solar cell panel (in terms of their efficiency and performance).
- Efficiency of the rest of the system i.e. the pump - motor- controller system.

Taking into consideration the recent developments, it can be stated that the electrical demand can be reduced significantly by making use of different components with high efficiency and durability such as:

1. Water pumps with high efficiency such as piston pump or progressive cavity pump.
2. Motor with high efficiency (upto 90%), and
3. A pulse-width-modulated controller with an efficiency of 95%.

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