CHAPTER 3

PHOTOVOLTAIC WATER PUMPING TECHNOLOGY

Fundamentals of solar cells

Although many fundamental concepts are well known, they will be explained in this section, particularly as many of them are not precisely defined in normal usage.

a) Voltage source

An electrical voltage source has the property that the voltage between its terminals is constant, regardless of the size of the current drawn.

The characteristic curve of an (ideal) voltage source can thus be drawn as a vertical line on the current - voltage graph:

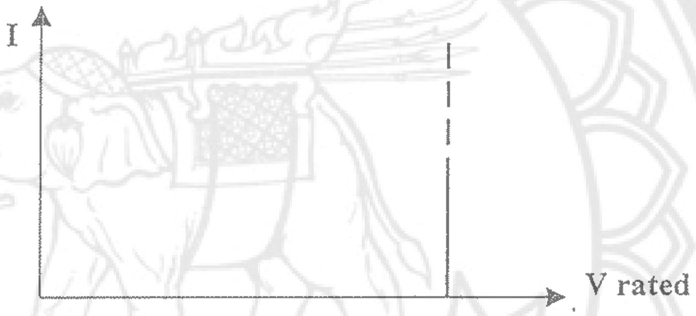

Figure 5 Current – voltage characteristic of an ideal voltage source.

b) Current source

A current source provides a constant output current, independent of the load, which is applied (constant current source). Thus, its characteristic curve is a horizontal line:

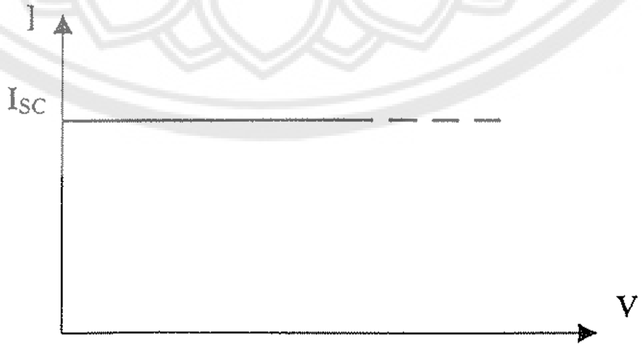

Figure 6 Current – Voltage Characteristic curve of an ideal current source.

The characteristic of a current source is that even when it is short - circuited, the constant current Isc is the maximum.

Apart from laboratory equipment and within some electronic circuits, there are few practical examples of current sources. An electric welder will be taken as an example, because its behavior is well known and its characteristics are similar to a solar generator.

An electric welder has approximately the following idealized characteristic curve:

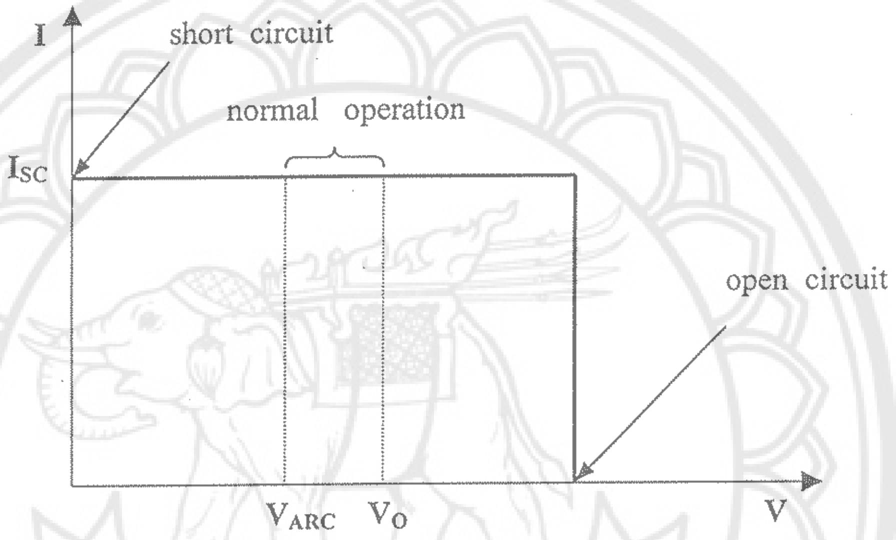

Figure 7 Idealized characteristic curves of an electric are welder.

Under open circuit conditions, it behaves like a voltage source with an open circuit voltage V_{OC}.

Characteristics of solar cells

Only three types of solar cells are available on the market today in larger quantities. They are monocrystalline Si cells, multicrystalline Si cells and amorphous Si cells

The third type is used almost exclusively in low - power applications (e.g. calculators, watches), whereas, modules of monocrystalline or multicrystalline silicon cells are used predominantly in the medium and higher power range. In the following section, the quantities needed to characterize solar cells and modules will be explained using crystalline cells as examples, but the concepts can also be applied to solar cells made with other manufacturing technologies.

a) Short circuit current Isc

The short circuit current Isc is proportional to the solar radiation over a wide range. The short circuit current depends on the cell temperature where the current increases by about 0.07 % °K (1° Kelvin corresponds to a temperature difference of 1 °C)

The shape of the characteristic curves indicates that near the short circuit point, a solar cell behaves like a constant current source (horizontal line), whereas near the open circuit condition it approximates a constant voltage source (vertical line).

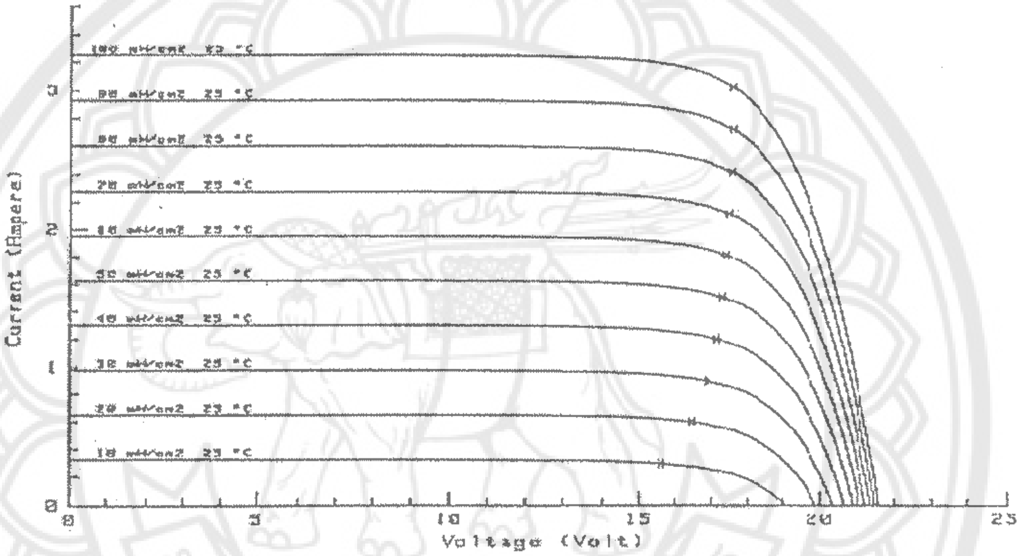

Figure 8 Characteristic curve of current – voltage of a solar panel at 25°C and varying solar radiation.

A short circuit is thus a completely normal, permissible working point for a solar cell, which can be maintained indefinitely. Further, it can be seen that this short circuit current is only slightly higher than the current at the typical working point. Depending on the radiation, it can also be significantly smaller than the rated current. These properties mean that solar generators need not be protected against short circuits with fuses or circuit breaker.

b) Open circuit voltage Voc

According to the explanation of the solar cell equivalent circuit and the shape of the characteristic curve, the open circuit voltage V_{OC} corresponds to the voltage across the internal diode when the total generated photocurrent flows through this diode. When the radiation intensity is low (and thus also the photocurrent), the open circuit voltage is also low - it increases exponentially as illustrated in Figure 18 with increasing radiation and reaches a typical value of 0.5-0.6 V for crystalline cells and 0.6-0.9 V for amorphous cells. Like the solar generator characteristic curve, the dependence of the open circuit voltage on the radiation corresponds to an inverted diode characteristic.

Whereas the open circuit voltage and also the working point voltage can be assumed to be almost independent of the radiation value for the typically high intensities outdoors, these voltages drop markedly in poorly lit indoor rooms with intensities of only a few Wm^{-2}. This is particularly evident when the solar cell has a low filling factor due to a low parallel resistance. Account should be taken of this effect, when designing power supplies for indoor appliances, by connecting a larger number of solar cells in series.

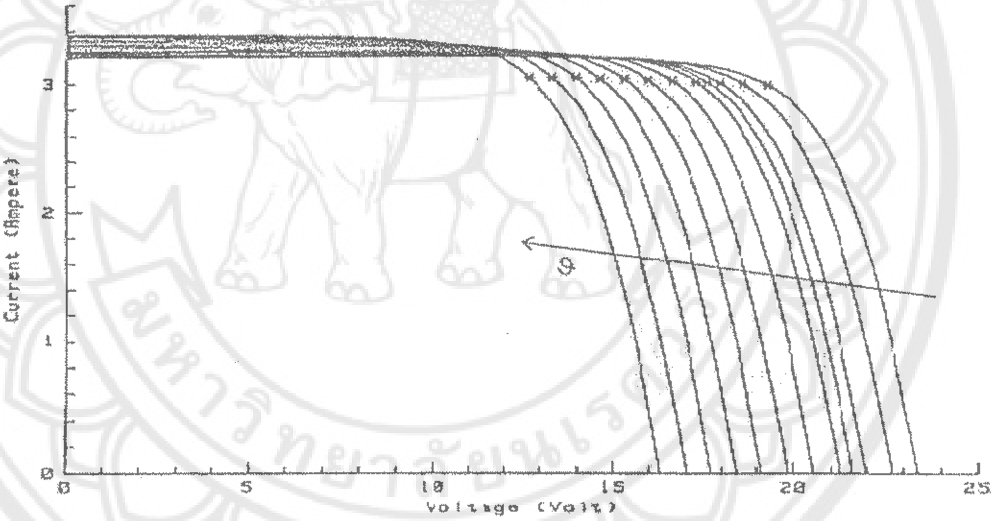

Figure 9 Characteristic curve of current – voltage compare with 0 – 100 and 25°C of temperature at 1000 W/m^2.

Further, the open circuit voltage (and also the working point voltage) is strongly temperature – dependent with the voltage sinking by about 0.4 % / °K

This should also be considered during the design phase, as solar cells installed outdoors can reach temperatures, depending on the installation (ventilation), which are up to 40 K higher than the ambient temperature.

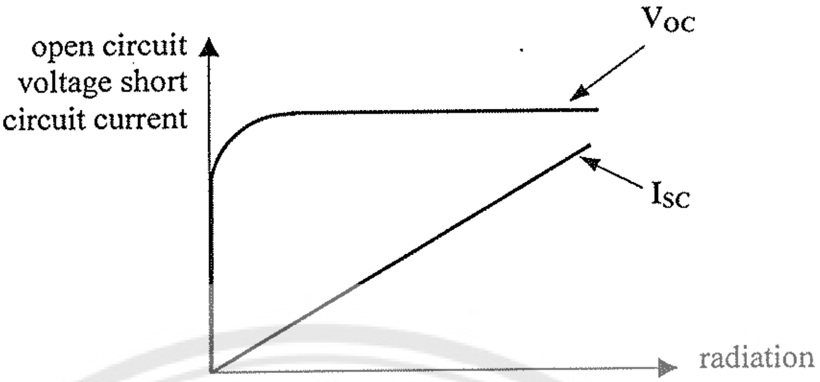

Figure 10 Open circuit voltage and short circuit current as a function of the radiation intensity.

c) Power

The power delivered by a solar cell is the product of current and voltage. If the multiplication is made, point for point, for all voltages from short circuit to open circuit conditions, the power curve illustrated in figure 19 is obtained for a given radiation level:

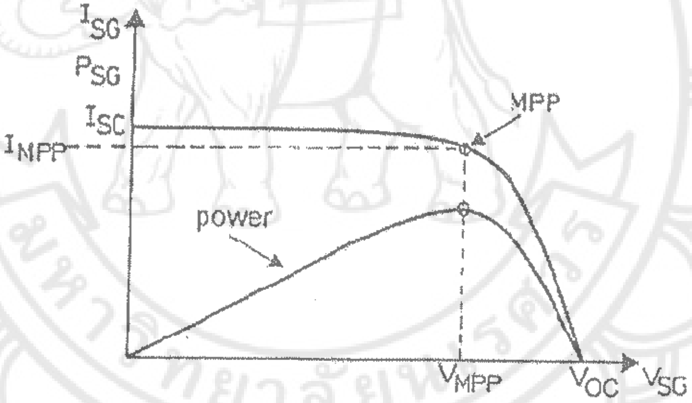

Figure 11 power curve and maximum power point (MPP).

In addition, the power at any point can found by using the formula.

$$P_m = I_m \times V_m \qquad \ldots(1)$$

Although the current has its maximum at the short circuit point, the voltage is zero and so the power is zero.

The situation of current and voltage is reversed at the open circuit point, so again the power here is zero. In between, there is one particular combination of current and voltage for which the power reaches a maximum (graphically the area of the rectangle indicated).

d) Maximum power point

The working point at which the solar generator can deliver maximum power for a given radiation intensity (MPP) is positioned near the bend in the characteristic curve. The corresponding values of V_{MPP} and I_{MPP} can be estimated from the open circuit voltage and the short circuit current:

$$V_{MPP} \sim (0.75 - 0.9)\, V_{OC},\ I_{MPP} \sim (0.85 - 0.95)\, I_{SC}$$

As the cell voltage and Current depend on the temperature, the supplied power also changes with the temperature which the power sinks by about 0.4 - 0.5 % / K

The rated power of a solar cell or a module is measured under internationally specified test conditions (STC or SRC = Standard Test or Reporting Conditions; $G = 1000\ Wm^{-2}$, $T_{cell} = 25\ ^{\circ}C$, AM 1.5) and is reported in Wp (peak watt). The term " peak power " is misleading, as e.g. at lower cell temperature or higher radiation intensities, this value can well be exceeded.

e) Efficiency value

Not the entire solar radiation incident on the solar cell is convert to electricity. The ratio of the output electrical energy to the input solar radiation is defined as the efficiency value, which depends on the type of cell. So, the maximum efficiency value can be found from this formula:

$$\eta_{MAX} = \frac{P_{MAX}}{\textbf{Solar Radiation x Area of solar cell}}$$

$$= \frac{I_{MAX} \times V_{MAX}}{G_T \times A_{CELL}} \qquad \ldots(2)$$

For the module efficiency value, the output power is divided by the total radiation incident on the module. As not the entire area of the module is covered with solar cells, the module efficiency value is lower than the efficiency value of the single cell.

f) Filling factor

The simplified equivalent circuit diagram in fig. 12 to explain the fundamental behavior of solar cells must be extended to include two resistances for a more exact description. The series resistance Rs is composed of the resistance through the silicon wafer, the resistance of the back surface contact and the contact grid on the front surface, and further circuit resistances from connections and terminals. The parallel (or shunt) resistance Rp results in particular from the loss currents at the edges of the solar cell and surface inhomogeneities.

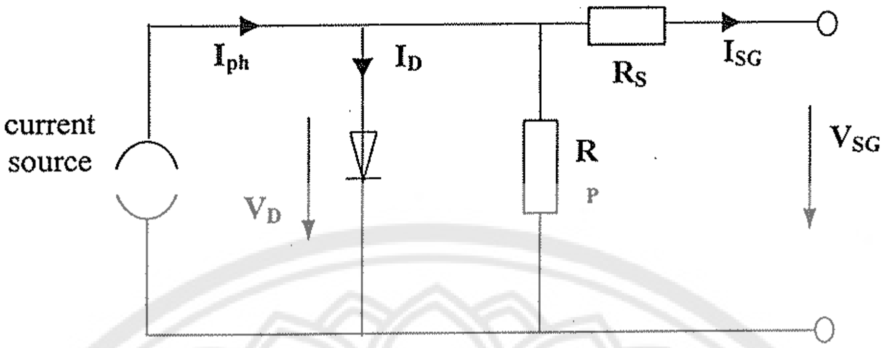

Figure 12 More sophisticated equivalent circuit diagram for a solar cell.

Both resistances make the characteristic curve rectangular, and the maximum power output is reduced. A further measure for the quality of a solar cell is therefore the filling factor, which describes how closely the current - voltage characteristic curve approximates the ideal rectangular form

$$FF = \frac{V_{MPP} \times I_{MPP}}{Voc \times Isc} \qquad \ldots(3)$$

The filling factor for crystalline solar cells is about 0.7 to 0.8.

Photovoltaic pumping systems

The main components of a PV pumping system are illustrated schematically in Fig 13 A solar PV pumping system can be divided conceptually into three parts:

- The PV array which converts solar energy
- The Motor and pump subsystem comprising the components which convert the electrical output of the PV array into hydraulic power .
- The storage system which delivers the water to its point of use

The capital cost of PV arrays is directly proportional to the electrical output of the array and the PV array is at present a large proportion of the overall system cost. Consequently, the cost of a solar pump is almost directly proportional to the hydraulic output and there are only economies of scale for small systems.

The efficiency of the subsystem determines how large the PV array needs to be for a particular hydraulic duty and hence has a large influence on the overall solar pumping system cost – a more efficient subsystem will require a smaller PV array and the solar pumping system will cost less.

It is common for little thought to be given to the design of the delivery side of a pumping system. In many cases, especially in irrigation systems, the pump wastes water. For a conventional diesel pump this means pumping for a longer period that means more fuel will be consumed, maintenance costs will increase and the diesel engine lifetime will be shortened. This increases the system running costs, but has no effect on the capital cost of the pump. The effect of a wasteful distribution system is far more significant for a solar pump. Since the capital cost of a solar pump is almost proportional to the quantity of water pumped, it is particularity important to ensure that the water is distributed efficiently and to take into account the distribution system when assessing the overall system costs.

With conventional gasoline or diesel fuelled pumps, storage is not important because energy is stored in the fuel itself and the pump can be started when there is a demand. With a solar pump, energy is not available on demand and the day by day variations is solar irradiation mean that for some locations, with successive cloudy days, it may be prudent to consider storage of a surplus of water pumped or surplus of electricity generated on sunny days for use on cloudy days.

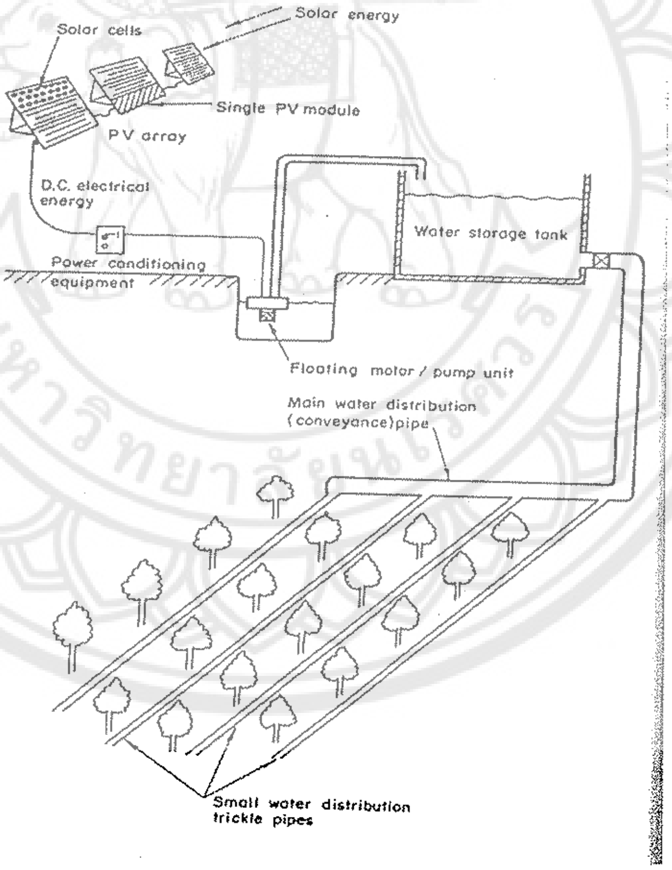

Figure 13 Main components of a PV pumping system.

(From solar water pumping a handbook)

a) The Motor and Pump Subsystem

- General

In many cases it is feasible to utilize off the shelf, mass produced motors and pumps. However, special pumps and motors have been developed by some manufacturers with an above average efficiency to minimize overall system costs. The operation of the subsystem is unlike conventional power conversion devices, because the power supply system must be designed to work efficiently over a range of voltage and current levels.

Because of these variations and the resulting changes in subsystem efficiency, it is useful to define two types of efficiency:

(i) the power efficiency of the subsystem, which is the ratio of hydraulic output power to electrical input power, at any instant in time. This will have a peak value when the subsystem operates at its design conditions.

(ii) the energy (or daily) efficiency of the subsystem, which is the ratio of hydraulic output energy to electrical input energy over a day. It is a time average of the power efficiency and consequently depends on the daily variations in power efficiency and hence on the solar irradiance profile for the day.

The energy efficiency is the more important parameter because it determines the array size for a particular hydraulic duty and consequently largely how much the solar pump costs.

- Motor technology

Solar water pumps that are currently available make use of the following motor technologies

1. brushed type permanent magnet d.c motors
2. brushless permanent magnet d.c motors
3. a.c motors

The choice of a d.c motor is of course attractive because the array provides a d.c power supply. However, for high power applications a.c motors in conjunction with d.c-a.c inverters can be used. The range of a.c. motors is greater than d.c motors, and the prices are generally lower. However, for small systems the savings made by using a low cost a.c motor may be offset by the additional cost of an inverter.

Permanent magnet brushed and brushless d.c motors are shown in cross section in Fig 14. Also shown is a conventional wound field d.c motor for comparison. In the conventional, motor both the magnetic fields of the armature and the surrounding field coil are powered by the d.c supply. The field in the armature is cycled by use of a commutator, thus causing the armature to rotate.

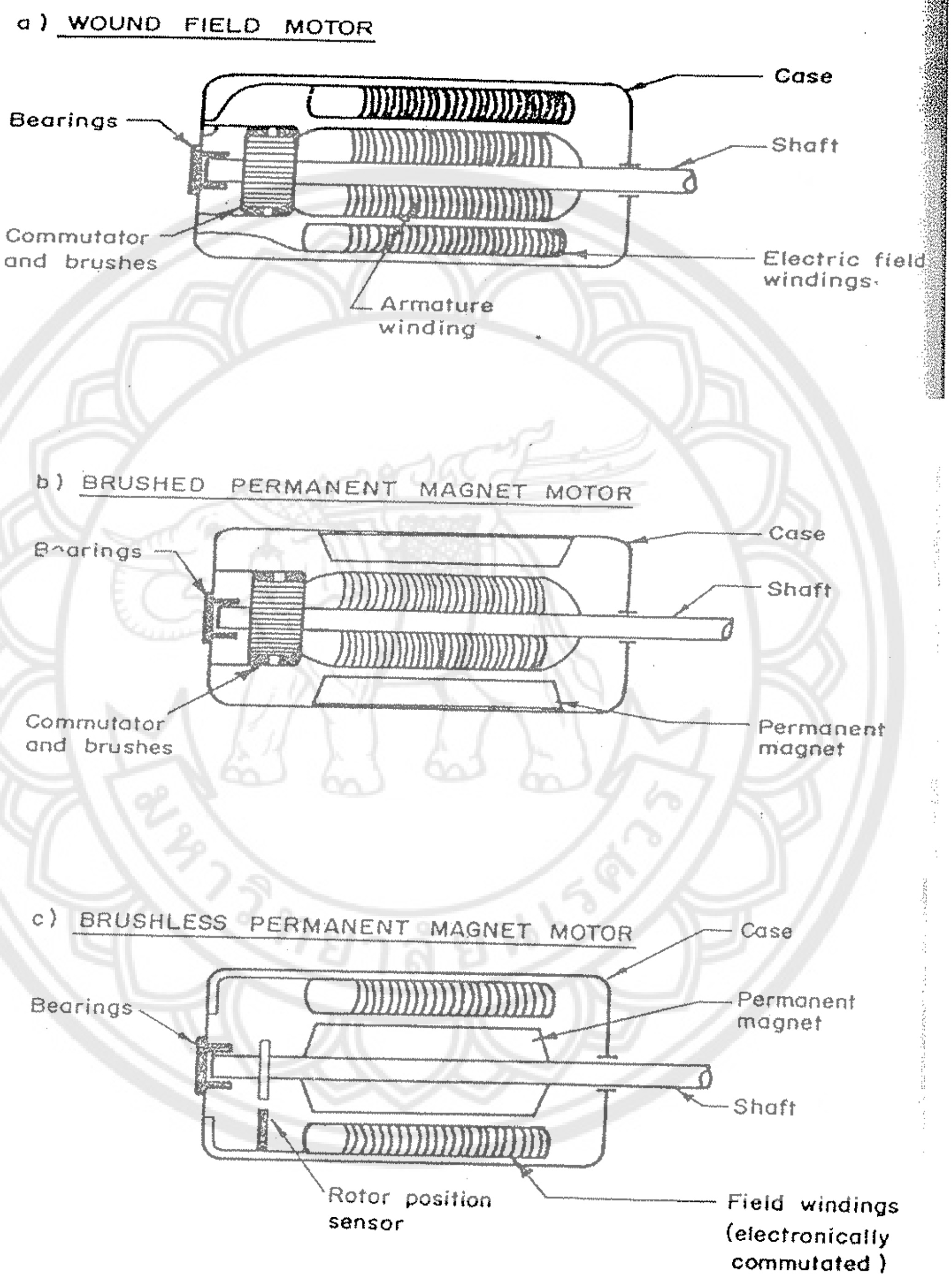

Figure 14 Construction of d.c. motors.
(From solar water pumping a handbook)

The permanent magnet brushed d.c. motor also achieves rotation by having a brushed commutator but the surrounding magnetic field is not induced electrically. This leads to higher efficiencies as no power is consumed in the field windings (and in turn, lower PV array sizes may be used for the same hydraulic duty).

Brushed motors generally require new brushes at intervals in the order of 2000-4000 hours (equivalent to one to two years of continuous use with a solar pump) with obvious implications for maintenance costs. The brushless d.c. motor has a permanent magnet rotor and electronically switched field winding. Brushless d.c. motors in use with solar pumps are, at present, relatively new and early reliability problems with the electronics are being tackled by the industry. The long terms potential for brushless d.c. motors shows every likelihood of being large.

The use of an a.c. motor in a solar pump requires an inverter, which introduces additional costs and some energy losses. Hence, a.c. motors have not been seriously suggested for low power (less than 250W) applications where the increased cost may be a significant proportion of the overall cost. A.c. motors are generally less efficient than d.c. motors but special improved efficiency models are now available for use in solar powered systems.

- Pump technology

In the design of a solar powered pumping system, the pump itself is the most important component. Pumps can be divided into two categories centrifugal and positive displacement, and they have inherently different characteristics.

1. Centrifugal pumps (Fig 15) are designed for a fixed head and their water output increases with rotational speed. They have an optimum efficiency at a design head and a design rotation speed. At heads and flows away from the design, point their efficiency decreases. However, they offer the possibility of achieving a close natural match with a PV array over a broad range of operating conditions. Centrifugal pumps are seldom used for suction lifts of more than 5 to 6 metres and are more reliably operated in submerged and floating motor/pump sets. This is because they are not inherently self-priming, and can easily lose their prime at higher suction heads.

2. Positive displacement pumps (Fig 15) have a water output, which is almost independent of head but directly proportional to speed. This means that the efficiency of a pump of fixed piston diameter increases with head and therefore for optimum efficiency different diameter pumps need to be used for different heads. At high heads the frictional forces become small relative to the hydrostatic forces and consequently at high heads positive displacement pumps can be more efficient than centrifugal pumps. At lower heads, below about 10m, the total hydrostatic forces are low in relation to the frictional forces and hence positive displacement pumps are less efficient and less likely to be used.

A major factor to consider when coupling a positive displacement pump to a PV array is the cyclic nature of the load on the motor. This causes cyclic variations in electrical impedance corresponding to the variations in torque. Electronic power conditioning is sometimes used to smooth out these effects by matching the current/voltage characteristics of the array with those of the motor. It is also important to match the motor operating characteristics to those of the pump by choosing appropriate gear ratios. Additional smoothing can be provided by the addition of a flywheel

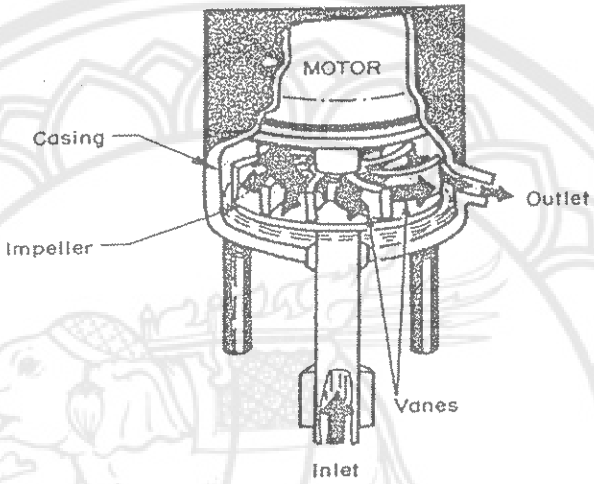

Figure 15 Principle of a centrifugal pump (Water is thrown out from the center of the pump because of the centrifugal force created as the impeller rotates).
(From solar water pumping a handbook)

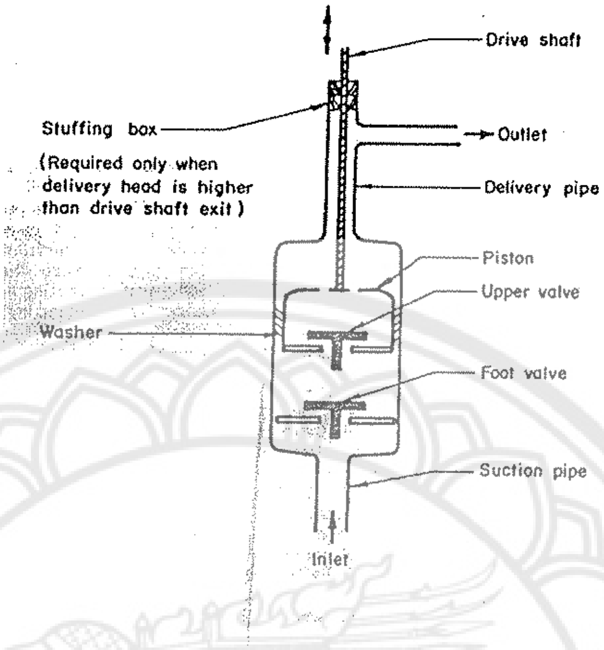

Figure 16 Schematic of a positive displacement pump. When the piston moves down, the foot valve closes and water passes to the chamber above the piston. On the upward stroke the upper valve closes, the foot valve opens and water is lifted to fill the chamber below the piston. (From solar water pumping a handbook)

- **Power out from the motor/pump (P_P)**

$$P_P = \rho * g * H_p * Q \qquad \dots(4)$$

When

ρ is density of water, (1,000 kg / m^3)
Q is flow rate, m^3 / s
H_P is Total head, m
g is gravity constant, (9.8 m/s^2)

- **Efficiency of motor/pump (η_{MP})**

$$\eta_{MP} = \frac{P_P}{P_{Pv}} * 100 \qquad \dots(5)$$

- **Total head (H_P)**

Total head can divide into two-head types, one is head loss (h_L or dynamic head) and the other is the vertical distance between the surface of the source water and the surface of the water in the tank (H or static head). Therefore, the total head is sum of head loss and head to the tank. We can find total head by use of this equation.

$$H_p = H + h_L \qquad \ldots(6)$$

When h_L can be estimated from this equation

$$h_L = \frac{32\,\nu L V}{g\,D^2} \qquad \ldots(7)$$

When

ν is kinematics viscosity, m^2 / s
L is distance from pump to tank, m
D is diameter of pipe, m
V is flow velocity, m / s

- **Typical PV water pumping system**

System are broadly configured into 5 types as described below:

1. Submerged multistage centrifugal motor pump-set

This type is probably the most common type of solar pump used for village water supply. The advantages of this configuration are that it is east to install, often with lay-flat flexible pipe-work, and the motor pump-set is submerged away from potential damage. Either AC or DC motors can be incorporated into the pump-set although an inverter would be needed for AC used. Use of a brush type DC motor means that the equipment will need to be pulled up from the well (approximately every 2 years) to replace brushes. If brusheless DC motors are incorporated then electronic commutation will be required. The most commonly employed system consists of an AC pump and inverter with a PV array of less than 1500 Wp.

2. Submerged pump with surface mounted motor

This configuration was widely installed with turbine pumps. It gives easy access to the motor for brush changing and other maintenance. The low efficiency from power losses in the shaft bearings and the high cost of installation has been disadvantages. In general, this configuration is largely being replaced by the submersible motor and pump-set.

3. Reciprocating positive displacement

The reciprocating positive displacement pump (often known as the jack or nodding donkey) is very suitable for high head, low flow applications. The output is proportional to the speed of the pump. At high heads, the frictional forces are low compared to the hydrostatic forces often making positive displacement pumps more efficient than centrifugal pumps for this situation. Reciprocating positive displacement pumps create a cyclic load on the motor which, for efficient operation, needs to be balanced. Hence the above ground components of the solar pump are often heavy and robust and power controllers for impedance matching often used.

4. Floating motor-pump set

The versatility of the floating unit set makes it ideal for irrigation pumping from canals and open wells. The pump set is easily portable and there is a negligible chance of the pump running dry.

Most of these types use a single stage submersed centrifugal pump. The most common type uses a brushless (electronically commuted) DC motor. Often the solar array support incorporates a handle or 'wheel barrow' type trolley to enable transportation.

5. Surface suction pump sets

This type of pump set is not recommended except where an operator will always attend. Although the use of priming chambers and non-return valves can prevent loss of prime, it is impractical to have suction heads of more than 8 meters.

- Power conditioning

Power conditioning may be of several types:

1. impedance matching devices
2. D.C to A.C. inverters
3. batteries
4. switches, protective cut outs etc.,

In almost all cases, the use of power conditioning equipment implies a power loss (typically 5%), additional cost and an additional potential failure mode. Hence, to justify their use the increased costs must be compensated for by the extra water output or in the case of switches and protective cut outs, better reliability.

1. Impedance matching devices are used:

a) to produce high currents so that the motor pump will start in low solar irradiance conditions. (This is particularly important when using reciprocating pumps.).

b) to maximize the power available from the PV array.

Maximum power point trackers (MPPT's or maximum power controllers) are "intelligent" devices, usually employing a microprocessor. They achieve these functions by sampling the power output of the array at frequent intervals (typically every 30 milli-seconds). They compare each new value of the array output and if it has increased then the array voltage is stepped in the same direction as the last step, whereas if the power output has decreased then the array voltage is stepped in the opposite direction. The power consumption of maximum power controllers is typically between 4 and 7% of the array output.

2. D.C to A.C. inverters:

D.C to A.C. inverters for use with PV arrays are currently undergoing considerable development and can be expected to become increasingly important. To maximize their benefit, the electronics involved should also provide some means of impedance matching such that a PV array can operate near to its maximum power point. The efficiencies of some commercially available inverters are claimed to be greater than 90%. Some inverters have poor part load efficiency and are therefore unsuitable for use with solar pumps.

3. Batteries:

Batteries also provide impedance matching and allow the motor to start at low or zero irradiance levels. They provide energy storage and allow designers to accurately optimize the sub-system because they operate at a fixed voltage. However, they have several disadvantages: they involve a power loss, increase the risk of reliability problems, have a shorter operational life than the rest of the solar pump, and require regular maintenance. At present, most solar pumping systems do not include batteries although where water storage is not required they may justify further consideration.

4. On-Off switches and devices:

On-Off switches and devices to protect components against power surges are recommended for use with solar pumps. Safety considerations must not be neglected - for example, protection against high voltage shock should be present.

b) Photovoltaic arrays

- Performance

Photovoltaic modules are rated in peak Watts (Wp), This is a reference value of the maximum power output from the module when operating at a cell temperature of 25 °C under a solar irradiance of 1000 W/m^2, and is a higher power output than is achieved on average in the field. If the cell efficiency is 10%, a 1 kWp array would contain a cell area of 10 m^2. Typically the packing factor (the ratio of cell area to array area) for circular cells is about 75% giving a gross area of 13.3 m for a 1 kWp array. Using square cells can increase the packing factor, but this involves cutting the cells. As cells become cheaper to produce, higher packing factors can be expected.

The efficiency (and hence power output) of the cell depends on the electrical load because of the relationship between current and voltage for the cells.

Figure 17 Photovoltaic arrays Energy Park, Naresuan University.

- **Power of PV array (P_{PV})**

$$P_{PV} = I_{PV} * V_{PV} \qquad \ldots(8)$$

When

I_{PV} is current from PV array, A

V_{PV} is voltage from PV array, V

- **Efficiency of PV array (η_{PV})**

$$\eta_{PV} = \frac{P_{PV}}{G_T * A} \quad \ldots(9)$$

When

G_T is global solar radiation, W / m^2

A is the area of PV array, m^2

- **Efficiency of PV Pumping system (η_{sys})**

$$\eta_{sys} = \frac{P_P}{(G_T * A_a)} \quad \ldots(10)$$

When

A_a is the total area of PV array, (9.1872 m^2)

The efficiency of solar cells falls off with increasing operating temperature. Typically the efficiency will drop by 0.5% fractionally per degree centigrade increase in operating temperature. With the daytime ambient temperatures found in many developing countries, cell operating temperatures can be as high as 60 °C, resulting typically in a 16% fractional reduction in the peak output from that at the reference operating temperature. Also since solar irradiance is generally less than 1000 W/m^2, the average power output from an array is always significantly less than the rated output. It a good 'solar' location, the solar irradiance averaged over the hours of daylight may be 500 W/m^2. Hence, the average array output will generally be less than half of the rated output.

c) Storage of Water

One of the major problems with solar energy is that power is not available on demand. For irrigation applications, it may be critical that water is available to prevent a crop from dying, and it is usually equally important to have water on demand for rural water supplies. Therefore, when using solar powered pumping, the problem of water storage must be considered.

- For irrigation: two types of water storage can be identified:

    a) long term storage in which water is stored from month to month to even out the demand pattern. This type of storage will permit irrigation on demand, and minimize the effect of variations in monthly water demand.

b) short term storage which allows a farmer to store water from one day to the next. This serves the dual purpose of;

   I. giving the farmer improved water management control

   II. smoothing out the day to day variations, i.e. on a day with a high level of solar energy, when the solar pump could provide so much water that it would saturate the soil, the excess water would be stored so that it could be used for a day with a low level of solar energy.

Long term storage for irrigation system is not usually feasible for practical and economic reasons, and to a certain extent, the soil itself can sometimes act as a short-term storage to even out the effect of good and bad days in a month. However, for most applications, the use of short-term water storage systems should be considered.

- For rural water supplies:

For rural water supplies, it is essential to include a storage tank when using solar pumps. Preferably, this should meet several days water demand. Where there is a piped distribution system, the storage tank will have to be raised above ground level to provide sufficient pressure for the water to flow in the pipes.

Since increases in total water lift have a proportional effort on the cost of a solar pump, it is important that any storage tank should have a low aspect ratio (i.e ratio of height to diameter). It should also be remembered that water could be lost by evaporation and seepage if the tanks are not covered and lined, thereby decreasing the efficiency of the storage system. Tanks should always be covered to minimize the entry of dirt, insects and animals.