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"Photovoltaic Systems"

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These are preliminary lecture notes, intended only for distribution to participants.

PHOTOVOLTAIC SYSTEMS

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1. DEFINITION

A photovoltaic system 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.

2. CATEGORIES

There are two main categories :-

1) Standalone

2) Grid-connected

Grid-connected systems are sub-divided into those in which the grid acts only as an auxiliary supply (grid back-up) and those in which it may also receive excess power from the PV generator and thus act as a form of storage (grid interactive).

3. TYPES OF SYSTEM

In its simplest form, a standalone PV system consists of an array of one or more modules supplying the load directly (Fig.1). Such a system can be used for battery charging (with a simple charge regulator) or for water pumping, where the storage medium is water.

Fig.1 STANDALONE DC SYSTEM WITHOUT BATTERY

The addition of an inverter, a device which converts dc to ac, makes the system suitable for ac loads. (Fig.2).

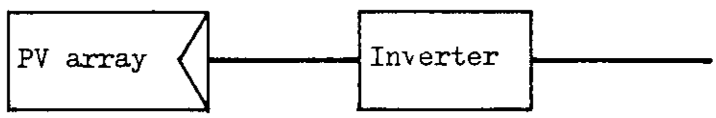

Fig.2 STANDALONE AC SYSTEM WITHOUT BATTERY

For dc loads such as telecommunications equipment, cathodic protection, navigational aids, traffic control warnings, dc lighting, refrigerators, TV, radio, etc. a storage battery with charge regulator must be added to the basic dc system, (Fig.3), to carry the load during the night and periods of low irradiance.

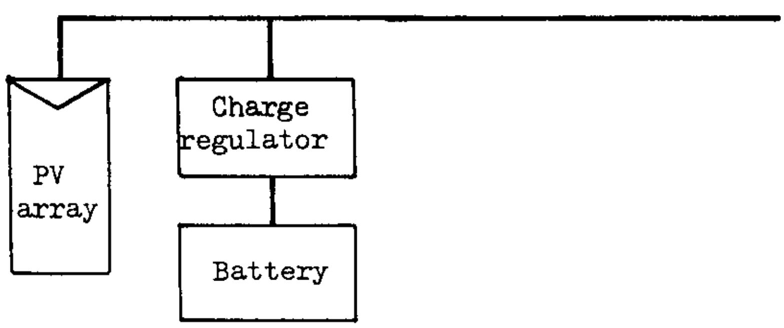

Fig.3 STANDALONE DC SYSTEM WITH BATTERY

If the load consists of ac appliances, an inverter must be added, (Fig.4). The dc and ac systems in Figs. 3 and 4, or a combination of both, are appropriate for domestic supplies in remote houses and villages.

A back-up generator can be incorporated to improve the security of supply and reduce the required battery storage capacity. Fig.5 shows an example of such a hybrid system. The auxiliary source can be a wind turbine, a hydro-electric generator or a diesel, gasoline or propane generator. If the auxiliary generator is fossil-fuelled, it is usually limited by automatic control to short running periods at or near its most efficient operating point, when the battery has reached its maximum depth of discharge and the irradiance is low.

Fig.6 illustrates a grid interactive system. The controller switches the load to the grid when the PV power is insufficient to meet the demand and it connects the inverter to the grid when there is surplus PV power. If the utility pays less per unit of electricity received than for the power they supply, as is usually the case, two meters are necessary.

In a grid back-up system, the controller simply switches the load to the grid when required and only one meter is necessary.

Some grid-connected systems have small batteries to provide overnight storage and stabilise the input voltage to the inverter.

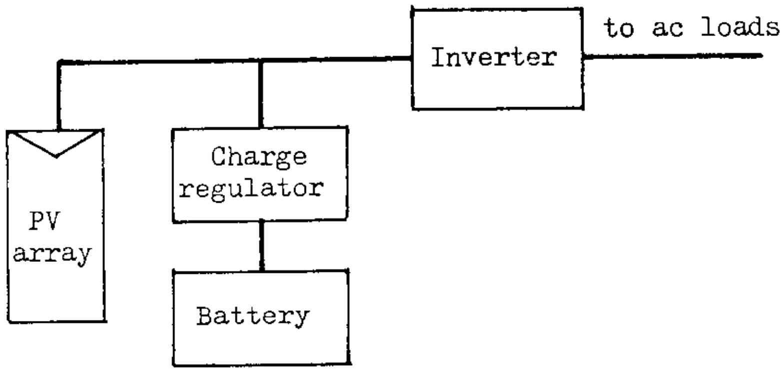

Fig.4 STANDALONE AC SYSTEM WITH BATTERY

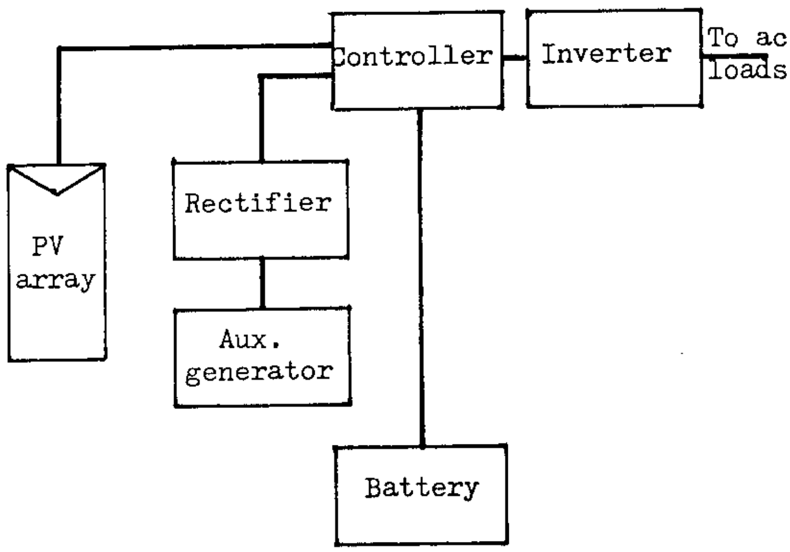

Fig.5 STANDALONE HYBRID SYSTEM

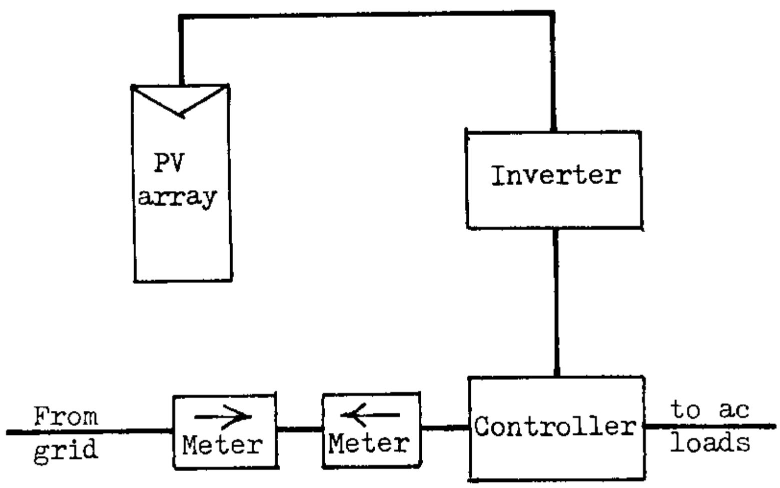

Fig.6 GRID INTERACTIVE SYSTEM

These basic schemes can be varied to suit particular applications. For example, a dc/dc converter may be used to convert the array output to a voltage suited to the battery or load. The converter may be of a special type, called a "maximum power point tracker" (MPPT) to ensure that the array always operates at its maximum power point, irrespective of changes in irradiance, temperature or load.

4. ARRAYS

The modules in a PV array are connected in series strings to provide the required voltage and, if one string is not enough to provide the required power, two or more strings are connected in parallel, as shown in Fig.7.

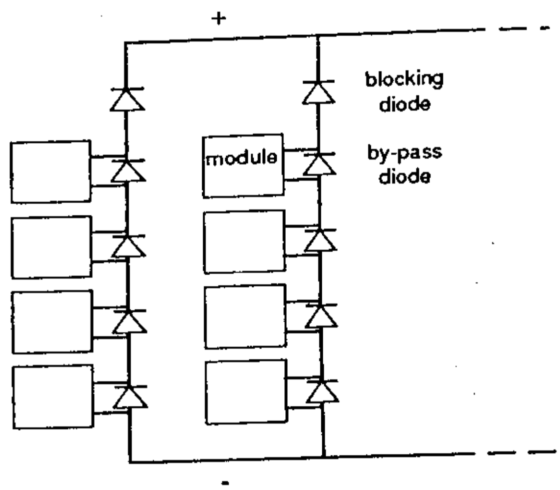

Fig.7 ARRAY CONNECTIONS

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 module 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 current 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.

The voltage drop across the blocking diodes (about 0.9V in the case of silicon diodes) represents a power loss which, when added to the losses from cable resistance and module mismatch, reduces the array output to less than the aggregate from the modules. Such array losses should be limited, preferably to less than 5%.

Some PV generators may consist of more than one array, in which case the installation is called an "array field". Array fields 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 help to reduce storage requirements in standalone systems.

By mounting arrays on 2-axis sun trackers, up to 40% more energy can be collected over the year. 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) installations. But, with small, manually adjustable arrays, useful gains can be obtained by changing the tilt once 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 minimised by mounting all the modules in one plane. This is common practice with arrays mounted on the roofs or walls of buildings. For large installations, however, it can increase the cost of the supporting structure and make access to the modules difficult.

The more usual approach is to arrange the arrays in easily accesible rows, spaced so as to prevent too much shadowing of one row by its neighbour 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.

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

5. BATTERIES

The batteries in most PV systems are of the lead-acid type. They consist of one or more battery cells, each of which is rated at 2V. The cell has a positive plate of lead peroxide and a negative plate of sponge lead immersed in a solution of sulphuric acid in distilled water.

When current is drawn from the battery, the material of both plates is converted to lead sulphate by reaction with the sulphuric acid. At the same time, the water content is increased, resulting in a reduction of the specific gravity of the electrolyte. The reverse action takes place when the battery is charged by passing current through it in the opposite direction. During the charging process, the cell voltage rises. Typically, it is about 1.9V in a deeply discharged battery and about 2.4V in a fully charged one but the actual levels are temperature-dependent.

The capacity is expressed in ampere hours (Ah). It is the total amount of electricity (current x time) that can be drawn from a fully charged battery at a specified discharge rate and electrolyte temperature, until the voltage falls to a specified minimum. The higher the discharge current, the lower the capacity. Manufacturers usually rate their batteries at C_{10}, the capacity corresponding to discharge at a constant current I_{10} over a period of 10 hours. However, in most PV systems the battery is expected to perform for a number of days before recharge, so the higher C_{100} rating is normally used for sizing purposes.

At temperatures below 25°C, the capacity of the battery is reduced by about 0.6% per degree C. As the battery ages, there is an initial rise in capacity of about 10%, followed by a gradual decline. The depth of discharge, i.e. the percentage of the total capacity withdrawn, should in no circumstances exceed 80% and the battery should not be left uncharged in this state for long. Failure to observe these precautions will result in a loss of capacity and higher internal resistance.

A battery in a PV system is subjected to repeated daily and seasonal charge/discharge cycles. The depth of discharge is the biggest factor affecting cycle life. Typically, at 40% depth of discharge, the battery may be expected to last for 3500 cycles or about 10 years but, at a constant

80%, it would last for only 3 years. In practice, the depth of discharge varies considerably from winter to summer and modern lead-acid batteries in properly designed, well maintained systems should have a life of 7 to 8 years.

If current continues to be fed into a lead-acid battery after it has reached full charge, oxygen and hydrogen are produced, with a consequent loss of electrolyte. To prevent this, some batteries have catalytic devices over the cell vents, which cause the gases to recombine into water. Overcharging also results in corrosion, plate growth and loss of active material from the plates, leading to reduced life. On the other hand, repeated failure to reach full charge can also have an adverse effect, because it can cause stratification of the electrolyte and inter-cell variations.

Lead-acid batteries will slowly discharge when not in use, typically losing about 2% of the nominal capacity per month. The self-discharge rate increases with temperature.

Nickel-cadmium pocket plate batteries are in many ways more suited to operation in PV systems than are lead-acid types but their use has so far been restricted by their high cost - about £ 340/kWh compared with about £ 90 /kWh.

The nickel-cadmium cell consists of a positive plate of nickel packed with nickel hydroxide and a negative plate of cadmium immersed in a solution of potassium hydroxide in water. The electrolyte plays no part in the electrochemical reaction but serves only as a charge carrier between the plates. Consequently, nickel-cadmium batteries do not suffer from the problems of electrolyte depletion and stratification which afflict lead-acid batteries. Other advantages over lead-acid are :-

- The capacity is not as strongly influenced by the rate of discharge.
- There is less loss of capacity with temperature rise - typically 0.25% of rated capacity per degree C.
- Freezing is not such a problem.
- The battery can be fully discharged and is not damaged by long periods in this condition.

6. BATTERY CONTROLLERS

The simplest form of battery controller is a device which regulates the charge current and prevents over-charging. Most charge regulators start the charging process with a high current and reduce it to a trickle charge level when a certain battery voltage is reached. In PV systems, such devices can regulate the charge current either by interrupting the array current (series type) or by short-circuiting sections of the array (shunt type). As short-circuiting will aggravate any tendency to hot-spot failure, the series type is not always advisable. The power consumption of charge regulators is typically under 0.2% of the power being controlled.

A more sophisticated type embodies a microprocessor which monitors battery current, voltage and temperature, computes the state-of-charge and regulates the input and output currents so as to avoid overcharging and excessive discharge. The performance of such controllers with lead-acid batteries is not yet satisfactory, as the relationship between the state-of-charge and the measured parameters changes with age and is affected by the type of usage. Another problem is that the capacities of nominally identical cells can vary in a lead-acid battery, so the cell with the smallest capacity may run to a depth of discharge lower than the computed value.

7. INVERTERS

The inverter converts the dc from the array or battery to single- or three-phase ac 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 voltage requirement may necessitate an additional transformer and the harmonic requirement special filtering, both of which add to the losses in the device and increase the cost. But, in standalone systems and for some non-critical loads like motors, the requirements may be eased.

Modern solid-state inverters usually employ one of two techniques to construct a sinusoidal output :-

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 to a sine wave. The more inverter stages used, the better the approximation and the lower the harmonic distortion.

Pulse-width modulation (PWM). 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-commutated" inverter, the type commonly used in standalone ac systems, is one in which the switching is performed wholly within the unit, using power from the dc input. A "line-commutated" 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 PV system will be operating at less than full load most of the time, it is important to choose one of an appropriate size with a good part-load efficiency. In some large systems, the dc/ac conversion efficiency is improved by using multiple inverters, which are automatically switched in and out to suit the load demand.

Inverters for PV systems usually incorporate the following protective features :-

- Automatic switch-off if the dc input voltage is too high or too low.
- Automatic re-start when the dc input voltage rises above a set minimum.
- Protection against short circuits and overloading.

8. CONVERTERS

In modern solid-state converters, the transformation from one dc voltage to another is usually achieved by high frequency chopping, using transistors. Efficiencies of over 95% at full load can be expected. Of course, a converter is not necessary if the desired voltage or voltages can be provided direct from the array, by suitable arrangement of modules.

A MPPT has built-in control logic, usually operated by a microprocessor, that senses the array voltage and current at frequent intervals, computes the power output and compares it with the previous value. If the power has increased, the array voltage is stepped in the same direction as the last step. If the power has decreased, the array voltage is stepped in the opposite direction. Eventually, the array voltage reaches and is kept at or near the maximum power point.