Energy losses in photovoltaic systems

Wagdy R. Anis[a] and M. Abdulsadek Nour[b,*]

[a]*Electronic and Communication Department, Faculty of Engineering, Ain Shams University, 1 Sarayat Street, Abbsia, Cairo (Egypt)*

[b]*Electrical and Electronic Department, Yanbu Industrial College, P.O. Box 30436, Yanbu, Al Sinaiyah 21477 (Saudi Arabia)*

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Abstract

The maximum power generated by photovoltaic (PV) arrays is not fully used. During summer, the main cause for the energy loss is the system design that necessitates an oversizing of the PV array to supply the load during the winter season when the solar energy is limited. Other reasons that cause energy loss are: the mismatch between the array and the load or battery; the loss in the batteries; the loss due to the PV array disconnect. The array disconnect loss takes place during summer season when the battery is fully charged. To avoid the disconnect loss, a novel battery voltage regulator (BVR) is used. This supplies the load directly from the array when the battery is fully charged. In this work, energy losses have been analysed and divided into fundamental (unavoidable) and non-fundamental losses. Both conventional (using a conventional BVR) and new (using a novel BVR) PV systems are studied. A load that consumes constant power for 24 h a day through the year is considered. The climatic condition of Cairo city is taken as the test case.

Introduction

A conventional photovoltaic (PV) stand-alone system is designed using a conventional battery voltage regulator (BVR). The BVR functions are: (i) to disconnect the load when it is deeply discharged, and (ii) to disconnect the PV array when the battery is fully charged [1, 2]. The main objective of the BVR is to protect the battery against deep discharge and overdischarging so that its lifetime is prolonged. Such regulators are widely used in solar-powered telecommunications systems [3].

Directly-coupled PV systems, such as pumping systems, do not employ BVRs since the PV array is directly coupled to the load. These systems utilize most of the solar energy that is available [4].

The tilt angle of the array is chosen in such a way that the array size is minimized for a given load. For a constant load, the optimum tilt angle is about the latitude angle +15° [5]. Such a tilt angle maximizes the solar energy received on the array plane during winter, while the solar energy received is reduced during the summer. Thus, the objective of the design is to keep to a minimum the seasonal variations in the solar energy.

*Author to whom correspondence should be addressed.

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Power losses in conventional system

A block diagram of a conventional (PV) system is given in Fig. 1. The maximum power curve and the battery voltage range superimposed on *I–V* characteristics of a PV array are given in Fig. 2. If the battery voltage at a given solar irradiance corresponds to power P_p, while the maximum power is P_{max}, then the mismatch loss P_{mm} is defined as:

$$P_{mm} = \frac{P_{max} - P_p}{P_{max}} \quad (1)$$

where P_{max} is the instantaneous array peak power. The mismatch loss cannot be eliminated completely unless a maximum-power tracking circuit is used. P_{mm} may be minimized, however, if the battery voltage is chosen carefully, as shown in Fig. 2. Under such a condition, P_{mm} will be less than 10%. The main reasons for the mismatch loss are: (i) variation of battery voltage due to continuous change in the battery state-of-charge (SOC) that results from battery charge and discharge, and (ii) continuous variation of ambient temperature which changes both battery voltage and maximum-power voltage.

Since the battery has a limited efficiency, part of the energy supplied by the PV array to the battery is lost. This power loss in the battery, P_{lb} is determined by the battery charging efficiency, η_{ch}. As η_{ch} increases, P_{lb} decreases, and vice versa. The energy lost in the battery is converted into heat. Excessive charging of the battery leads to gasification and this may damage the battery. Gasification is prevented by inclusion of a BVR that disconnects the battery. The third loss is the power loss that is due to the array disconnect, P_d. This takes place during summer when the battery is fully charged due to the surplus in solar energy. The load and array powers during a sunny summer day are given in Fig. 3. The excess energy is stored in the array. If

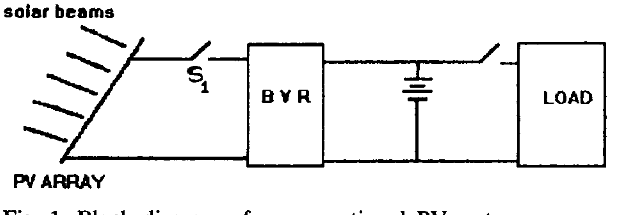

Fig. 1. Block diagram of a conventional PV system.

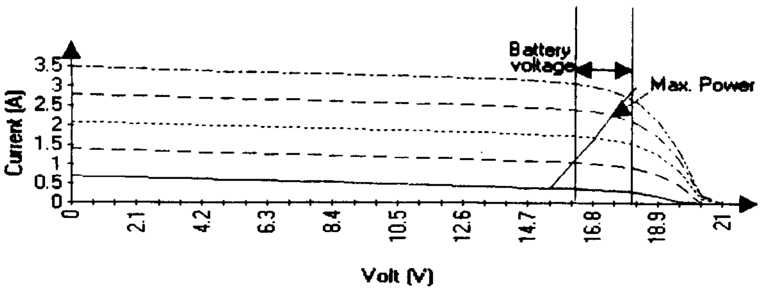

Fig. 2. PV array characteristics, maximum power curve and battery voltage range.

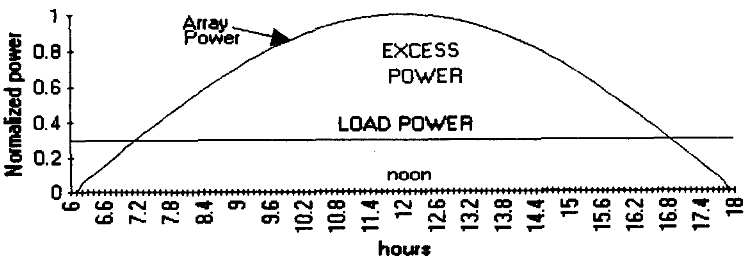

Fig. 3. Array and load power during a typical sunny summer day.

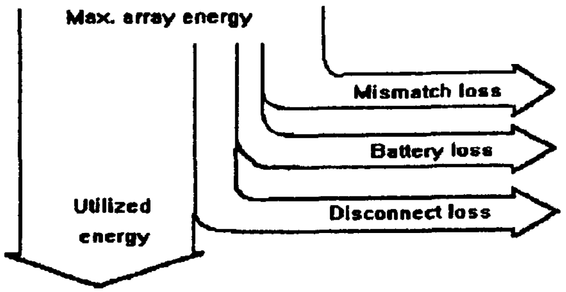

Fig. 4. Energy flow diagram of a conventional PV system.

the battery is fully charged, the BVR opens switch S_1 (Fig. 1) and the array power, P_a, is lost. During the disconnect period, the total array power is lost and the load is supplied by the battery. In the following analysis, all losses are expressed in terms of the percentage of the maximum daily energy, E_{max}, from the array. The latter is given by:

$$E_{max} = \int P_{max} \, dt \tag{2}$$

The integration is performed over the period during which solar energy is received by the array plane. The energy flow diagram during a sunny day is presented in Fig. 4. The disconnect loss takes place when the battery is fully charged. This is commonly the case during sunny summer days. The probability of array disconnect decreases as the battery storage size increases, but such a solution leads to higher system cost. The disconnect loss represents the major part of the energy loss, since energy losses due to mismatch and battery losses are relatively small.

Power losses in novel system

A block diagram of the proposed new system is given in Fig. 5. In this system, the PV array is never disconnected. During high insolation periods, the load is supplied directly by the array through a chopper circuit.

Although the array is never disconnected, there is an unavoidable loss – called the fundamental loss – that results from the fact that the array power is larger than

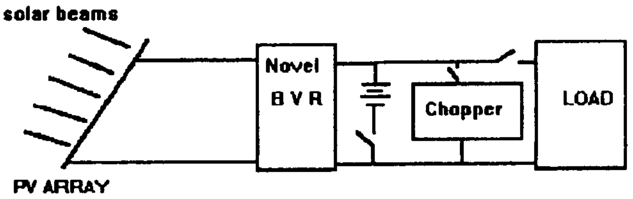

Fig. 5. Block diagram of the proposed new system.

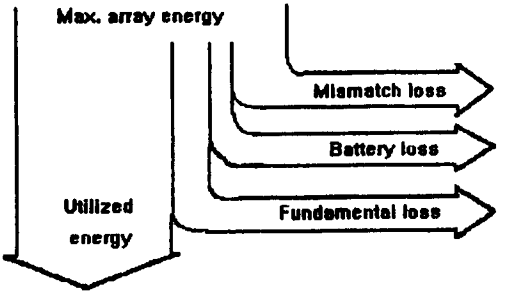

Fig. 6. Energy flow diagram of the proposed new system.

the load power during high insolation periods, as shown in Fig. 3. Therefore, the chopper may transfer only a part (equal to the load power) of the available array energy. The fundamental energy loss, E_{LF}, is expressed as:

$$E_{LF} = \int (P_a - P_L)\, dt / E_{max} \tag{3}$$

where the integration is performed over periods when the storage battery is fully charged and solar irradiance is higher than the load power. In eqn. (3), E_{max} is the maximum daily energy available, as determined by eqn. (2). The PV array is generally oversized to compensate for low insolation periods during winter, thus the fundamental loss is relatively large. For a given load and a given PV array size, there is no way to avoid the fundamental loss, unless the storage battery is excessively oversized to store energy from season to season. The energy flow diagram of the proposed new system is shown in Fig. 6. The disconnect loss in the conventional system is replaced by a smaller fundamental loss in the novel system. The fundamental loss increases as the ratio between the PV array peak power and the load power increases, and vice versa. For naturally matched loads – which require more energy during summer, such as pumping and refrigeration loads – the fundamental loss is smaller and the advantages of the proposed novel are greater. The performance of a PV pumping system using the novel BVR is discussed in ref. 7. The design of the chopper circuit of the novel BVR is discussed in ref. 8. If the energy transferred directly from the array to the load is denoted by E_{La}, and the energy transferred directly from the array to the battery is denoted by E_{Ba}, then the utilization factor, UF, is defined as:

$$UF = \frac{(E_{Ba} + E_{La})}{E_{max}} 100 \tag{4}$$

The *UF* represents the percentage of energy utilized by the load and the battery; it is higher during low insolation periods, and vice versa.

Effect of BVR characteristics

The design of the BVR affects the energy loss in the system. The BVR disconnects the array when the battery SOC reaches a predetermined value (usually 99 or 100%), denoted by SOC_4 as indicated in Fig. 7. The array is reconnected when the SOC drops to SOC_3. The difference between SOC_4 and SOC_3 is the array-disconnect hysteresis, H_a, which is a design parameter of the BVR. On the other side, there is a load-disconnect hysteresis that is denoted by H_L. The load is disconnected when the SOC drops to the value SOC_1, and then reconnected when SOC rises to SOC_2, as indicated in Fig. 7. H_L is the difference between SOC_2 and SOC_1.

The array disconnect loss decreases as the array hysteresis decreases. Under such a condition, the array is not allowed to be disconnected for long periods and, then, the array disconnect loss is reduced. A major drawback of this proposal is the increase of the on/off switching frequency of the BVR relays. The BVR designer compromises between the above-mentioned two contradictory effects. Sharp reduction of the H_a although decreasing the array disconnect loss allows the battery to operate in a fully-charged state for long periods. As a result, the probability of gasification increases and the battery may be damaged. Therefore, it is not recommended to reduce array hysteresis sharply.

Results

A detailed simulation program to compute the performance of a PV system that supplies a constant load has been conducted. The climatic condition of Cairo city (30 °N) has been considered. The array title angle is 45° facing south to maximize the energy received by the array during the winter season. The PV season is designed so that the load is supplied by electric energy for 24 h per day for 365 days of the year. This constraint implies oversizing of both the PV array and the battery size. Figure 8 gives the energy distribution for both conventional and novel systems during a sunny summer day. It is seen that the disconnect loss of the conventional system exceeds 40% of the available array energy. For the novel system, the fundamental loss is 37%. Thus, the proposed novel system gives only a slight decrease in the energy loss. The improvement is limited because of the fact that the array power is much larger than the load power.

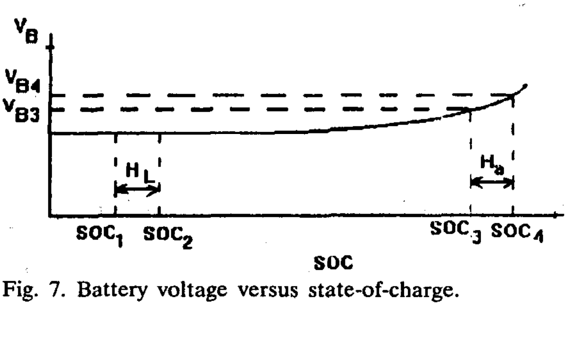

Fig. 7. Battery voltage versus state-of-charge.

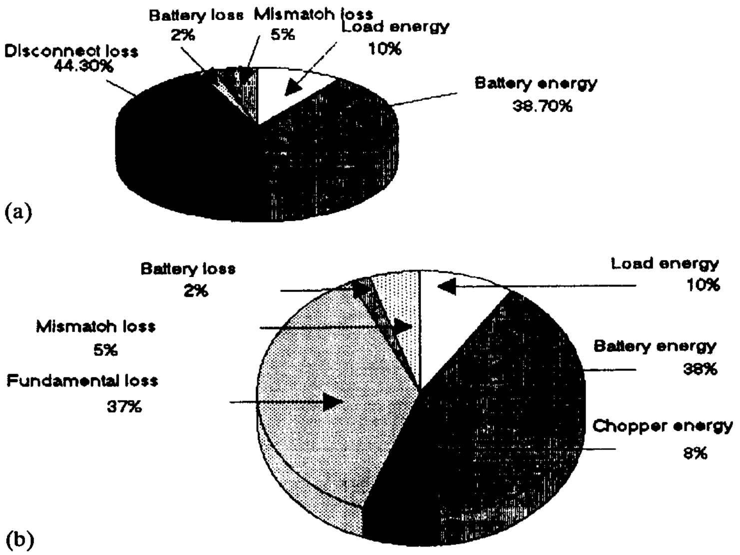

Fig. 8. Energy distribution for (a) conventional and (b) new systems during vernal equinox day in Cairo city (30 °N).

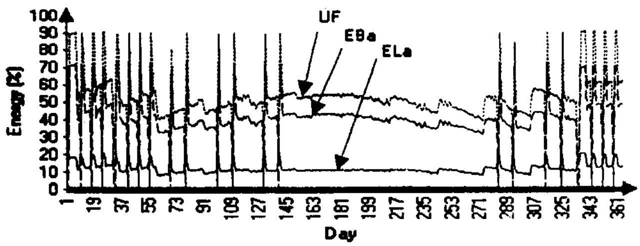

Fig. 9. Battery and load energy, as well as utilization factor (*UF*), of a conventional system during a complete year; tilt angle = 45°.

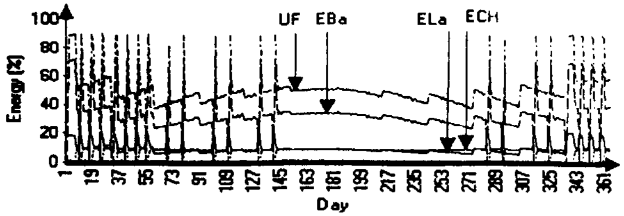

Fig. 10. Battery and load energy, as well as utilization factor (*UF*), of the new system during a complete year; tilt angle = 45°.

Both battery and load energies during a complete year for conventional and novel systems are presented in Figs. 9 and 10, respectively. It is observed that the sum of the load and battery energies is below 50% except for cloudy days where most of the available array energy is utilized. From Fig. 11, it can be seen that there is a slight

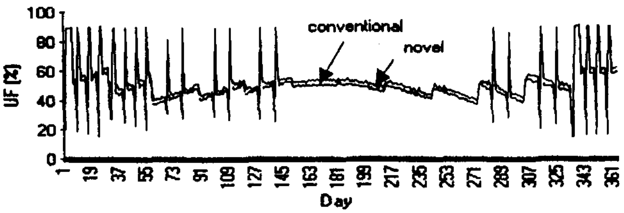

Fig. 11. Utilization factors (*UF*s) of both conventional and new systems during a complete year.

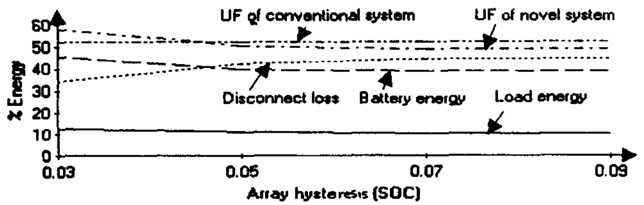

Fig. 12. Effect of array hysteresis on load and battery energy and disconnect loss of a conventional system.

improvement in the utilization factor if the proposed novel system is used. If the array hysteresis is decreased, however, the utilization factor of the conventional system may be equal, or exceed, that of the novel system, as shown in Fig. 12. It is obvious that the improvement in *UF* of the conventional system is attributed to a decrease in the disconnect loss when the array hysteresis is reduced. It is emphasized that elimination of the disconnect loss is impossible for a given constant load, and it is only possible to minimize this loss.

Conclusions

Energy losses of PV arrays under the conditions of a constant load in Cairo city (30 °N) have been analysed in this work. The results show that a major part of the energy loss is unavoidable; this is called the fundamental loss. The fundamental loss is attributed to the fact that PV arrays are oversized to compensate for low solar insolation periods during winter. Therefore, an energy loss of about one-third of the available energy during summer is unavoidable.

A new system has been proposed and exhibits some superiority in decreasing the energy loss compared with a conventional system. It is also shown that a careful design of the battery voltage regulator leads to some decrease in the energy loss, but at the expense of operating the battery at a fully charged condition for relatively long periods.

It is impossible, in fact, to eliminate entirely the PV array energy loss for a given load. Nevertheless, the energy loss is smaller, but not zero, for naturally matched loads that require more energy during the summer, e.g., pumping and refrigeration systems.

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