ATEE - 2004

ON THE DESIGN OF PHOTOVOLTAIC SYSTEMS WITH BUFFER ACCUMULATOR-BATTERIES, OPERATING ON AUTONOMOUS LOADS

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Abstract. *Taking into account the insolation variability on earth, whenever using solar-cell batteries operating on autonomous loads, usually they are buffered by accumulator batteries. In the paper, one presents a method – adequate for a computer-aided design – to get the main parameters of the system (number of solar cells connected in series and in parallel, accumulator capacity) satisfying the requirements of the load at a minimum cost. That – under the assumptions of a constant power required by the load, at a constant voltage, and a solar radiation profile approximated by a series of cycles; each cycle is made up of an interval in which the radiation is constant, at a maximum value, followed by an interval in which the radiation is zero.*

1. INTRODUCTION

Taking into account the insolation variability on earth, whenever using solar-cell batteries operating on autonomous loads, usually they are buffered by accumulator batteries (Fig. 1). The accumulator battery A (with the capacity Q_A) serves as an electrical-energy storage device, ensuring a permanent supply of load at a practically constant voltage, almost independent of the instantaneous insolation. The solar-cell battery BS is made up of several cells connected in series (n_s) and in parallel (n_p).

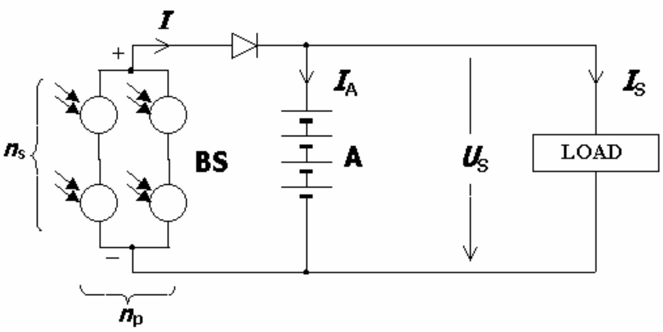

Fig. 1. Principle scheme of a photovoltaic system with autonomous load:
BS – solar battery; A – accumulator battery.

A problem arises in choosing n_s , n_p and Q_A , in order to get an optimal system, i.e. a system satisfying the load requirements at a minimum cost. The present paper tries to give a point of view on the answer to that problem.

2. CALCULATION OF THE NUMBER OF SOLAR CELLS CONNECTED IN SERIES

In order to get a given power from the solar battery – at a given insolation – with a minimum number of cells, it is necessary to have the cells operate at their maximum efficiency corresponding to that insolation.

It is known that the voltage U_M corresponding to the maximum efficiency of a solar cell is given by the equation :

$$U_{\mathrm{M}} = U_{\mathrm{g}} - \frac{kT}{e} \ln\left(1 + \frac{e}{k_{\mathrm{B}} T} U_{\mathrm{M}}\right) \tag{1}$$

where: U_g is the open-circuit voltage of the cell ; T – absolute temperature of the cell junction; k_B – the Boltzmann constant; e – the elementary electric load.

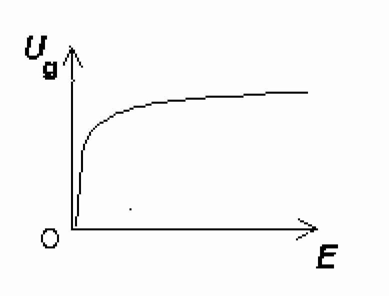

Fig. 2. U_g (E) for a solar cell (at T = const.).

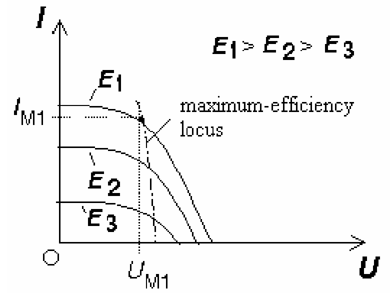

Fig. 3. $I(U)$ characteristics of a solar cell.

For T = const., the dependence of the open-circuit voltage U_g on the incident radiation E (density of the radiant power on the cell surface) shows that, for a rather large range of the radiation values – which is usually the range of interest –, U_g is almost constant (Fig. 2). It turns out that, in the same range, the voltage U_M is almost constant; that is also emphasized in Fig. 3, where the $I(U)$ characteristics of a cell are drawn, as well as the locus of maximum efficiency.

If the load has to operate at the voltage U_S , than it is obvious that – having in view the previous result and assuming identical cells – the following equation has to be satisfied:

$$n_s U_M = U_S \tag{2}$$

The number of cells connected in series will be approximated by the closest integer to n_s given by Eqn. (2). Usually, that approximation will be not rough, as the values of U_S are rather high in comparison with U_M (e.g., $U_S \geq 6$ V, $U_M \approx 0{,}4$ V), so that the actual operation of the solar cells will be very close to that at maximum efficiency.

3. CALCULATION OF THE ACCUMULATOR CAPACITY AND NUMBER OF SOLAR MODULES CONNECTED IN PARALLEL

The calculation of the number n_p of solar modules (made up of n_s cells in series) connected in parallel is rather tedious, as it is related to the power requirements of the load, the insolation profile on the site where the system is to operate, and the accumulator capacity.

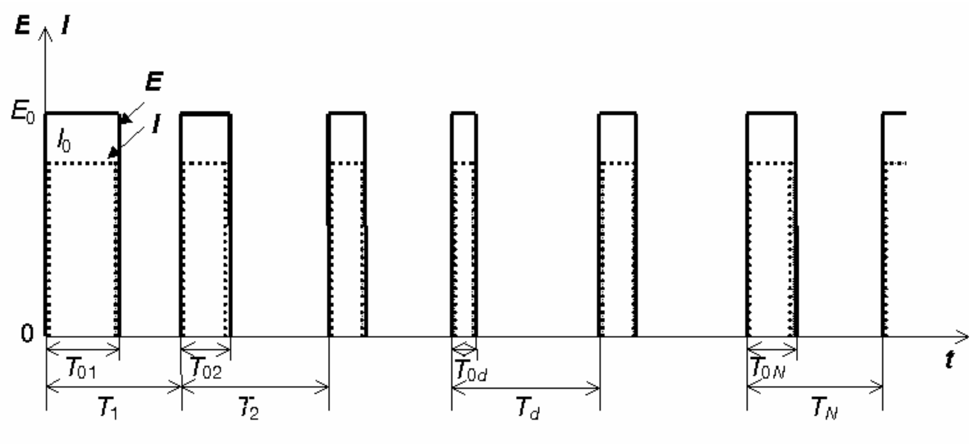

Fig. 4. Approximation of the time variation of the solar radiation E (and the corresponding idealized profile of the current I delivered by a solar module) during a year.

In order to simplify the calculations, usually it is assumed that the load requires a constant power P_S (sometimes, one can use an equivalent constant power); in the cases when the load power is widely variable, the system must be designed so as to cope with the most unfavorable conditions.

On the basis of the data concerning the insolation on the site where the system is to operate, one approximates the time variation of the solar radiation E during a year by a series of N cycles, a cycle "j" being made up of an interval with the width T_{0j} during which the radiation is constant, at a maximum value E_0 , followed by an interval of width $T_j - T_{0j}$, when the radiation is zero (Fig. 4). Based on that diagram and the $I(U)$ characteristics of the utilized solar cells, one determines the idealized profile of the current that can be delivered by a solar module (in Fig. 4, I_0 is the current corresponding on the $I(U)$ characteristics to the radiation E_0 and voltage U_S/ n_s).

In a very simple approach of the problem, one considers the most unfavorable situation concerning the insolation – characterized by the cycle "d", with $T_{0d} \le T_{0j}$ and $T_d - T_{0d} \ge T_j - T_{0j}$ (j = 1, 2,...,N ; $j \ne d$ – and the accumulator capacity, assuming that the accumulator is completely discharged at the beginning and at the end of the cycle "d". Under these conditions, during the interval T_{0d} , the solar battery has to provide the supply of the load with the power P_S and the recharge of the accumulator to its rated capacity Q_A , delivering the energy:

$$W_{BS} = W_S + W_A \tag{3}$$

where:

$$W_{BS} = \eta_a n_p I_0 U_S T_{0d} \tag{4}$$

$$W_S = P_S T_{0d} \tag{5}$$

$$W_A = Q_A U_S \tag{6}$$

η_a is the overall efficiency of the solar battery, related to the ambient conditions, which takes into account the fact that the actual power delivered by the solar battery differs from that one corresponding to the maximum radiation E_0 , due to several factors such as:

- variation of the solar radiation over the interval T_{0d} , corresponding to the site where the system operates, the season, and the random covering of the sky;
- pollution of the active surface of the solar cells, depending on the site, and way of cleaning that surface;
- inaccurate tracking of the sun;
- time variation of the cell parameters, both reversibly (e.g. due to the temperature variations), and irreversibly (by aging and mechanical deterioration).

Usually, $\eta_a \approx$ 0,7...0,8.

Over the interval $T_d - T_{0d}$, the accumulator has to deliver alone the energy demanded by the load, i.e.:

$$P_S(T_d - T_{0d}) \tag{7}$$

on account of the energy W_A accumulated in the previous interval. If the accumulator efficiency is η_A (usually, for lead accumulators, $\eta_A \approx$ 0,75), then – as one assumes that the accumulator is completely discharged at the end of the considered interval –, by using Eqns. (6) and (7), one obtains:

$$\eta_A Q_A U_S = P_S(T_d - T_{0d}) \tag{8}$$

If $Q_A^{(0)}$ and $n_p^{(0)}$ are the values of the accumulator capacity and the number of solar modules connected in parallel, under the above conditions, there results from Eqn. (8):

$$Q_A^{(0)} = \frac{P_S (T_d - T_{0d})}{\eta_A U_S} \tag{9}$$

and from Eqns. (3) – (6):

$$n_p^{(0)} = \frac{P_S T_{0d} + Q_A^{(0)} U_S}{\eta_a I_0 U_S T_{0d}} = \frac{P_S}{\eta_a I_0 U_S}\left[1 + \frac{1}{\eta_A}\left(\frac{T_d}{T_{0d}} - 1\right)\right] \tag{10}$$

$Q_A^{(0)}$ represents a minimum capacity that the accumulator must have, and $n_p^{(0)}$ is a covering value of the number of solar modules connected in parallel. The assumption that the accumulator is completely discharged at the beginning of the interval T_{0d} is frequently too rough, since it does not take into account the processes that occur during the previous cycles of the system operation. If one has in view those processes, it is possible to get a smaller value for n_p ($n_p < n_p^{(0)}$), and if one uses an accumulator with the capacity $Q_A > Q_A^{(0)}$, a further decrease of n_p may be obtained, which could have a positive effect on the cost of the whole system (taking into account the concrete costs of the accumulators and solar cells).

In the following, a method to get the values Q_A and n_p in such a way that the cost of the system should be minimum is proposed. It is assumed that $\eta_A \approx$ const. and $\eta_a \approx$ const.

For an accumulator capacity $Q_A^{(k)} \geq Q_A^{(0)}$, one considers a value $n_p = n_p^{(0)} - \Delta n$ for the number of solar modules connected in parallel. By placing the time origin for the radiation and current diagrams (Fig. 4) within the most favorable period (with the best insolation), one can consider that at the beginning of the interval T_{01} the accumulator is not completely discharged, and at the end of the same interval it is charged at the capacity $Q_A^{(k)}$, having an available energy:

$$W_1 = \eta_A Q_A^{(k)} U_S \tag{11}$$

After the interval $T_1 - T_{01}$, when the accumulator discharges, delivering to the load an energy $P_S(T_1 - T_{01})$, the accumulator still keeps a fraction γ_1 of the energy W_1, so that one can write:

$$W_1(1 - \gamma_1) = P_S(T_1 - T_{01}) \tag{12}$$

Over the interval T_{02}, the solar battery recharges the accumulator, delivering also to the load an energy $P_S T_{02}$. The available accumulator-energy W_2 at the end of that interval is:

$$\gamma_1 W_1 + \eta_A(\eta_a n_p I_0 U_S - P_S) T_{02} \tag{13}$$

The above expression does not have to lead to a value greater than W_1 (which corresponds to the accumulator capacity $Q_A^{(k)}$, and cannot be exceeded). Therefore, the final value of the energy W_2 will be chosen as:

$$W_2 = \min\left\{\left\lfloor \gamma_1 W_1 + \eta_A(\eta_a n_p I_0 U_S - P_S) T_{02} \right\rfloor;\ W_1\right\} \tag{14}$$

For the interval $T_2 - T_{02}$, an equation similar to Eqn. (12) can be written:

$$W_2(1-\gamma_2) = P_S(T_2 - T_{02}) \tag{15}$$

where γ_2 represents the fraction of the energy W_2 owned by the accumulator the end of that interval.

In a similar way, for the cycle of rank "*j*", one obtains the equations:

$$W_j = \min\left\{\left\lfloor \gamma_{j-1} W_{j-1} + \eta_A (\eta_a n_p I_0 U_S - P_S) T_{0j} \right\rfloor ;\ W_1 \right\} \tag{16}$$

and

$$W_j(1-\gamma_j) = P_S(T_j - T_{0j}) \tag{17}$$

Eqns. (11) – (17) give the values W_1 ... Wj and γ_1 ... γ_j . Assuming the yearly repeatability of the N cycles (Fig. 4), it is necessary that:

$$W_{N+1} = W_1 \tag{18}$$

If:

$$\gamma_j > \text{o} \tag{19}$$

for any j = 1, 2, ..., N, it turns out that the accumulator never discharges completely; consequently, a smaller number of solar modules can be adopted.

One resumes the above calculations for $n_p = n_p^{(0)} - 2\,\Delta n$,..., $n_p = n_p^{(0)} - z\,\Delta n$.

If for the calculation set of rank "z" there results :

$$\gamma_j \geq \text{o} \tag{20}$$

and Eqn. (18) is satisfied, one can stop, putting:

$$n_p^{(k)} = n_p^{(0)} - z\,\Delta n \tag{21}$$

the corresponding value of the number of solar modules connected in parallel. In this case, there are intervals $T_j - T_{0j}$ at the end of which the accumulator discharges completely, but the load supply is permanently provided with the power P_S .

If for the rank "z–1" of the calculation set, Eqn. (18) is satisfied, but it is not satisfied for the rank "z", then – in order to provide the annual repeatability of the process – it is necessary to hold the value:

$$n_p^{(k)} = n_p^{(0)} - (z-1)\Delta n \tag{22}$$

even though in this case $\gamma_j > 0$ and not $\gamma_j \geq 0$.

If for the first calculation set (z=1) there are values "*j*" for which $\gamma_j < 0$, or Eqn. (18) is not satisfied, one decreases the step value Δn and one resumes the above calculations.

In this way one gets a pair of values $Q_A^{(k)}$, $n_p^{(k)}$ which provides permanently, just on the line, the load supply with electrical energy at the required parameters. On knowing those values, one can calculate the annual cost of the energy delivered to the load. That cost can be written as follows:

$$C^{(k)} = \left(C_{\mathrm{BS}}^{(k)} + C_{\mathrm{A}}^{(k)} + C_{\mathrm{EA}}^{(k)}\right)\alpha_{\mathrm{e}} + C_{\mathrm{I}}^{(k)} \tag{23}$$

One has denoted :

$C_{\mathrm{BS}}^{(k)}$ – the cost due to the initial investment in the solar battery, having $n_{\mathrm{p}}^{(k)}$ modules (with n_{s} cells in series) connected in parallel;

$C_{\mathrm{A}}^{(k)}$ – the cost due to the initial investment in the accumulator battery, with the capacity $Q_{\mathrm{A}}^{(k)}$;

$C_{\mathrm{EA}}^{(k)}$ – the cost due to the initial investment in the auxiliary equipment (conductors, elements for measurement, control and protection etc.); it depends, to a certain extent, on the values $n_{\mathrm{p}}^{(k)}$ and $Q_{\mathrm{A}}^{(k)}$;

α_{e} – the economical-efficiency coefficient of the system (the fraction of the initial investments which has to be recovered annually, interests and payments included);

$C_{\mathrm{I}}^{(k)}$ – the annual expenses for the system maintenance; they are influenced by the values $n_{\mathrm{p}}^{(k)}$ and $Q_{\mathrm{A}}^{(k)}$.

By taking different values for $Q_{\mathrm{A}}^{(k)} \geq Q_{\mathrm{A}}^{(0)}$ and calculating, in the way presented above, $n_{\mathrm{p}}^{(k)}$ and $C^{(k)}$, one can establish in what situation one obtains the minimum annual cost of the system. The values $n_{\mathrm{p}}^{(\mathrm{op})}$ and $Q_{\mathrm{A}}^{(\mathrm{op})}$ corresponding to that situation represent optimal values – from the cost point of view – for the number of solar modules (with n_{s} cells in series) connected in parallel and the accumulator capacity.

Certainly, in order to provide a practical validity of these calculations, they have to be based on the statistical data concerning the insolation on the site where the system is to operate, obtained during a large number of years.

4. CONCLUSIONS

For a solar system, made up of a solar battery and a buffer accumulator, operating on an autonomous load, it is important to know the values of the main parameters of the system (number of solar cells connected in series and in parallel, accumulator capacity) satisfying the requirements of the load at a minimum cost.

In the paper, one proposes a method – adequate for a computer-aided design – to get those parameters, when assuming a constant power required by the load, at a constant voltage, and a solar-radiation profile approximated by a series of different cycles; each cycle is made up of an interval in which the radiation is constant, at a maximum value, followed by an interval in which the radiation is zero.

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