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Modeling of Stand-alone Photovoltaic Drive System without Electric Buffer Source

Abstract. *The paper presents a numerical tool created for designing and precise modeling of stand-alone PV system without electric buffer source, e.g. without electrochemical battery. This tool can be also used for modeling a system equipped with non-electric buffer source, e.g. water tank. The algorithm of this tool is based on a special model of PV generator. In addition, the model of the whole system requires entering the data of a power electronic converter as well as of a receiver (e.g. a drive unit), in the form of profiles of their efficiency as a function of input power.*

Streszczenie. *W artykule omówiono numeryczne narzędzie projektowe stworzone do dokładnego zamodelowania autonomicznego systemu PV bez elektrycznego źródła buforowego, czyli np. bez akumulatorów elektrochemicznych. Narzędzie może też modelować system z nie-elektrycznym źródłem buforowym, np. zbiornikiem na wodę. Algorytm narzędzia oparto na specjalnym modelu generatora PV. Ponadto, model całego systemu wymaga wprowadzenia charakterystyk sprawności przekształtnika energoelektronicznego oraz odbiornika (np. zespołu napędowego). (**Modelowanie autonomicznego fotowoltaicznego systemu napędowego bez elektrycznego źródła buforowego**).*

Keywords: photovoltaics, numerical model, electrical drive system, stand-alone system.
Słowa kluczowe: fotowoltaika, model numeryczny, system napędu elektrycznego, system autonomiczny.

Introduction

Stand-alone photovoltaic (PV) drive systems without an electric buffer source (Figure 1) are some of the easiest and cheapest PV system structures, in which the source of electrical energy is a PV generator (PVG), and the receiver of this energy is a drive unit (M/L) comprising electric motor M and its mechanical load L, such as e.g. a centrifugal water pump or fan [1]. This system typically requires, between PV generator and receiver, the presence of a power electronic converter (PEC) – chopper, inverter, or sometimes two cascade-connected converters [2]. Such systems are used in areas with problematic (technically or economically) access to the public power grid, and also when there is a good correlation between the production capacity of PV generator (the density of insolation) and the demand for the operation of receiver. Examples include: irrigation of fields, pumping water into tanks, ensuring the operation of fountains, water filtration in swimming pools, drying of hay or herbs.

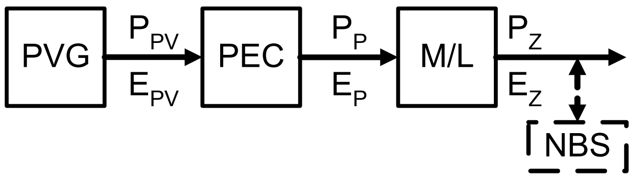

Fig.1. General block diagram of stand-alone PV system without electric buffer source: PVG – photovoltaic generator, PEC – power electronic converter, M/L – drive unit (electric motor M driving its mechanical load L), NBS – optional non-electric buffer source

When designing such structure of the system, it is necessary to appropriately select the nominal power of PV generator for a particular type of drive unit and for the way this system is intended to be used. This allows to obtain sufficiently efficient system, which requires the generator with nominal power not too small, while at the same time the system being possibly low cost, i.e. one whose generator is not excessively overrated. Therefore, the selected nominal power of the generator should be a compromise between the required supply certainty and acceptable cost of the system.

Classic tools for design, dedicated to PV systems co-operating with power grid (i.e. not stand-alone ones), or to stand-alone PV systems but with electric buffer sources (usually in the form of electrochemical batteries), do not provide precise simulation results for the discussed structure of the system. These tools presuppose, that the receiver of energy, as well as the possible power converter directly supplying this receiver, operate at constant efficiency of energy conversion, regardless of changes in the output power of generator.

In the case of grid-connected system, this assumption (i.e. immutability of converter's efficiency) is fairly well satisfied for high and medium insolation values (for sunny or little cloudiness moments), but it is not true for low insolation values (moments with strong cloud cover). Nevertheless, failure to meet this assumption for strong cloudy moments has no great significance in estimating the amount of energy supplied by the system to the grid, because this value is decisively influenced by the moments of sunshine, for which the presumption is met well.

On the other hand, in the systems with batteries, the mentioned assumption is in practice almost always met, because the battery, as the buffer, ensures that the receiver operates with constant input power, regardless of changes in values of generator's insolation, which in turn results in the operation of the receiver with fixed efficiency of energy conversion.

The situation is different in the discussed structure of the system. It is true that, as in other structures of PV systems, in order to the best use of cost-free energy from the generator, the converter provides generator's operation at a maximum power point (MPP). But here, the result of this maximization is distinctly different, because the receiver must operate with highly variable input power, varying together with the changes of output power of the generator, caused by changes of insulation. If, for the receiver (e.g. for a drive unit), its efficiency of conversion strongly depends on input power, then from the shape of receiver's typical efficiency curve (Figure 4) it results that, operating with widely variable input power, the receiver will also operate with widely variable efficiency of conversion of electrical energy into the useful energy (e.g. into the growth of potential energy of the pumped water).

So it follows, that the precise design of discussed structure of the system, requires the use of a special tool, that would take into account continuous variability of conversion efficiency of PEC and M/L, during their operation. The described later tool for numerical modeling, meets this requirement. Its algorithm is based on a special model of PV generator, as described in detail in [3], as well as it is based on additional data, mainly in the form of PEC converter's efficiency characteristics (Figure 3), and M/L drive unit's efficiency characteristics (Figure 4).

Input parameters of created model – for PV generator

The model, in the generator section, uses as primarily input parameters the ones called: relative times of threshold powers [3]. Relative time of threshold power w_j is the sum of periods in which the output power of PV generator was greater than a specific threshold P_{PVj}, related to the whole of analyzed period t_o. For example (Table 1), if generator's nominal power is equal to P_{PVn}=1000Wp, and relative time of threshold power equal to P_{PV2}=60Wp was within a certain day (12.03.2003): w_2=0,225, it means that by 0,225·24h=5h24min during that day the output power of the generator exceeded 60Wp, i.e. (in the relative scale) it exceed p_2=0,06 of the nominal power of the generator.

Table 1. An example of presentation of PV generator model parameters, for two specific days of the same month, with similar values of daily energy, but with significantly differing distribution of generated power.

j	P_{PVj}, Wp	p_j	w_j values for 12.03.2003	w_j values for 13.03.2003
0	0	0	0,354	0,409
1	20	0,02	0,344	0,397
2	60	0,06	0,225	0,313
3	150	0,15	0,064	0,089
4	300	0,3	0,026	0
5	600	0,6	0,02	0
6	1000	1	0	0
7	1200 (1300 for III, IV)	1,2 (1,3 for III, IV)	0	0
		E_{PV}	1132Wh	1062Wh

Knowing the w_j values for some P_{PVj} thresholds, allows you to accurately recreate E_{PV} energy generated by the PVG during the given period t_o. However, the E_{PV} parameter is being entered into the model as a separate value anyway, in order to improve the accuracy of the model. In the described model, eight values of P_{PVj} are used (from P_{PV0} to P_{PV7}).

The values of w_j and E_{PV} for the desired period t_o, can be obtained from the database created through a special measurement system, operating continuously in the Chair of Electrical Drive Systems and Machines of the Lublin University of Technology, from 1998 to the present [4].

The idea of generator's model can be presented graphically as a broken line p=f(w) (Figure 2), plotted on the basis of p_j and w_j data, reproducing (according to the certain assumptions) in relative units the course of P_{PV}=f(t), i.e. the course of real power generated by PVG during the period t_o. These assumptions are: accurate reproduction of periods in which the real relative power was contained between adjacent thresholds p_j, and accurate reproduction of area under the line p=f(w), since then generator's output energy calculated using the model is equal to the energy produced in fact by PVG. Once these assumptions are fulfilled, it is possible to achieve the effect of accurately modeled generator, which is expressed by the fact that energy behavior of the model of converter and receiver, for example the calculated amount of pumped water, will be the same, regardless of whether the converter would be supplied by the model of generator described by the course of p=f(w) line, or supplied by the real generator.

In addition to the parameters w_1÷w_6 and E_{PV}, the part of the model to do with the generator should be filled with auxiliary parameters, enabling the transition from relative to absolute units for the results of simulation. These are: the nominal power of the generator P_{PVn} and the length of the analyzed period t_o (in the described tool, there is a choice for t_o: hour, day, week, month).

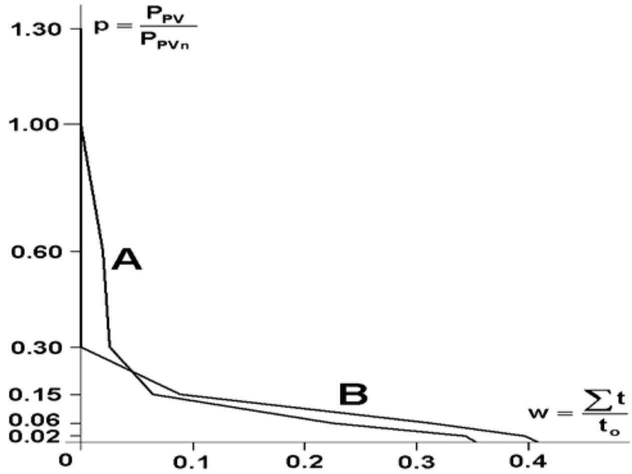

Fig.2. Graphical presentation of the model p=f(w) of the PV generator, for the days: 12 March 2003 (line A) and 13 March 2003 (line B)

Input parameters of created model – for PEC converter

The model, in the part concerning the converter, requires entering of the dependence η_P=f(P_{PV}), that is the characteristics of efficiency of converter as a function of its input power, which in the discussed system is at the same time the output power of PV generator. The example of the course of such characteristics can be seen in Figure 3. In the created model, it is approximated by broken line consisting of ten sections.

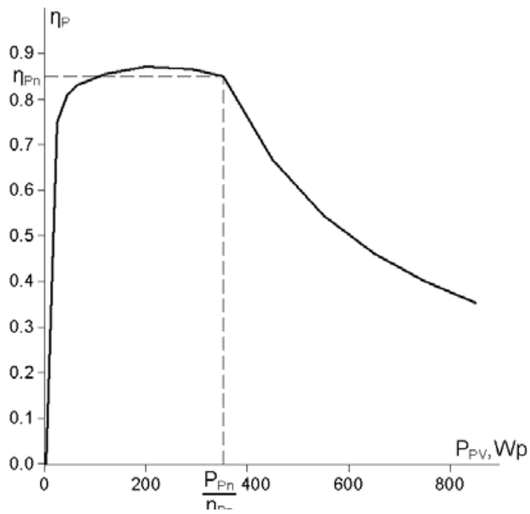

Fig.3. An example of converter's efficiency curve η_P=f(P_{PV})

This characteristics can be divided into two zones of converter's operation:

1) A zone of low, medium, and sometimes (when generator's nominal power is not too much oversized) of high output power of PVG (P_{PV}≤353Wp in Figure 3). For very low output power of generator, this power is sufficient only to cover a part or the whole of converter's own needs at idle state (no-load losses). So, the converter doesn't operate properly, and so it doesn't provide the power to the receiver. In such a case, all generator's output power is lost in the converter, and converter's efficiency is equal to zero. However, already for some higher values of power than that needed to

meet no-load losses, the converter transmits the power to the receiver, as well as it provides generator's operation in MPP. Depending on the relationship between idle and load losses of the converter, the characteristics η_P=f(P_{PV}) in the discussed zone can have an extreme-maximum (as seen in Figure 3 for a power of approx. 200W), or it can increase monotonically up to the border with the second operation zone of the converter.

2) A zone of high PVG output power (P_{PV}>353Wp in Figure 3), where the converter reduces its output power. This reduction is necessary to safeguard the receiver, especially with oversized, and at the same time well-insolated, generator. Without this limitation, the receiver could be damaged by too much power transmitted by PEC. In this zone, the converter doesn't maximize generator's power, therefore the efficiency of the generator decreases, and its operating point moves from MPP in the direction of open-circuit point. However, due to the nature of the database created for the generator, with assumption that PVG always operates in MPP [4], the described model assumes that in the discussed operation zone of converter, the generator still operates at MPP, but the efficiency of the converter decreases, according to hyperbolic relationship:

(1) $$\eta_P = \frac{P_{Zn}}{\eta_{Zn} \cdot \eta_{Pn} \cdot P_{PV}} = \frac{P_{Pn}}{\eta_{Pn} \cdot P_{PV}} = \frac{const}{P_{PV}}$$

where: P_{Zn} – nominal output power of the drive unit; η_{Zn} – the efficiency of the drive unit, when it operates with P_{Zn} power. It is generally: the nominal efficiency of the drive unit. η_{Pn} – a conventional nominal efficiency of the converter, which is the efficiency of PEC when it gives to the power equal to P_{Pn} to the receiver, which is also when PEC operates at transition point between two zones of operation. P_{Pn} – output power of the converter, ensuring the operation of drive unit with P_{Zn} power. For Figure 4: P_{Pn}=300W. It is assumed, that this is also the maximum allowable output power of the converter, that cannot be exceeded because of possibility of shortening the lifespan of drive unit, or even its very rapid failure.

The discussed shifting of losses from PVG to PEC in the second zone, is not critical for accuracy of simulation results. But it would be different, if the generator would be constructed of PV modules with very high conversion efficiency of solar energy into electrical energy (e.g. exceeding 30%), since in such a situation whether the operating point of the generator is at MPP, or between MPP and open-circuit point, it already has a discernible influence on the temperature of PV cells, and hence on the efficiency of the entire generator.

For a particular converter, the shape of η_P=f(P_{PV}) curve in the first zone can be obtained either on the basis of measurements taken for your converter (such a method was used for characteristics shown in [2]), or for some other converter (e.g. not existing but only being designed) it can be obtained on the basis of calculations based on the knowledge of idle and load losses of PEC. As presented in the following examples of simulations, the second method was used, with calculations of the curve η_P=f(P_{PV}) with assumptions: P_{Pn}=300W, η_{Pn}=0,85.

On the other hand, the curve shape in the second zone was determined analytically from Formula (1), for the constant *const* equal to 300/0,85=353Wp.

Input parameters of created model – for M/L drive unit

The model, in the part concerning the receiver, requires entering of dependence η_Z=f(P_P), which is a characteristics of drive unit efficiency as a function of its input power, which in this system is also converter's output power. An example of the course of such a characteristics is shown in Figure 4. In the created model, similarly to characteristics of η_P=f(P_{PV}), the relationship η_Z=f(P_P) is approximated by a broken line consisting of ten sections. A similarity to the characteristics of η_P=f(P_{PV}) is also the presence of the zone of low power received from converter, no greater than P_{P0} (P_{P0}=68W in Figure 4), which does not lead to effective operation of the drive unit, e.g. to flow of water through the pump. In this power range, the efficiency of the drive unit is equal to zero. On the other hand, a dissimilarity in comparison to characteristics of the converter, is the lack of an equivalent of zone two.

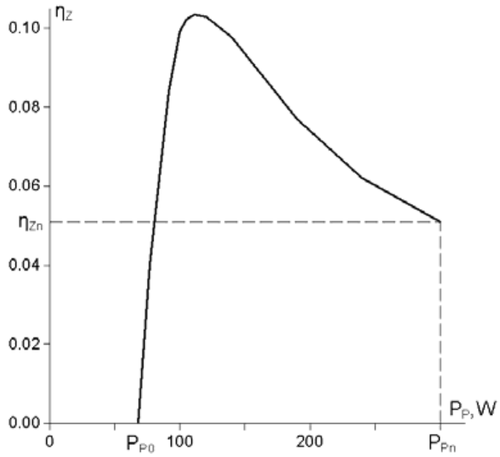

Fig.4. An example of receiver's efficiency curve η_Z=f(P_P)

The shape of η_Z=f(P_P) curve, for a particular receiver, can be obtained either on the basis of measurements taken for an existing drive unit, or (for one only being designed) it can be calculated on the basis of knowledge of idle and load losses of the motor and its load. Further presented exemplary simulations exploit the characteristics determined on the basis of measurements.

The test concerned a pump unit consisting of a single-phase induction motor driving a centrifugal water pump. The lifting height of water displaced by pump was set at *H*=3m. Measurements were made by increasing the power P_P supplied to the motor (this power was measured with a watt-meter), and the output power of the pump was calculated using the formula:

(2) $$P_Z = 0{,}167 \cdot Q \cdot H$$

where: *Q* **–** the flow in l/min, defined as the amount of pumped water (measurements were performed using a water-meter) within one minute.

The efficiency of the drive unit was calculated from the formula:

(3) $$\eta_Z = \frac{P_Z}{P_P}$$

As can be seen in Figure 4, the efficiency of the used receiver is very low. This is due to the use of a cheap and popular device. In real photovoltaic drive system, the drive unit with greater efficiency would be recommended, preferably also with other type of the motor, e.g. a BLDC (Brushless DC) motor, with electronic commutation carried out by PEC.

Created model of the entire PV system

After entering into the model the PVG, PEC and M/L data discussed earlier, the useful energy E_Z produced by the receiver (the drive unit) in the period t_o can be calculated according to the formula:

$$E_Z = \frac{K_{PV} \cdot t_o}{n} \cdot \sum_{i=1}^{n} (P_{PVi} \cdot \eta_{Pi} \cdot \eta_{Zi}) \tag{4}$$

where: K_{PV} – the coefficient increasing the accuracy of the generator model, discussed in [3]; n – the number of simulation steps; in the described model it was assumed that: n=10000; η_{Pi} – the value determined from the discussed characteristics η_P=f(P_{PV}) for the value of P_{PVi}; η_{Zi} – the value determined from the discussed characteristics η_Z=f(P_P) for the value of $P_{Pi}= P_{PVi} \cdot \eta_{Pi}$

The calculated energy E_Z can be expressed in J (when t_o is substituted in seconds), or in Wh (for t_o in hours). On the other hand, the E_Z value expressed in J, for pump unit can be converted into the amount of pumped water V expressed in m^3, using the converted formula for dependence of the increase of the potential energy of the pumped water:

$$V = \frac{E_Z}{\gamma \cdot g \cdot H} \tag{5}$$

where: γ – the density of water: γ=1000 kg/m^3, g – gravitational acceleration: g=9,81m/s^2

Examples of simulation results

Examples of simulations carried out for the aforementioned data of PVG, PEC and M/L, resulted in the following quantities of the pumped water:

1) For the nominal power of PV generator equal to P_{PVn}=350Wp, on 12 March 2003: V=1,24m^3, on 13 March 2003: V=0,37m^3. As it is apparent from Table 1, the E_{PV} energy produced by the generator on both days is similar, because on 13 March it is lower by only 6.6% than on 12 March. Despite this, according to the simulations, the amount of water obtained varies enormously: for 12 March it is more than 3 times higher than for 13 March.
2) For the nominal power of the generator equal to 500Wp, the amount of water obtained in both study days is similar, i.e. of the order of V=1,9m^3.
3) For the nominal power of the generator equal to 750Wp, on 12 March: V=3,49m^3, on 13 March: V=4,49m^3.

As can be seen, on the day of insolation lower by 6.6% (13 March), the amount of the obtained water is higher by approx. 30% than on the day with slightly less sunlight (12 March).

Conclusions

As is apparent from the given sample results, it is impossible to perform the precise model of the stand-alone PV system without the electric buffer source, when one has only the input data of the energy supplied to the generator (irradiation energy), or the electrical energy received from the generator E_{PV} during the period of time t_o. This is because, for different days with almost the same values of E_{PV}, the E_Z values may vary significantly. Errors of such model could be, in some cases, as high as several hundred percent. And unfortunately, most of the available databases offer only this one important generator's parameter.

The described model, based primarily on the relative times of threshold powers, eliminates this drawback, which allows to obtain high accuracy.

This model can be also used to design low-power PV systems co-operating with the grid, particularly for the systems containing, as PECs, micro-converters integrated with PV modules, because micro-converter's efficiency curve is characterized by considerable volatility: for low power its efficiency is considerably lower than for power close to the nominal one.

The created model belongs to the group of mathematical (abstract) models. Their advantage, comparing with material models or the ones based on hardware simulators, are: low cost of the model and of the studies carried out on it, easily introduced changes and consequently high speed of testing, as well as the security of the model and the environment in the case of investigator's error. For these reasons, this model is recommended at the initial stage of designing of PV systems.

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