Marek NIECHAJ

Department of Electrical Drive Systems and Machines, Lublin University of Technology, Lublin, Poland

Modeling of photovoltaic generator operating in stand-alone system without electric buffer source

Abstract. *While the computer design of stand-alone photovoltaic (PV) system without electric buffer source, it is not possible to obtain precise simulation results if you know only the amount of energy that PV generator could produce at given location in defined period of time. In order to allow for accurate simulations, a special analytical and numerical model of PV generator has been developed. It uses, as basic input data, parameters called: relative period of threshold power. Their knowledge allows to recreate both power and energy produced by generator.*

Streszczenie. *Podczas komputerowego projektowania autonomicznego fotowoltaicznego (PV) systemu bez elektrycznego źródła buforowego, nie jest możliwe uzyskanie dokładnych wyników symulacji jeśli zna się jedynie ilość energii którą generator PV mógłby wytworzyć w określonym czasie i lokalizacji. Aby umożliwić precyzyjne symulacje, opracowany został model generatora PV wykorzystujący, jako podstawowe dane, parametry zwane: względny czas mocy progowej. Dzięki temu możliwe jest odtworzenie zarówno przebiegu mocy, jak i energii wytworzonej przez generator.* ***(Modelowanie generatora fotowoltaicznego pracującego w autonomicznym systemie bez elektrycznego źródła buforowego)***.

Keywords: photovoltaics, analytical and/or numerical model, electrical drive system.
Słowa kluczowe: fotowoltaika, model analityczny i/lub numeryczny, system napędu elektrycznego.

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Introduction

Photovoltaic (PV) stand-alone systems, i.e. not co-operating with public electroenergetic grid, often contain electric buffer source (EBS), mostly in the form of set of electrochemical batteries.

However, due to significant shortcomings of batteries, such as very high cost, relatively short lifetime and sensitivity to deep discharging, it is sometimes legitimated to apply a structure without EBS for some of PV stand-alone systems applications (Fig.1). These systems are a lot cheaper, both at the stage of installation and exploitation, due to the lack of cost of first purchasing, and then multiple exchanging of electrochemical batteries – approximately every 5÷8 years.

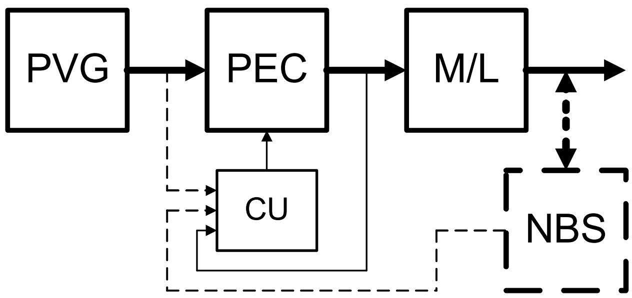

Fig.1. A block diagram of sample of stand-alone PV system without electric buffer source: PVG – photovoltaic generator, directly converting solar irradiation energy into DC current electrical energy; PEC – power electronic converter: chopper DC/DC for DC energy receivers (for example for commutator motors in electrical drive systems), or inverter DC/AC for AC energy receivers (for example for induction or brushless motors), or the combination of these two converters, when you need to make two stages of conversion: increasing the value of voltage and converting its form into AC voltage – an example of such combination was described in [1]; M/L – electrical energy receiver, for example electrical motor M with its mechanical load L (e.g. propeller) in electrical drive systems; NBS – non-electric buffer source (optional); CU – controlling unit of the system, for MPPT (maximum power point tracking of PV generator – examples were described in [2]), for switching on/off the receiver (motor), and for overcurrent, overvoltage and overspeed protection of the receiver (motor)

The use of structure without electric buffer source is particularly recommended when there is a good correlation between schedule of solar irradiation and schedule of load's demand [3]. The examples of receivers and their applications, that meet the above requirement, are:

- water pumps: for filling pressure tanks or tanks mounted above the surface of the ground, for irrigating farmlands and greenhouses, for filtration systems in swimming pools, for fountains, and the like;
- circulation pumps in solar collector systems;
- fans and blowers improving drying of hay, corn and herbs, or for aerating fishing ponds.

It is worth noting, that the issue of energy storage in the systems without EBS can be sometimes satisfied by using a non-electric buffer source (NBS), storing energy in the form already converted by electrical energy receiver (e.g. by motor's load L). For example, it may be the tank for pumped water, or it may be hygroscopic capacity of irrigated land.

However, the featured system's structure has significant drawbacks, that are caused by strong and poorly predictable (random) variations of power produced by PV generator in function of time, both during short-term periods (minutes, hours), as well as during medium-term ones (days, weeks).

For most of systems with electric buffer source, e.g. with EBS of relatively high energetic capacity, the short-term and medium-term variations of PV generator power do not have significant impact on operation of the receiver, since the shortage of energy is complemented by energy previously accumulated in the battery, so the receiver can almost always operate at conditions of constant input power. Thus, in most of systems with EBS, the receiver can almost always operate with constant efficiency of energy conversion, for example with its maximum efficiency.

But in properly designed systems without EBS (properly means: with PV generator not excessively unnecessarily oversized), the receiver almost always operates in tact of PV generator power changes, because PVG's maximum power point tracker (MPPT) almost always ensures the transmission of approximately all (after omitting losses in PEC) available power from PV generator to the receiver. In consequence, the receiver is continuously operating with variable efficiency, because the mentioned above receivers (motors with their loads: pumps or fans) are typified by conversion efficiency strongly depending on the value of their input power.

To be sure, the periods while the irradiation of PV generator is very good for quite long time, are the exceptions of the state of receiver's operation with variable efficiency. In such periods, MPPT function becomes inactive, and PEC limits power consumption from PVG, and transmits to the receiver, regardless of PVG irradiation fluctuations, the constant power – with, consequently, constant receiver's efficiency. Such conditions assure the operation of receiver with its maximum permissible yield, which is usually the same as the operation with its nominal power [1]. But unfortunately, such periods are relatively rare in Central European climatic conditions.

During an initial stage of design of system without electric buffer source, for example with the receiver in the form of electric motor driving water pump, it is advisable to carry out a computer simulation of such system's operation. The main objective of such simulation is the selection of appropriate value of PV generator nominal power, providing required yield of the pump, represented by required quantity of displaced water in the given period of time, or providing minimum of unit cost of displacing water. Unfortunately, due to the mentioned above continuous variations of pump's efficiency at time, what is synonymous with variations of efficiency of converting motor's input electrical energy into potential/kinetic water energy, it is not possible to obtain accurate simulation results, if the only "energetic" information about PV generator is the amount of energy E_{PVr} that the generator could produce at given location in defined period of time (within hour, day or month).

For example, for two days of almost the same amount of E_{PVr} energy (in Tab.1 these are the sample days: 12.03.2003 and 13.03.2003, with differences about E_{PVr} of the order of 6%), the PV generator located in Lublin would had generated greater power for shorter time on the first day (12.03), and lower power for longer time on the second day (13.03). This would had resulted in different operation conditions of the pump. On the first day, it would had operated for short time with high power, and so with high conversion efficiency. In turn, on the second day it would had operated for long time with little power, and therefore with low efficiency. And finally, at almost the same amount of PV generator energy E_{PVr} in both days, the difference between quantity of displaced water in those days would had reached even as much as several hundred percent, in favor on the first day! The exact numeric value of this difference depends on several factors, mainly on the ratio of PV generator's nominal power to motor's nominal power. For the more oversized PVG, the lower would had been the difference of displaced water quantity. But of course, oversizing the PVG results in clearly higher system cost.

The proposed model of PV generator

In order to enable carrying out exact simulations of stand-alone PV systems without EBS, a special model of PV generator has been developed. It uses primarily, as the basic input data, parameters of PV generator called: relative period of threshold power.

Relative period of threshold power w_{Pj} is the sum of time periods, referred to the entire period of analysis t_o, in which the power produced by PV generator was greater than a specific value (threshold) P_j.

For example (take a look at the Table 1), if nominal power of PV generator was equal to P_{PVN}=1000Wp, and the threshold power was equal to P_2=60Wp, and relative time of this threshold power was within one day (12.03.2003) equal to: $w_2=w_{60Wp}$=0,225 – this means, that during that day (24h) the power produced by PV generator exceeded for 5h24min (because: 0,225·24h=5h24min) the value of 60Wp (or, on relative scale, it exceeded for 5h24min the value p_2=0,06 of PV generator nominal power).

The values of w_{pj} parameters may be obtained from the database created by availing a special measurement system, operating at continuous mode from June 1998 until now, at Lublin University of Technology, in Department of Electrical Drive Systems and Machines. This measurement system, and detailed description of determination of w_{pj} parameters from the measurements, was described in [4].

The more power thresholds P_j will be included in the model, the more accurate simulation results will be obtained. The presented model uses six P_j values (from P_1 to P_6), referred to PV generator with 1kWp nominal power, that is shown in the second column of Table 1.

In addition, the model takes into account two estimated values for thresholds P_0 and P_7.

The first estimated value, for the threshold of P_0=0Wp, assumes w_{0Wp}=1,03·w_{20Wp}, which implies that the total time of PV generator operation is 1,03 times longer than its operation with power greater than p_1=0,02 of its nominal power, where the total time of PVG operation means the time with output PVG power greater than almost zero. However, in the real conditions, the total time of PVG operation may be clearly greater than this estimated value, but this situation does not have a great effect on accuracy of the model. This is due to the fact, that PV generator's energy in the range of 0÷0,02 of its nominal power is not only negligible, but it is still mostly lost, because it covers power consumption of CU and loses in stationary motor M. Therefore, even significant underestimation of w_0 (w_{0Wp}) value does not result in significant errors in final simulation results obtained owing to this model.

Table 1. Summary presentation of model parameters: general parameters (columns 1,2,3,4) and values of the parameters for two specific days of the same month, with similar values of generated energy E_{PVr}, but with significantly different schedule of PVG power

j	P_j [Wp]	p_j	w_j (w_{Pj})	Values of w_j for 12.03.2003	Values of w_j for 13.03.2003
0	0	0	w_0=1,03·w_1 (w_{0Wp}=1,03·w_{20Wp})	0,354	0,409
1	20	0,02	w_1 (w_{20Wp})	0,344	0,397
2	60	0,06	w_2 (w_{60Wp})	0,225	0,313
3	150	0,15	w_3 (w_{150Wp})	0,064	0,089
4	300	0,3	w_4 (w_{300Wp})	0,026	0
5	600	0,6	w_5 (w_{600Wp})	0,02	0
6	1000	1	w_6 (w_{1000Wp})	0	0
7	1200 (or 1300 for III, IV)	1,2 (or 1,3 for III, IV)	w_7=0 (w_{1200Wp} or w_{1300Wp})	0	0
			E_{PVr}	1132Wh	1062Wh
			K_{PV}	0,962	0,941

j – the ordinal of the given threshold

P_j –the absolute value of PVG output power for j-power threshold

p_j – the value of P_j on relative scale, with respect to PV generator nominal power P_{PVN}

w_j or w_{Pj} – the two forms of presentation for parameters called: relative time of threshold power

E_{PVr} – energy that PV generator could produce at given location in defined period of time t_o

K_{PV} – a factor which increases the accuracy of the model, as described later in the paper

The second estimate assumes the value w_{1200Wp}=0 (or w_{1300Wp}=0) for the threshold P_7=1200Wp (or 1300Wp for

March and April). This assumption is the reference arising from 15-year study using mentioned measurement system, that maximum instantaneous power of PV generator, operating in Lublin climatic conditions, generally does not exceed 120% of PVG nominal power, except for cold days of spring months (March and April), when it could reach 130% of PVG nominal power.

The idea of proposed model for the given period of time (e.g. for specific day) can be represented graphically (Fig.2) as a broken line p=f(w), based on the set of sample data p_j and w_j taken from Table 1. This line (A or B) maps, according to the certain (presented below) assumptions, the P_{PVr}=f(t) chart – the changing as function of time of behavior of real power P_{PVr} produced by PV generator. This chart, in the terms of relative, could be also plotted as p_r=f(w), just like p=f(w) chart that represents the model, where:

$$p_r = \frac{P_{PVr}}{P_{PVN}} \quad (1)$$

where: P_{PVN} – nominal power of PV generator

According to the assumptions, it is not important, and even not possible now, to recreate exact shape of p_r=f(w) line. So, first and foremost, the idea is to reproduce exactly the time periods in which real relative PVG power p_r was between particular thresholds p_{j-1} and p_j. Secondly, the area below the broken line p=f(w) that graphically represents the model, should be exactly equal to the area below the chart of relative real PVG power p_r=f(w), because then energy E_{PVc} calculated using the model is equal to energy E_{PVr} generated by PVG in real operating conditions. Under these two assumptions, it is possible to achieve the effect of precise PVG modeling, which is that energy behavior of the model of receiver (for example, the quantity of water displaced by the pump) would be the same, regardless of whether the model of receiver would be powered from the PVG model described by p=f(w) line, or powered from the real PVG described by p_r=f(w) line.

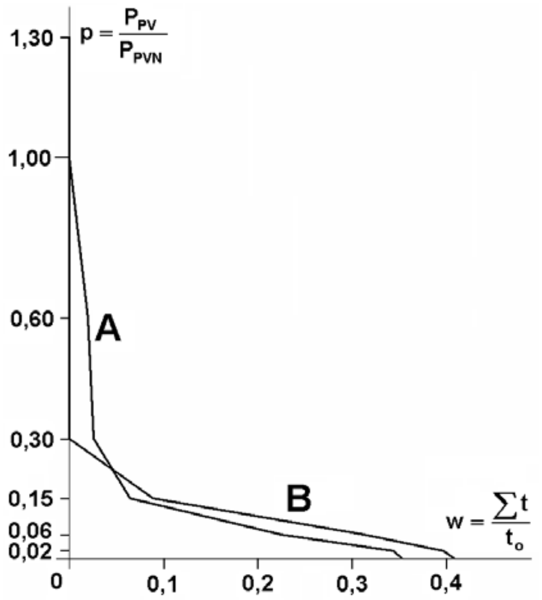

Fig.2. Graphical presentation p=f(w) of PV generator model, for two sample days: 12.03.2003 (line A) and 13.03.2003 (line B)

Analytically, the model in the form making possible the calculation of PV generator energy E_{PVc}, can be presented by formula (2), that allows for the calculation of the field under the graph p=f(w) and the conversion of it on the size of absolute:

$$E_{PVc} = P_{PVN} \cdot t_o \cdot \sum_{j=1}^{k} \left[\frac{p_{j-1} + p_j}{2} \cdot \left(w_{j-1} - w_j \right) \right] \quad (2)$$

where: E_{PVc} – calculated, using the model, energy produced by PV generator within t_o, assuming continuous MPPT (maximization of PV generator output power); t_o – analyzed period of operation of PV system; k – amount of intervals between thresholds from p_0 to p_7

After placing into equation (2) the values: P_{PVN}=1000Wp, t_o=24h, k=7, and the values from p_1 to p_7 from the third column of Table 1, a simplified form of analytical model may be presented by formula (3):

$$\begin{aligned} E_{PVc} &= 967{,}2 \cdot w_1 + 1560 \cdot w_2 + 2880 \cdot w_3 + \\ &+ 5400 \cdot w_4 + 8400 \cdot w_5 + a \cdot w_6 \end{aligned} \quad (3)$$

where: a=8400 for March and April, or a=7200 for other months.

To take advantage of the analytical model for the numeric design of PV systems, it is necessary to present equation (2) not in the form to recreate energy E_{PV}, but in numerical form with extracted value of actual PVG output power P_{PVi}, because the actual value of PEC efficiency, and consequently the actual value of efficiency of receiver (in particular: the drive unit M/L), directly depends on P_{PVi} parameter, as described before.

The basic numerical form of the model is presented with formula (4):

$$E_{PVcc} = \sum_{j=1}^{k} E_{PVj} \quad (4)$$

where: E_{PVcc} – the value of E_{PVc} (calculated PVG energy), adjusted with K_{PV} factor (description of K_{PV} later in the paper); E_{PVj} – the value of energy produced by PV generator, in the time periods for which relative power p of PV generator contained within the range of (p_{j-1};p_j).

The value of E_{PVj} may be obtained from formula (5):

$$E_{PVj} = K_{PV} \cdot \frac{t_o}{m} \cdot \sum_{i=1}^{n_j} P_{PVi} \quad (5)$$

where: K_{PV} – the correction factor of PVG energy; m – number of calculation steps, e.g. m=10000; $\frac{t_o}{m}$ – the value of calculation step; n_j – number of calculation steps per j-power interval, that is per interval (p_{j-1};p_j).

The value of n_j may be obtained from formula (6):

$$n_j = (w_{j-1} - w_j) \cdot m \quad (6)$$

And finally, the value of actual PV generator output power P_{PVi} may be obtained from formula (7), resulting from the formula for the equation of the line segment connecting two points with coordinates (p_j;w_j) and (p_{j-1};w_{j-1}):

$$P_{PVi} = P_{PVN} \cdot \left\{ \frac{p_{j-1} - p_j}{w_{j-1} - w_j} \cdot \left[w_{j-1} - \frac{i}{n_j + 1} \cdot \left(w_{j-1} - w_j \right) \right] + \frac{p_j \cdot w_{j-1} - p_{j-1} \cdot w_j}{w_{j-1} - w_j} \right\} \quad (7)$$

Equation (7) may be directly transformed into final, a lot simpler form (8):

$$P_{PVi} = P_{PVN} \cdot \left[p_{j-1} + \frac{i}{n_j + 1} \cdot \left(p_j - p_{j-1} \right) \right] \quad (8)$$

As you can see in equation (8), seemingly the values of w_j and w_{j-1} do not have effect on the P_{PVi} values. But in fact, note that the parameters w_j and w_{j-1}, accordance to the equation (6), are hidden in n_j value.

Improving the accuracy of the model

The K_{PV} factor, adjusting the energy of PV generator, has been introduced into the model to improve its accuracy, according to the second of the foregoing assumptions.

It is true that the knowledge of w_{Pj} values, for some of P_j thresholds, allows for recreating the value of E_{PVr} energy, produced by PV generator in the given period of time (hour, day or month). This may be calculated with equations (2) or (3). But despite this, it is recommended to put E_{PVr} parameter into the model as an additional volume, to improve accuracy of simulations.

K_{PV} is calculated with simple formula (9):

$$K_{PV} = \frac{E_{PVr}}{E_{PVc}} \tag{9}$$

where E_{PVr} is, mentioned in the introduction, the additional parameter set into the model – the value of real energy produced by PV generator in the given period of time, and E_{PVc} is the value calculated with formulas (2) or (3) on the basis of w_j parameters.

Theoretically, for infinite amount of power thresholds (i.e. when $k \to \infty$), the value of E_{PVc} calculated from formula (2) would approach the value of E_{PVr}, i.e. the value of K_{PV} would approach 1. In practice, due to limited quantity of thresholds (k=7), and so due to not perfect mapping of area below line p_r=f(w) by area below broken line p=f(w) (the model), the values of K_{PV} can differ from 1. The research carried out for dozens of different days shown that the values of K_{PV} contain in the range from 0,82 to 1,08. This means, that without the adjustment by the factor K_{PV} (i.e. adjustment possible owing to the additional data E_{PVr}), the errors of the model could reach several percent.

Summary

The described model belongs to mathematical (abstract, or not material) group of models. Advantages of such models, comparing with material ones, are: low cost of the model and the research, ease of making changes in the model, and as the consequence: high speed of simulations, as well as the safety of the model and of its environment in the case of researcher's mistake. For these reasons, such type of the model is recommended in preliminary design phase of the PV system.

As mentioned, it is not possible to perform accurate simulation of operation of PV stand-alone system without EBS, performed on abstract model, including the numeric one, when the energy supplied to PV generator (solar irradiation energy) or PVG output energy E_{PVr} (electrical energy) is the only data. In such cases, the errors of simulations sometimes may reach hundreds of percent. And unfortunately, most of available databases provide the only one essential parameter – the energy. The described model eliminates this drawback, that makes possible obtaining simulations with very high accuracy.

However, one should be aware that nothing but the described forms of the model are of very narrow practical applications. For example, in the form according of formula (3), it has been sometimes used to supplement the data from measurement system, in situations where, for example due to disappearance of supply voltage, the measurements have been held over some time. But the primary goal of creation of this model has been its implementation, mainly using formulas from (4) to (9) with additional modifications enabling introducing the values of converter PEC and driving unit M/L efficiency curves, in a software dedicated for designing PV systems without EBS. What's more, this software also could be used for the design of low power PV grid-connected systems, especially with converters integrated with PV modules (the so-called: microconverters), because the efficiency of DC/AC converter with low nominal power, containing boost chopper and then inverter, is clearly lower for small power than for nominal one. The software based on the described model is currently at the stage of testing.

REFERENCES

[1] Niechaj M., Autonomiczny fotowoltaiczny system napędowy bez elektrycznego źródła buforowego z silnikiem indukcyjnym jednofazowym, *Zeszyty Problemowe - Maszyny Elektryczne,* 98 (2013), 189-194

[2] Niechaj M., Maksymalizacja mocy generatora w fotowoltaicznych systemach napędowych, *Electric driving systems supplied from unconventional power sources. Selected problems,* Postępy Napędu Elektrycznego i Energoelektroniki PAN, Lublin 2000, 24-39

[3] Niechaj M., The Operation of Power Electronic Converters in Photovoltaic Drive Systems, *13th International Power Electronics and Motion Control Conference EPE-PEMC,* Poznań 2008, 1913-1918

[4] Niechaj M., Komputerowa rejestracja parametrów energetycznych systemu fotowoltaicznego podczas jego pracy ciągłej, *IV Konferencja Zastosowania Komputerów w Elektrotechnice ZKwE'99,* Poznań-Kiekrz 1999, 409-412

Author:

dr inż. Marek Niechaj, Lublin University of Technology, Department of Electrical Drive Systems and Machines, 38a Nadbystrzycka Str., 20-628 Lublin, Poland, E-mail: m.niechaj@pollub.pl.