Modeling and research of photovoltaic system with microinverter

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***Abstract*— The article presents modeling of a grid-connected photovoltaic system with microinverter. The system consists of PV panel, a single-phase inverter connected to the grid and data logger. A mathematical model for calculating the power of a photovoltaic system using meteorological data has been developed. The inverter efficiency characteristics are represented in dependance of input DC power and fitted with appropriate mathematical function. The obtained simulation results of the photovoltaic systems are validated with experimental data. Real characteristics for the production of energy from PV system are also shown.**

Keywords—photovoltaic system, microinverter, mathematical models

I. Introduction

The cost of electricity for office buildings, service or production facilities is the main monthly cost of any business. In search of ways to reduce energy costs, many companies are choosing different options to increase the energy efficiency of their production processes by integrating photovoltaic generators into their energy supply systems.

Photovoltaic systems are the most efficient and sustainable technology of generating electricity. Mounted on roofs, facades, sheds or other vacant spaces, these systems are the most cost-effective option for utilizing vacant space, reducing electricity expenses and ensuring sustainable electricity production without additional transmission losses.

The purpose of this study is to develop a mathematical and computer model for calculating the power of a photovoltaic system, which consists of a photovoltaic panel and a single-phase microinverter connected to the grid.

The proposed approach consists in developing mathematical and simulation models for the efficiency of two main parts of the energy conversion chain – PV panel and microinverter. This is commonly used technique by the authors for calculation of generated power and energy by PV installations. There are many different efficiency models of PV panels. May be the most accurate is the model of Durisch [1], [2]. It is also the most complicated because it takes into account the influence of solar radiation and cell temperature on the efficiency of the PV module. For inverter efficiency most often approximations of manufacturer or experimental data with appropriate mathematical functions are used [3], [4], [5].

II. Structure of the PV system

The studied photovoltaic system is connected to the grid via a single-phase inverter. The PV system consists of a microcrystalline silicon PV panel with a power of 128W, a single-phase microinverter with a power of 250W and a monitoring system with data logger. Data logger collects data on energy production from the system in real time. The data is stored on a web server. The block diagram of whole system is shown in Fig.1

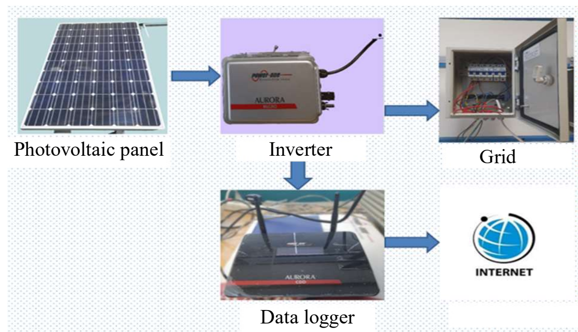

Fig. 1. Block diagram of the studied PV system with data logger.

III. Modeling of efficiency of PV modules based on I-V characteristics

In order to fulfil the aim of the study it is necessary to build a mathematical model of the PV panel of type input-output (energy model). This model will give the possibility to calculate the generated power by the panel under given operating conditions – solar radiation and ambient temperature. This type of models suppose that the PV panel operates at its maximum power point. Many authors use mathematical functions to fit experimental data thus obtaining relatively precise model [1], [2]. But this approach requires experimental data for a concrete PV module to be available, which is not possible in case of preliminary design of PV installations. Here, an entirely theoretical approach for deriving of PV panel model is proposed. The efficiency values at different solar radiation and cell temperature are calculated based on electrical model of PV panel, which gives its I-V curves.

The PV module model is based on single-diode equivalent circuit of a PV cell [7], [8]. When the PV cell is irradiated, the saturation current I_d is subtracted from the photocurrent I_{pv}. The mathematical equation for PV module is:

$$I = I_{pv} - I_d \quad (1)$$

where: I_{pv} is the photocurrent, I_d - the diode current.

The current-voltage (I–V) relation is expressed as follows:

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_s)}{CkT}} - 1\right) \quad (2)$$

where: I_0 is diode saturation current, T – temperature of cell in (K), k - Boltzmann constant, q - electron charge, V – voltage

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across the PV cell, R_s – series resistance, C - nonideality factor.

Several simulations were carried out with the developed PV module model. The results shown in Fig. 2 and Fig. 3 are for used microcrystalline silicon panel under different values of irradiation and cell temperature.

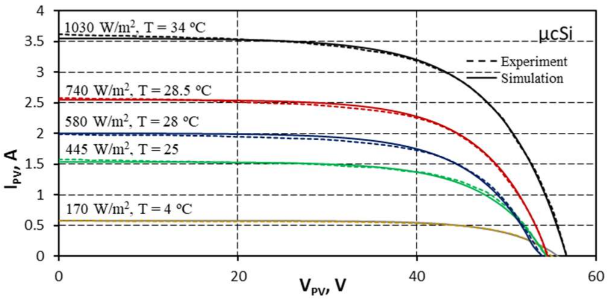

Fig. 2. Comparison of the theoretical I-V characteristics with experimentally obtained characteristics for µc-Si PV panel.

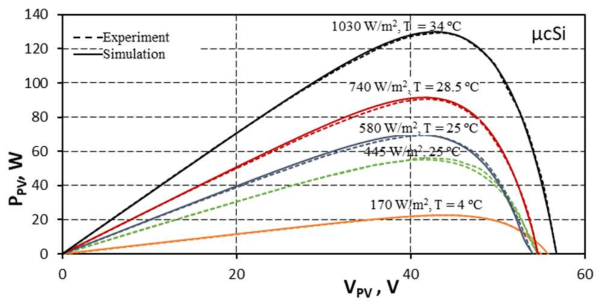

Fig. 3. Comparison of the theoretical power characteristics with experimentally obtained characteristics for for µc-Si PV panel.

In the same figures a comparison between theoretical and measured characteristics of PV module is made. As it can be seen the theoretical results show very good match with the experimental ones.

In each power curve, the point of maximum P_{mpp} power is determined by the expression:

$$P_{mpp} = V_{mp} I_{mp} \tag{3}$$

where I_{mp} and V_{mp} are current and voltage at the point of maximum power.

The power curves are calculated from the I-V characteristics of the modules at different values of the solar radiation and the module cell temperature. The determination of the efficiency is accomplished as for different values of solar radiation (from 10 to 1200W/m^2), the maximum power of PV module P_{mpp} is calculated. Then, the total light power on the PV module is calculated using following expression:

$$P_{sol} = G_a S \tag{4}$$

where G_a is solar radiation, S is the area of PV module. Efficiency of the PV module is calculated as follows:

$$\eta = \frac{P_{mpp}}{P_{sol}} \tag{5}$$

The characteristics of the efficiency as a function of solar radiation at two different cell temperatures (25°C and 40°C) are shown on Fig. 4.

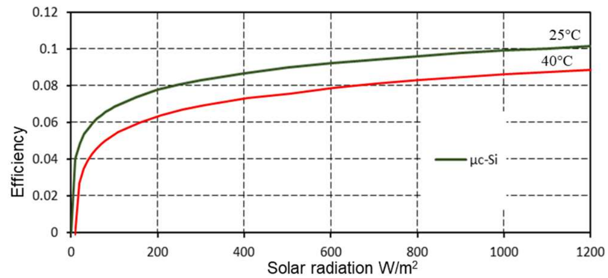

Fig. 4. Calculated µc-Si PV module efficiency as a function of solar radiation at two cell temperatures.

These characteristics were further approximated with the following mathematical function (modified Durich model [1]):

$$\eta_{pv} = p\left[q\frac{G_a}{G_{ar}} + \left(\frac{G_a}{G_{ar}}\right)^m\right] \times \left[1 + r\frac{T_c}{T_{cr}}\right] \tag{6}$$

where G_a is the solar radiation, T_c – cell temperature, the reference conditions are G_{ar} =1000W/m^2, T_{cr} =25ºC and AM0=1.5; p, q, m, and r, are coefficients definite to each PV module type.

The values found for the coefficients are as follows:

p = 0.1114, q = -0.1895, m = 0.2748, r = - 0.054.

The results for the approximation are illustrated in Fig5.

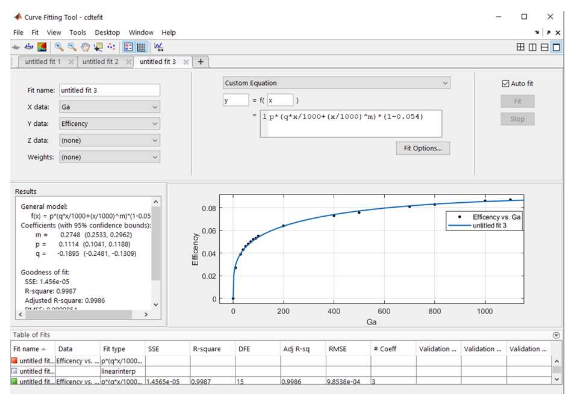

Fig. 5. Aproximated efficiency curve of a µc-Si PV module.

The theoretical model for PV module efficiency (6) allows to determine the generated power of PV panel under certain conditions (solar radiation and cell temperature) if the module operates at the point of maximum power.

In the case of microcrystalline silicon modules, the temperature affects the efficiency, which is due to their temperature dependence on the voltage. The temperature of the module cells is calculated from the air temperature and solar radiation using the approach presented in [4], [5]. The influence of wind on the cooling of the panel is ignored.

IV. Modeling of Efficiency of Solar Microinverter

As it was stated in the beginning, the aim of this study is to calculate the power of a photovoltaic system, which consists of a photovoltaic panel and a microinverter connected to the grid. The structure of the model of the photovoltaic panel and the inverter is shown on Fig. 6.

In the first block, the power of the photovoltaic panel is calculated by using the mathematical model developed in Chapter III. In the second block, the efficiency of the inverter is calculated, which will be discussed in detail here.

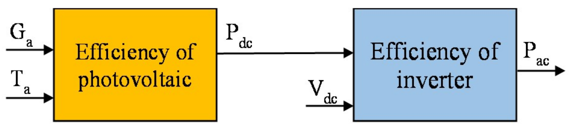

Fig. 6. Diagram of the model of photovoltaic installation.

In the first block for calculating the efficiency of photovoltaics, input data for the solar radiation in the plane of the photovoltaic and the temperature of the module are used. The power of PV panel P_{dc} is fed to the input of the inverter. The input data for determining the efficiency of the inverter is the input power P_{dc} and the input DC voltage. From the point of view of the produced electrical power at the output of the whole PV system, it is important to know the output power of the inverter P_{ac}. The output power of inverter P_{ac} is calculated as follows:

$$P_{ac} = P_{dc}\eta_i \qquad (7)$$

where η_i is efficiency of inverter.

The efficiency depends on the output power and the input DC voltage of the inverter V_{dc}. The efficiency data of the microinverter is provided by the manufacturer in the form of graphs, which are a function of the output power in relative units and at a constant input voltage of the inverter.

$$\eta_i = f(p_{ac}) \qquad (8)$$

where p_{ac} - the output power of the inverter in relative units, which is calculated as follows $p_{ac}=P_{ac}/P_{rated}$. P_{rated} is rated power of inverter.

In order to be able to use the efficiency data, it is approximated with an appropriate function.

The task set here is to calculate the output power of the inverter P_{ac} at a known input power P_{dc}. Therefore, it is necessary to know the efficiency of the inverter η_i as a function of the input power P_{dc}. For this purpose, the input power of the inverter is calculated based on the efficiency and the output power:

$$p_{dc} = \frac{p_{ac}}{\eta_i} \qquad (9)$$

where p_{dc} is input power of inverter in relative units, referenced by rated output power $p_{dc}=P_{dc}/P_{rated}$.

The obtained data is approximated by a fractional-rational function of the type:

$$\eta_i = \frac{p_{dc} - n}{n_3 p_{dc}^3 + n_2 p_{dc}^2 + n_1 p_{dc} + n_0} \qquad (10)$$

where n, n_0, n_0, n_2 and n_3 are unknown parameters to be determined.

A fractional-rational function with a third-order denominator was chosen due to the more peculiar shape of the efficiency curves of the specific inverter, in which the known approximation with a function with a second-order denominator does not give sufficiently accurate results [5]. The approximation was performed using the data fitting tool cftool in Matlab software. The results are summarized in TABLE I. The efficiency curves of the inverter – given by the manufacturer and fitted - are shown in Fig. 7.

TABLE I. VALUES OF THE COEFFICIENTS OF THE APPROXIMATING FUNCTION AT DIFFERENT INVERTER INPUT VOLTAGE

Parameter	V_{dc} = 40V	V_{dc} = 24V
n	0.12	0.01
n_3	-0.03246	-0.3394
n_2	0.07527	0.07823
n_1	0.9859	0.9925
n_0	-0.00155	3.2E-05

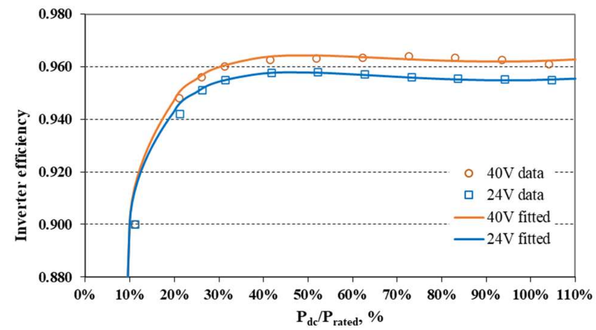

Fig. 7. Inverter efficiency curves depending on the input power at V_{dc}=24V and 40V, given by the manufacturer (with markers) and approximated (solid lines).

The accuracy of the approximation is better than 1% for both curves.

V. Verification of the Developed Model with Experimental Data

The developed models are applied for calculation of the power injected to the grid by PV system, consisting of one panel of microcrystal silicon and single-phase inverter. The values of the solar radiation in the plane of the panel and the ambient temperature were used as input data. The whole model was developed in Matlab.

Fig. 8 shows the simulation results obtained from the PV system model for a sunny day. Experimental data were used to compare the obtained results and the coincidence is good enough for the engineering practice.

Fig. 9 shows the results obtained for a series of days with different weather conditions. Once again, the theoretical and experimental data are close, which proves the adequacy and accuracy of the developed models.

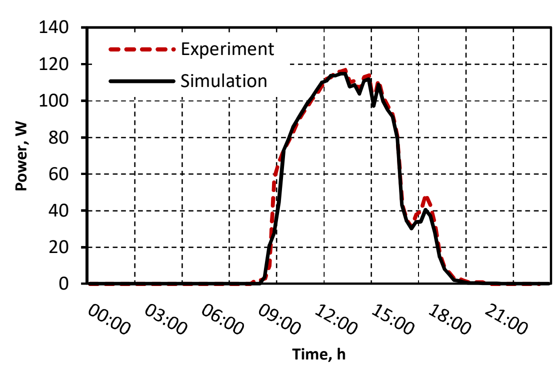

Fig. 8. Comparison between theoretical (solid line) and experimental (dashed line) AC output power of PV system at sunny day.

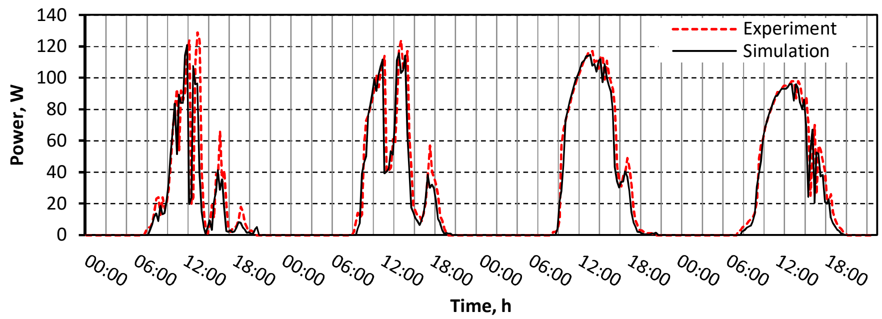

Fig. 9. Comparison between theoretical (solid lines) and experimental (with markers) AC output power of PV system in a series of days.

VI. Experimental Results for Electricity Production by the Studied PV System

The microinverter is equipped with an intelligent monitoring system. It allows the electricity produced to be monitored using the Aurora Vision monitoring portal. The following figures represent some results obtained by the monitoring system.

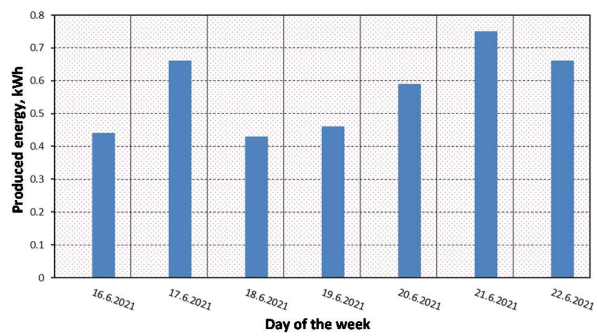

Fig. 10. Produced energy by the studied PV instalattion for one week.

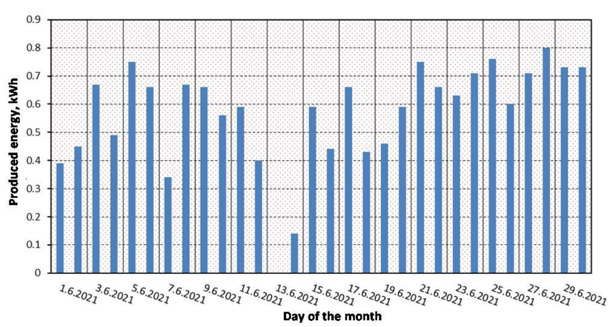

Fig. 11. Produced energy by the studied PV instalattion for one month.

The produced energy varies by days because of changing weather conditions – presence of clouds in the majority of days. The total energy production for the month of June 2021 is 17,62 kWh. Average daily electricity production is 570 Wh.

VII. Conclusion

The article presents a theoretical and experimental study of a photovoltaic system connected to the grid via a microinverter. A mathematical model for the efficiency of the PV module is developed based on theoretically calculated I-V characteristics of the panel.

Mathematical model of the efficiency of single-phase microinverter is developed using approximation by a fractional-rational function. The obtained models are applied for calculation of the power generated by a small PV system. The values of the solar radiation in the plane of the panel and the ambient temperature are used as input data. The whole model was developed in the environment of Matlab software.

Specialized equipment is used to obtain the electrical characteristics of the system. The power generated for a long period of time of the system is registered using data logger and dedicated electricity power analyzer. Actual data on the operation of the system under different solar radiation are shown, using the Aurora Vision monitoring portal. The monitoring system allows for the accumulation of a large database of experimental data and thus can compare the production in different weather conditions - winter and summer.

The article can be upgraded in the future using different types of panels and inverters and making comparisons under different operating conditions.

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