Modeling of Electrical Characteristics of Various PV Panels

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Abstract—**The article presents mathematical models of the electrical characteristics of different types of photovoltaic (PV) panels. The developed model of the current-voltage (I-V) characteristics of PV panels is valid for wide range of operating conditions - different solar radiation and temperature of the modules. The model is based on data given by the manufacturer. The software used for mathematical modelling is Matlab. The obtained simulation results are validated with experimental characteristics under identical operating conditions.**

Keywords— computer and simulation models, experimental characteristics, modelling of electrical characteristics, photovoltaic panels, validation of models.

I. INTRODUCTION

Sustainable energy supply remains one of the basic requirements of today's society to respond to increased demand, caused by higher energy consumption and the continued growth of the population. For a long time, the energy boom was based on fossil fuels. Not only that the supply of traditional energy sources such as oil, coal and natural gas is limited but also causes a lot of pollution that creates serious environmental problems.

The electrical characteristics of solar cells depending on materials and physical configurations are important to estimate and to evaluate their performances. In the domain of photovoltaic systems (PVS) much research is being done underway on the development of appropriate mathematical models for estimation of output power of PV generators, optimal design of PV systems, common operation with electronic converters, load management and evaluation of their performances. Different approaches for modelling the electrical characteristics of PV panels are known in the literature [1], [2]. For this purpose, the photovoltaic cell or the whole module is represented in the form of an equivalent electrical circuit. The modelling of electrical characteristics (current, voltage and power) allows them to be determined for different loads and changes in weather conditions, so that an estimate of the steady-state and dynamic behaviour of a PV generator is obtained. The best way to verify the developed mathematical and simulation models is the comparison with experimental data [3], [4].

The main goal of this work is the development of mathematical and simulation models of PV panels from different materials and technologies. The data from the manufacturers are used for determination of the model parameters. In addition, the simulation results are verified with measured data obtained from an experimental platform for study of PV generators.

II. MODELING OF PHOTOVOLTAIC PANELS

Mathematical models use equivalent circuits of varying complexity [5]. The developed PV cell and panel model is based on the equivalent circuit shown in Fig. 1, which uses a diode and a series resistor [6]. The photocurrent I_{ph} represents the generated current from the cell (module). This current is proportional to the solar irradiance G_a, because the increase in radiation leads to an increase in the number of created electrons and holes.

An unlit photovoltaic cell has the same characteristics as a conventional diode. When the cell is illuminated, the saturation current I_{d1} is added to the photocurrent I_{ph}. The mathematical equation describing the equivalent circuit of a PV cell is as follows [7]:

$$I = I_{ph} - I_{D1} \tag{1}$$

where: I_{ph} - photocurrent, I_{D1} - the diode current.

The diode current I_{D1} can be represented with the Shockley equation [8]:

$$I_{D1} = I_0 \left(e^{\frac{q(V+IR_S)}{AkT}} - 1 \right) \tag{2}$$

where: I_0 is reverse saturation current, T - actual cell temperature (K), k - Boltzmann constant, q - electron charge, V - voltage of PV cell, R_s - series resistance, A - ideality factor.

The reverse saturation current I_0 could be expressed as a function of the material and temperature characteristics:

$$I_0 = D(T)^3 e^{\frac{-q\varepsilon_g}{AkT}} \tag{3}$$

where:

- D is diode diffusion factor;

- ε is the material bandgap energy;

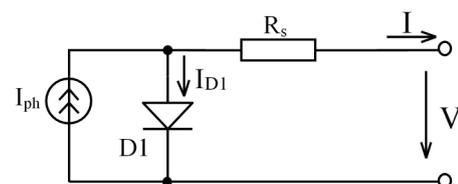- $\varepsilon_g = 1.12$ eV for Si;

Fig. 1. Equivalent circuit of photovoltaic cell with one diode and series resistance.

- $\varepsilon_g = 1.50$ eV for CdTe;
- $\varepsilon_g = 1.70$ eV for CIGS and μc-Si.

I_0 is related to the temperature. It can be determined under operating conditions other than Standard Test Conditions (STC) using the formula:

$$I_0 = I_{0stc}\left(\frac{T}{T_{stc}}\right)^3 e^{\left[\left(\frac{q\varepsilon_g}{kA}\right)\left(\frac{1}{T_{stc}} - \frac{1}{T}\right)\right]} \qquad (4)$$

where: I_{0stc} is the saturation current at STC calculated by (3), $T_{stc} = 298K$ is STC temperature.

The module current-voltage (I-V) relation is given by:

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_S)}{CkT}} - 1\right) \qquad (5)$$

The following expression defines the shape factor C:

$$C = \frac{v\left((V_{mp,stc} + I_{mp,stc}R_s)\right)}{ln\left(1 - \frac{I_{mp,stc}}{I_{sc,stc}}\right)} \qquad (6)$$

where: $V_{mp,stc}$ – voltage at the point of maximal power at STC; $I_{mp,stc}$ – current at the point of maximum power at STC.

Reverse saturation current $I_{0,stc}$ at STC is given by the following expression:

$$I_{0stc} = I_{sc,stc}\,exp\left(\frac{-vV_{oc,stc}}{C}\right) \qquad (7)$$

The serial resistance R_s and shape factor C are assumed to be constant.

The current I_{ph} is it influenced by the solar radiation and the panel's temperature. The current I_{ph} can be determined for different radiation and temperature by following expression:

$$I_{ph} = \left(\frac{G}{G_{stc}}\right)\left(I_{sc,stc} + k_i(T - T_{stc})\right) \qquad (8)$$

where: $G_{stc} = 1000W/m^2$ is solar radiation at STC; $I_{sc,stc}$ – short-circuit current at STC; T_{stc} – STC temperature (25°C) and k_i - thermal coefficient of the short-circuit current.

A basic factor which describes the quality of the I-V curve is the fill factor:

$$FF_{stc} = \frac{P_{stc,max}}{V_{oc,stc}I_{sc,stc}} \qquad (9)$$

The serial resistance is calculated as follows:

$$R_s = \frac{\ln\left(\frac{I_{sc,stc} - I_{mp,stc}}{I_{0,stc}}\right)N_S V_t - V_{mp,stc}}{I_{mp,stc}} \qquad (10)$$

where: Ns is the number of cells connected in series per module.

III. REALIZATION AND VERIFICATION OF THE MATHEMATICAL MODEL

The presented mathematical model is implemented as a programming code in the Matlab environment. As input parameters for the model are entered:

- Solar radiation G_a in plane of the panel;
- Temperature of the modules T;
- All necessary parameters involved in the model from the manufacturer datasheet as I_{0stc}, $I_{mp,stc}$, $V_{mp,stc}$ etc.

The described mathematical model is developed for five types of PV panels – monocrystalline silicon (mSi), polycrystalline silicon (pSi), microcrystalline silicon (μcSi), copper indium-gallium selenide (CIGS), and cadmium telluride (CdTe). The calculated model parameters for the five systems are summarized in Table I.

TABLE I. CALCULATED PARAMETERS OF THE MODELS FOR DIFFERENT TYPES OF PV MODULES

Technology	mSi	pSi	μc-Si	CIGS	CdTe
$I_{0,ref,}$ A	$5.14 \cdot 10^{-6}$	$3.55 \cdot 10^{-6}$	$2.71 \cdot 10^{-4}$	$1.05 \cdot 10^{-5}$	$8.97 \cdot 10^{-7}$
Shape factor C	100.53	98.46	246.46	308.41	246.92
k_i, A/K	$6.2 \cdot 10^{-4}$	$7 \cdot 10^{-4}$	$7 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
R_s, Ω	0.17	0.15	1.29	1.62	6.5

As output data, the model gives arrays of current and voltage values under the determining operating conditions.

The verification of developed mathematical models has been done with real experimental data from a photovoltaic platform, located in the site of the Technical University of Sofia [9]. It includes PV systems with modules from the five different types listed above. The main parameters of the studied modules are summarized in Table II.

TABLE II. PARAMETERS OF PV MODULES

Technology	mSi	pSi	μc-Si	CIGS	CdTe
Open circuit voltage V_{oc}, V	37.2	37.0	59.8	94.7	89.6
Short circuit current, I_{sc}, A	8.61	8.72	3.45	1.65	1.23
Voltage at the point of maximum power, V_{mp}, V	29.5	29.6	45.4	73.8	68.2
Current at the point of maximum power I_{mp}, A	8.2	8.12	2.82	1.49	1.1
Peak power at STC, W	240	240	128	110	75
Rated efficiency at STC, %	14.8	14.8	9.01	11.70	10.42
Fill factor FF_{stc}	0.74	0.75	0.62	0.70	0.68
Temperature coefficient of short circuit current k_i, [%/K]	-0.30...-0.45		-0.28…-0.50	-0.26…-0.50	-0.20…-0.43
Temperature coefficient of open circuit voltage k_v, [%/K]	+0.02...+0.08		+0.06...+0.10	+0.04…+0.10	+0.02…+0.04
Temperature coefficient of maximum power k_P, [%/K]	-0.41	-0.47	-0.24	-0.38	-0.25

Fig. 2. Specialized analyzer for PV panels.

A PV analyzer is used to obtain the volt-ampere characteristics of the tested modules, which allows examination of PV plants with power up to 12kW. The analyzer with its adjacent probes and sensors is shown in Fig. 2.

The device has a display to visualize the obtained results. It illustrates the volt-ampere characteristic curve and power characteristic, as well as basic parameters of the photovoltaic plant under test – open circuit voltage V_{oc}, short circuit current I_{sc}, peak power P_{mp}, current and voltage at peak power I_{mp}, V_{mp}, solar radiation, temperature of panel and etc.

IV. MODELING OF EFFICIENCY OF PV MODULES BASED ON VOLT-AMPERE CHARACTERISTICS

Maximum power by definition is the product of the current and voltage at the maximum power point:

$$P_{mp} = V_{mp} I_{mp} \qquad (11)$$

This point is determined by the power curve $P(V)$ of the panel. Power curves are calculated from the I-V characteristics of modules at different solar radiation and module temperatures.

The efficiency of a PV panel is determined as the ratio of the maximum power and received solar power:

$$\eta = \frac{P_{mp}}{P_{sol}} \qquad (12)$$

The total solar power on a PV module is calculated by the following expression:

$$P_{sol} = GS \qquad (13)$$

where: G is the solar radiation on the surface of module, S is the area of the module.

Determination of efficiency is carried out for different solar radiation from 10 to 1200W for all studied types of PV panels.

V. MODEL VERIFICATION

Multiple I-V curves under various meteorological conditions are calculated with the proposed mathematical model. The obtained simulation results for five different PV panels (mSi, pSi, μcSi, CIGS, CdTe) are compared with experimental data in order to validate the models. Fig. 3 shows the calculated I-V characteristics for monocrystalline silicon modules, which are compared with experimentally obtained curves under the same conditions – solar radiation and temperature.
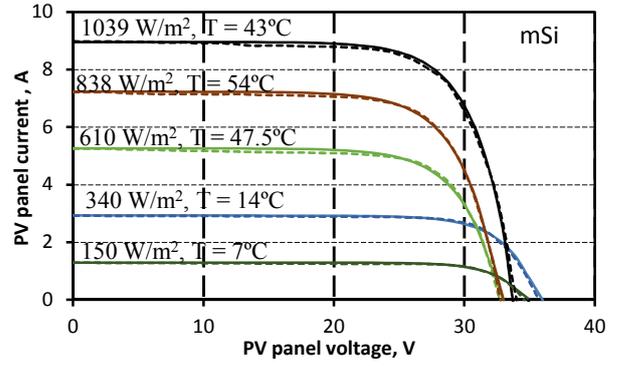

Fig. 3. Comparison of the model I-V characteristics with real characteristics for mSi, experimental curves (dashed lines) and theoretical (solid line).
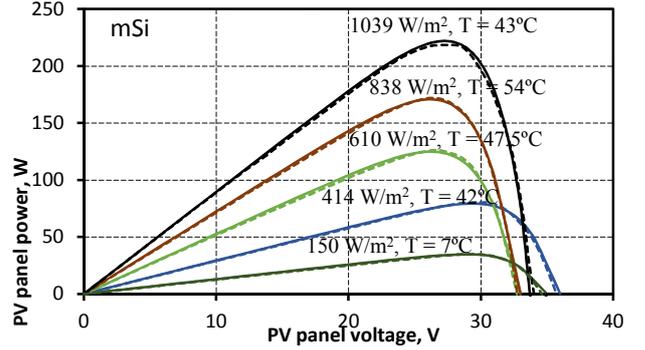

Fig. 4. Comparison of the model power characteristics with real characteristics for mSi panels, experimental curves (dashed lines) and theoretical (solid line).
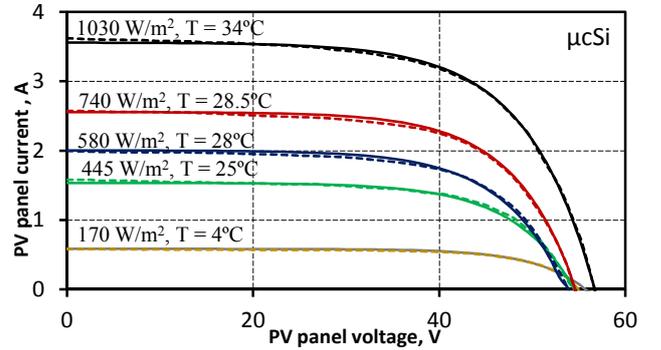

Fig. 5. Comparison of the model I-V characteristics with real characteristics for μcSi panels, experimental curves (dashed lines) and theoretical (solid line).
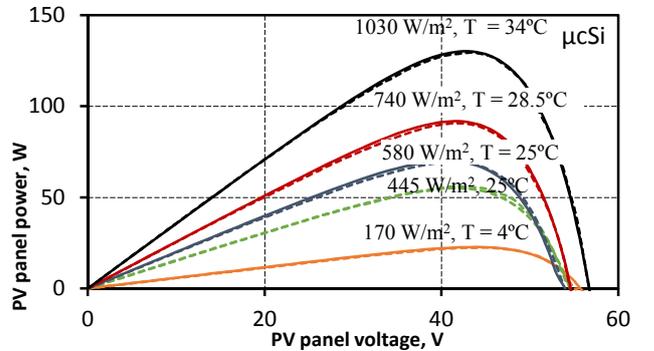

Fig. 6. Comparison of the model power with real characteristics for panels of μcSi, experimental curves (dashed lines) and theoretical (solid line).
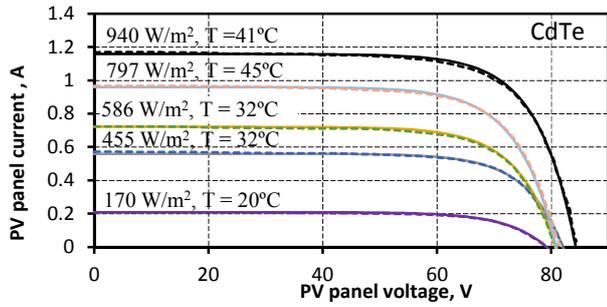
Fig. 7. Comparison of the model I-V characteristics with real characteristics for CdTe panels, experimental curves (dashed lines) and theoretical (solid line).
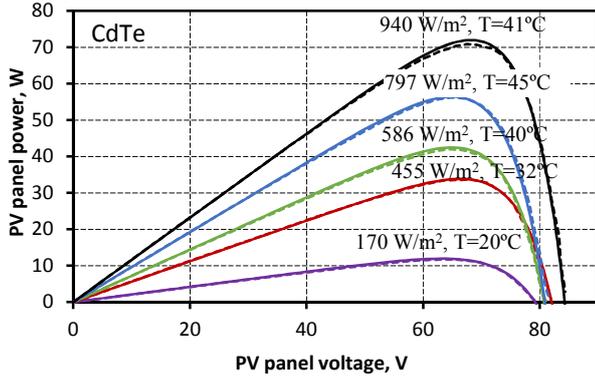

Fig. 8. Comparison of the model power with real characteristics for CdTe panels, experimental curves (with dashed lines) and theoretical (solid line).

From the graphs, it can be seen the good coincidence between the theoretical and experimental characteristics for different operating conditions. The deviations are up to 2%. This result confirms the correctness of the chosen approach and the exact determination of the unknown parameters of the models for five different types of PV panels.

The model also allows to study the efficiency of modules at different solar radiation and temperature.

Fig. 9 shows calculated efficiency characteristics in function of solar radiation, which are compared with experimentally obtained curves.

Fig. 10 demonstrate a comparison of the efficiency of PV modules at different temperatures (25° and 40°).
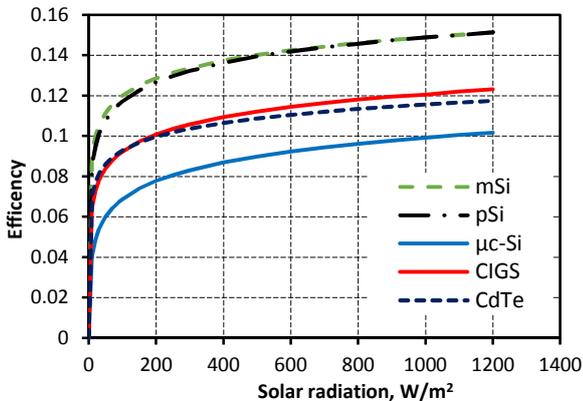

Fig. 9. Theoretically calculated efficiency of PV modules at constant temperature of 25°C.

The theoretically calculated curves of efficiency allow to compare the qualities of five types of modules produced by
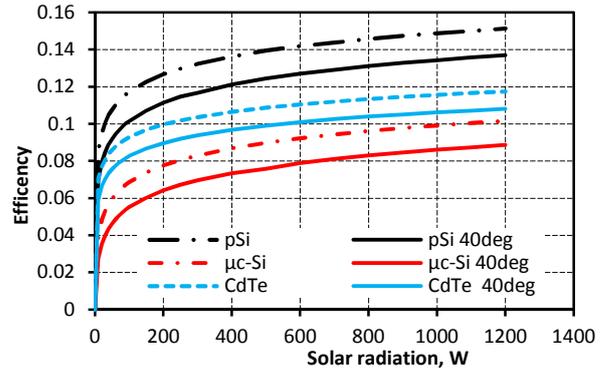

Fig. 10. Comparison of theoretical efficiency of studied PV modules at two different temperatures 25°C and 40°C.

different technology. The model is used to study the efficiency of modules at different solar radiation and temperature. Highest efficiency have the modules produced by crystalline technology (mSi and pSi), followed by the thin-film modules (CIGS и CdTe), and lowest efficiency has the microcrystalline silicon (μcSi) modules. Expectably, with the temperature increase, the efficiency of all modules decreases (see Fig. 10). CIGS modules have biggest decrease of efficiency, due to the high temperature dependence of the open circuit voltage. The temperature has lowest effect on the efficiency of microcrystalline silicon modules, due to the lower temperature dependence of open circuit voltage.

In order to obtain a of the modules, which is suitable for calculation of the produced energy in long time intervals an energy model for the efficiency at the maximum power point is developed. It consists in approximation of the efficiency curves from Fig. 9 and Fig. 10 with the Durish formula

$$\eta_{pv} = p \left[q \frac{G_a}{G_{ar}} + \left(\frac{G_a}{G_{ar}} \right)^m \right] \cdot \left[1 + r \frac{T_c}{T_{cr}} \right] \qquad (14)$$

where: G_a is moment solar radiation, G_{ar} is a referent solar radiation (1000W/m²), T_c is temperature of module, T_{cr} is referent temperature (25°), p, q, m, r are empirical coefficient, which are different for every PV technology.

It should be noted that (14) represents a modified version of the original Durish formula where the air mass is neglected and the temperature dependence is changed to comply with the conventional temperature coefficient of the maximum power given by the manufacturers in the datasheet of the PV modules.

Empirical coefficients in (14) are determined by approximation using curve fitting tool in Matlab. The values obtained for the coefficients for the studied PV modules are shown in Table III.

TABLE III.   VALUES OF EMPIRICAL COEFFICIENTS FOR STUDIED PV MODULES

Coefficient/ Type of module	mSi	pSi	μc-Si	CIGS	CdTe
p	23.1	0,1853	0,247	20.4	0,1363
q	-0.281	-0,0568	-0,1201	-0.251	-0,04508
m	0.155	0,1272	0.210	0.271	0,114
r	-0.150	-0,149	-0.054	-0.152	-0,112

The parameter *r*, which represents the temperature dependence of the efficiency is taken from the manufacturer's data.

The Fig. 11 shows comparison of the calculated efficiency of PV systems using both methods – from the I-V curves and from the approximation formula (14).
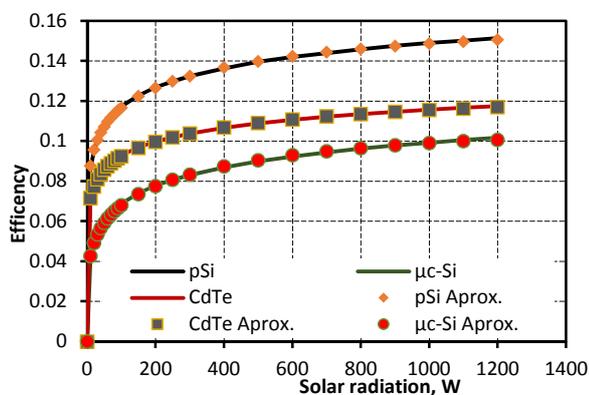

Fig. 11. Comparison of efficiency of PV systems obtained from Durish model (dashed lines) and calculated efficiency from I-V model (solid lines) at temperature 25°C.

CONCLUSIONS

The paper presents modelling of the electrical characteristics of PV panels, manufactured by different technologies and by different semiconductor materials. A model of the I-V characteristics for PV panels of different types has been developed. Using this model, an approach for calculation of PV modules efficiency curves is proposed. The developed model uses data for PV panels provided by manufacturers. The model is validated with experimentally obtained characteristics. The coincidence between the theoretical and experimental characteristics is good for variety of operating conditions, with deviations of up to 2%. An energy model for calculation of efficiency of different PV modules is also developed. The model is entirely analytical and allows for calculation and prediction of the efficiency of PV modules under different meteorological conditions (solar radiation and temperature). As a whole, the result from this work is a development of detailed model of different PV modules that is suitable for modelling of module behavior in common operation with electronic converters and an energy model that can be used for long-term performance of PV systems.

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