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MODELLING OF ELECTRICAL CHARACTERISTICS OF PHOTOVOLTAIC POWER SUPPLY SOURCES

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Summary: The photovoltaic (PV) generators are a major element of PV power systems, characterized by a low conversion ratio. This accounts for the necessity to study the current-voltage and power-voltage characteristics of PV sources in order to obtain maximum power output when there are changes both in the modules themselves and in the environment where they operate. In this paper the classical and the modified single-diode models have been used to model the electrical characteristics of PV cells and modules. Mathcad software package has been used for the modelling. The impact of solar radiation, temperature and shading both on electrical characteristics and on the PV cells and modules efficiency has been studied.

Keywords: electrical characteristics, single-diode model, modelling, efficiency.

1. INTRODUCTION

When photovoltaic conversion is used to produce electric power, the most important condition is to provide maximum efficiency at a lower price. At present the efficiency does not exceed 24% in laboratory conditions, and 15-18% up to 20% in real conditions. Therefore, the modelling of electrical characteristics of PV cells and modules - current-voltage (I-V) and power-voltage (P-V) is important in order to determine their efficiency.

Figure 1 shows current-voltage and power-voltage characteristics of a PV cell. To evaluate effectiveness of the real PV cell, in addition to the efficiency, the fill factor (*FF*) is used which shows to what extent the real effectiveness of the cell, $U_{mp}.I_{mp}$ approximates the idealized $U_{oc}.\ I_{sc}$:

$$FF = \frac{Ump\,\mathrm{Im}\,p}{UocIsc}, \qquad (1)$$

where:

U_{mp} and I_{mp} are respectively the voltage and current at the maximum power rate point (MPP) - P_{mp};

U_{oc} is the open-circuit voltage at $R_L = \infty$;

I_{sc} is the short-circuit current at $R_L = 0$.

For the real PV cells the fill factor ranges from 0,75 to 0,85.

2. PV CELLS MODELING

2.1. Classical Single-Diode Model

The most common mathematical model employed to define the PV cell current-voltage characteristics (direct and reverse) was proposed by Bishop (1988). It is based on the equivalent circuit shown in Figure 2 [1]. The analytical expression of the model is as follows:

$$I = I_{ph} - I_s\left[\exp\left\{\frac{U + IR_s}{mU_t}\right\} - 1\right] - \frac{U + IR_s}{R_p}, \qquad (2)$$

where:

I is the PV cell current [A];

I_{ph} is the photocurrent [A];

I_s is the saturation current [A];

U is the cell voltage [V];

R_s is the series resistance [Ω];

R_p is the parallel resistance [Ω];

m is the diode factor;

U_t = kT/q is the temperature voltage [V].

Using Mathcad software package, the equation (2) can be transformed so that the PV cell current I can be calculated in the function of its voltage U and solar radiation *E* [W/m^2]:

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$$I(U,E)=\frac{\lfloor -R_sU-(A(U,E))\exp(A(U,E))mU_tR_p\rfloor}{(R_p+R_s).R_s}-\frac{[(A(U,E))\exp(A(U,E))mU_tR_s]}{(R_p+R_s)R_s}+\frac{\lfloor R_s.I_{ph}(E)R_p+R_sI_sR_p\rfloor}{(R_p+R_s)R_s}, \quad (3)$$

where:

$$A(U,E)=R_sI_sR_p\frac{\exp\left[R_p\frac{(R_s.I_{ph}(E)+R_sI_s+U}{mU_t(R_p+R_s)}\right]}{mU_t(R_p+R_s)} \quad (4)$$

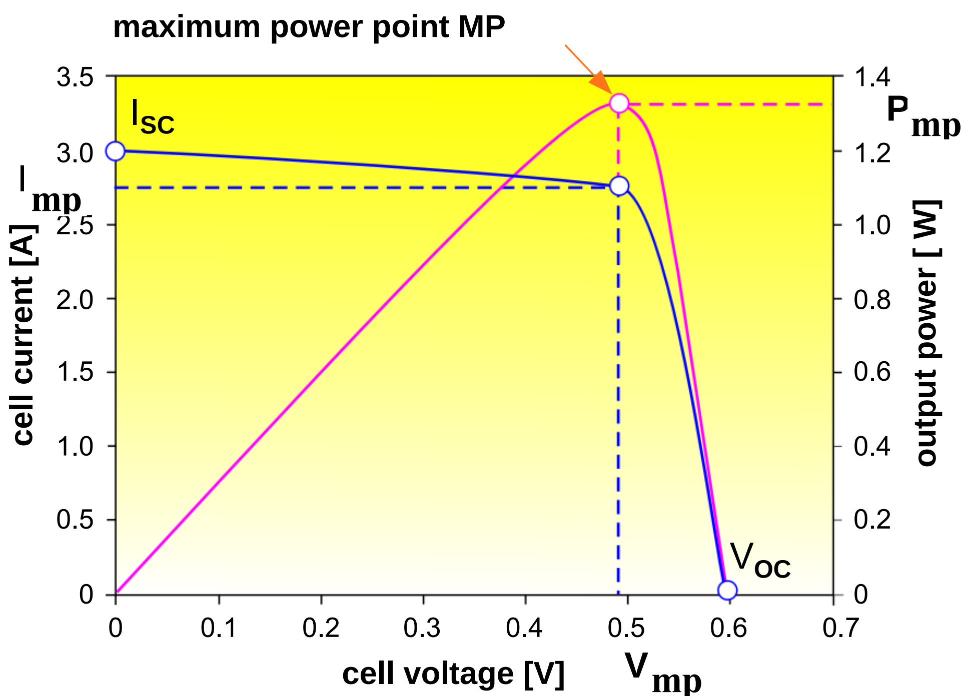

Figure 1. Current-Voltage and Power-Voltage Characteristics of a PV Cell

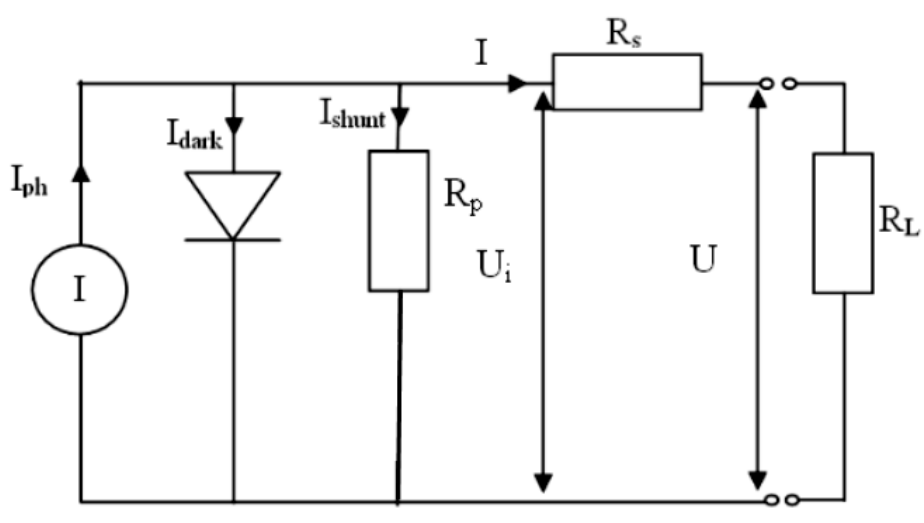

Figure 2. Equivalent circuit of the PV cell

2.2. PV Cells Modelling Results under Standard Test Conditions

The electrical characteristics of polycrystalline solar cells of type *Main Cell*, with dimensions of *125 x 125 mm* and thickness of *300 μm,* manufactured by RWE SCHOTT Solar have been modelled under standard test conditions (STC) and the following input data:

$I_{ph} = 5,13$ [A] $I_s = 1,90\cdot 10^{-10}$ [A]
$R_s = 0,012$ [Ω] $R_p = 27$ [Ω]
$U = 0, 0,005...0,617$ [V] $U_t = 25,7\cdot 10^{-3}$ [V]
m = 1.

The following values have been obtained for the major electric cell parameters during modelling: $I_{mp} = 4,87$ *[A]*, $U_{mp} = 0,471$ *[V]*, $I_{sc} = 5,13$ *[A]*, $U_{oc} = 0,53$ *[V]*, and for the fill factor - *FF = 0,85*. The graphic results from modelling are presented in Figure 3.

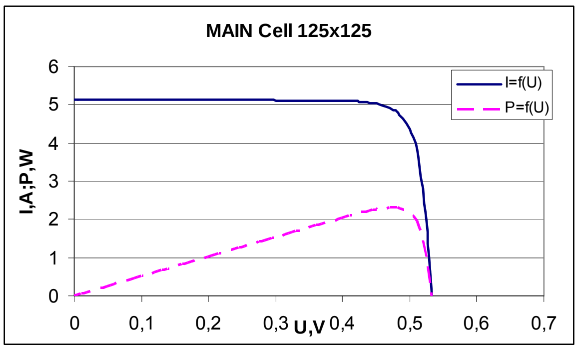

Figure 3. I-V and P-V Modelled Characteristics of 125 x 125 mm Main Cell under STC

The current-voltage characteristics of *125* x *125 mm Main Cell* from the model and STC catalogue have been shown in Figure 4 to evaluate the model used. It can be seen that the maximum difference is obtained in the area of the maximum power point, which results in insignificant increase in the fill factor FF, calculated during modelling. For the horizontal section and for the section in the proximity of the open-circuit voltage U_{oc} of the current-voltage characteristic, the accuracy does not differ from the accuracy of the characteristic and its parameters given in the company catalogue: 3% for I_{sc} and 2% for U_{oc}.

2.3. Electrical Characteristics Modelling of Shaded PV Cells

The generated current, i.e. power, respectively, is in direct relation with solar radiation. When the solar cell or part of it is shaded, its current-voltage characteristic changes [2]. This effect is described mathematically by the so called shading factor S_{sh}:

$$S_{sh} = 1 - \frac{\overline{E}}{E_0}, \tag{5}$$

where:
$\bar{E}$ is the average value of solar radiation falling on the shaded solar cell;
E_0 is the value of solar radiation falling on the non-shaded solar cell.

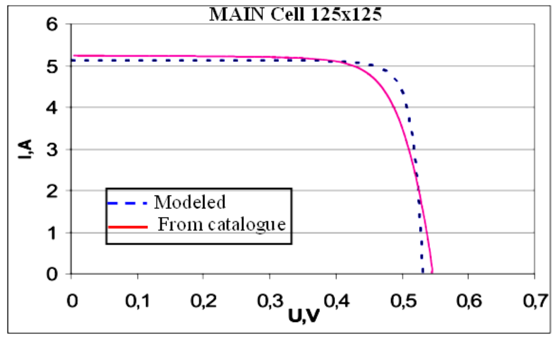

Figure 4. Comparison of Modelled characteristics to the Catalogue Current-Voltage Characteristics of 125 x 125 mm Main Cell under STC

If we assume that the photocurrent I_{ph} of the PV cell is approximately equal to its short-circuit current I_{sc}:

$$I_{sc} = I_{sc0}(1 - S_{sh}), \tag{6}$$

then, taking into account that $I_{sc0} = C_0 E$, the equality obtained for photocurrent is:

$$I_{ph} = C_0 \overline{E}, \tag{7}$$

where:
I_{sc0} is the short-circuit current of the non-shaded cell;
C_0 is the conversion coefficient [A.m^2/W].

Then taking into account the shading factor S_{sh}, the expression (3) in Mathcad takes the form:

$$I(U,S_{sh}) = \frac{\left[-R_s U - (A(U,S_{sh}))\exp(A(U,S_{sh}))mU_t R_p\right]}{(R_p + R_s)R_s} - \frac{\left[(A(U,S_{sh}))\exp(A(U,S_{sh}))mU_t R_s\right]}{(R_p + R_s).R_s} + \frac{\left[R_s I_{ph}(S_{sh})R_p + R_s I_s R_p\right]}{(R_p + R_s)R_s} \tag{8}$$

The current-voltage and power-voltage characteristics of the PV cell of type *Main Cell 125* x *125 mm* at 25^{0}C (STC) and different shading rate: 0% (STC), 20%, 40%, 60% и 80%, are shown in Figs. 5 and 6, respectively.

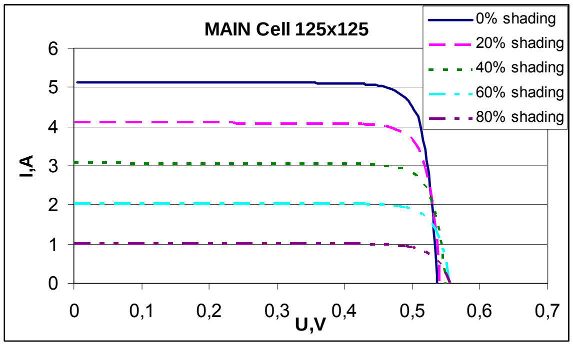

Figure 5. Modelled Current-Voltage Characteristics of 125 x 125 mm Main Cell under different shading

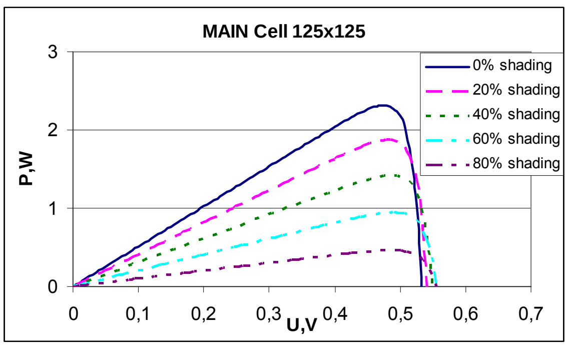

Figure 6. Modelled Power-Voltage Characteristics of 125 x 125 mm Main Cell under different shading

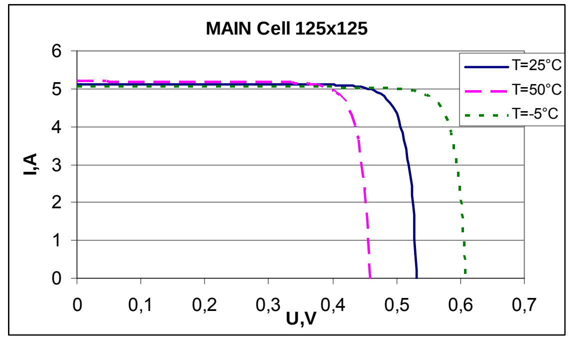

Figure 7. Modelled Current-Voltage Characteristics of 125 x 125 mm Main Cell at different temperatures

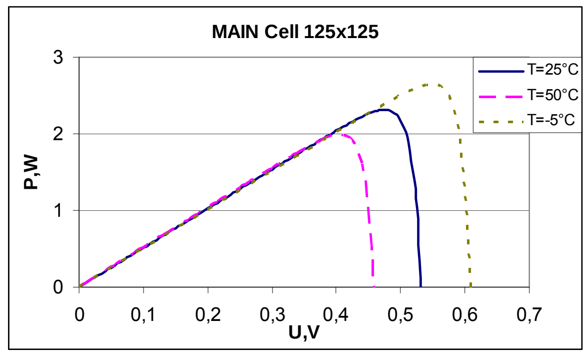

Figure 8. Modelled Power-Voltage Characteristics of 125 x 125 mm Main Cell at different temperatures

2.4. Influence of Temperature on Electrical Characteristics of PV Cells

The following relations [3] have been used to estimate the impact of temperature on PV cell electrical characteristics:

$$I_{ph,new} = I_{ph}\left[1+5{,}1010^{-4}\left(T_{new}-25\right)\right] \quad (9)$$

$$I_{s,new} = I_s \exp\left[0{,}0967\left(T_{new}-25\right)\right] \quad (10)$$

$$R_{s,new} = R_s\left[1+3{,}37\cdot10^{-3}\left(T_{new}-25\right)+9{,}71\cdot10^{-5}\left(T_{new}-25\right)^2\right] \quad (11)$$

$$R_{p,new} = \frac{R_p}{1+5{,}80\cdot10^{-3}\left(T_{new}-25\right)-1{,}61\cdot10^{-4}\left(T_{new}-25\right)^2} \quad (12)$$

Figure 7 and Figure 8 show the current-voltage and power-voltage characteristics of the PV cell of type *Main Cell 125* x *125 mm,* respectively, at various temperatures: -5^{0}C, +50^{0}C и 25^{0}C and solar radiation in compliance with STC - 1000W/m^2. The curves confirm that the temperature change is more significant in the area of the open-circuit voltage U_{oc}, which falls when temperature rises.

3. PV MODULES MODELING

3.1. Modified PV Modules Model

In order to implement the models described above, it is necessary to introduce the physical parameters of the photovoltaic cells and modules as input data; however, they are not always provided by the manufacturers. Therefore, a simplified model can be used with adequate accuracy, which needs fewer input data which are always provided by the manufacturers and are the key electrical parameters of PV cells and modules: I_{mp}, U_{mp}, I_{sc}, U_{oc}. The principal equation for this model is [4]:

$$I(U) = I_{sc}\left[1-C_3\left(\exp\left(C_4U^n\right)-1\right)\right], \quad (13)$$

where:

$$C_3 = 0{,}01175 \quad (14)$$

$$C_4 = \frac{C_6}{U_{oc}^{\ m}} \quad (15)$$

$$C_5 = \ln\left[\frac{I_{sc}(1+C_3)-I_{mp}}{C_3.I_{sc}}\right] \quad (16)$$

$$C_6 = \ln\left(\frac{1+C_3}{C_3}\right) \quad (17)$$

$$n = \frac{\ln\left(\frac{C_5}{C_6}\right)}{\ln\left(\frac{U_{mp}}{U_{oc}}\right)}. \tag{18}$$

3.2. PV Modules Modelling Results under Standard Testing Conditions

The model described is employed in studying the performance characteristics of PV module *ASE-250-DG-FT/MC*, built of 120 PV cells type *Main Cell 125* x *125 mm*, whose characteristics have been modelled above. The input data are the basic electrical parameters of the module, as follows: $I_{mp} = 4,6\ [A]$, $U_{mp} = 61,5\ [V]$, $I_{sc} = 5,15\ [A]$, $U_{oc} = 74\ [V]$.

The results obtained for current-voltage and power-voltage characteristics of *ASE-250-DG-FT/MC* PV module are presented in Figure 9 and Figure 10, respectively. The fill factor is calculated to be: *FF = 0,75*.

Figure 11 illustrates a comparison between the current-voltage characteristics of *ASE-250-DG-FT/MC* PV module, obtained, respectively, in modelling and listed in the manufacturer's catalogue. In this case, in the maximum power point area both characteristics match best.

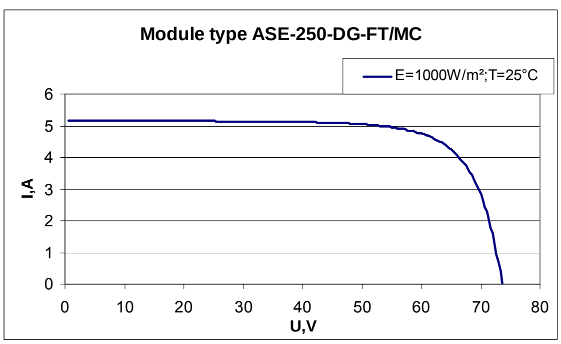

Figure 9. Modelled Current-Voltage Characteristics of ASE-250-DG-FT/MC PV Module under STC

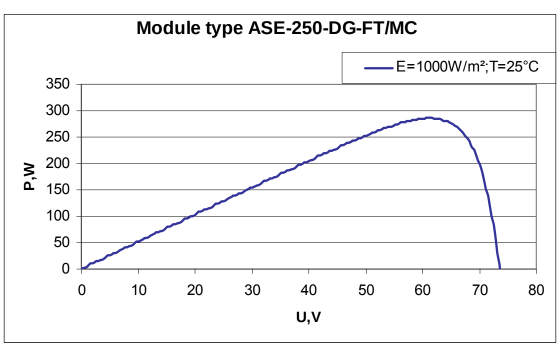

Figure 10. Modelled Power-Voltage Characteristics of ASE-250-DG-FT/MC PV Module under STC

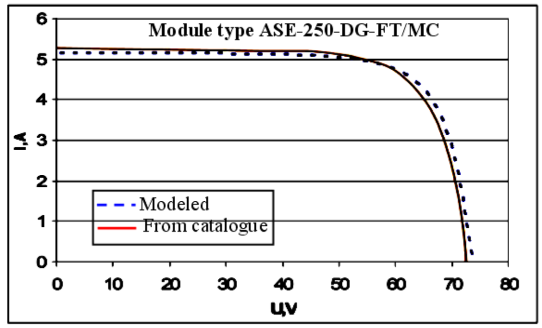

Figure 11. Comparison of Modelled characteristics to the Catalogue Current-Voltage Characteristics of ASE-250-DG-FT/MC PV Module under STC

3.3. Influence of Solar Radiation and Temperature on the Electrical Characteristics of PV Modules

The solar radiation and temperature changes in the modified model are found by way of the following relations [5]:

$$\Delta T = T - T_{ref} \tag{19}$$

$$\Delta I = \alpha\left(\frac{E}{E_{ref}}\right)\Delta T + \left(\frac{E}{E_{ref}} - 1\right)I_{sc} \tag{20}$$

$$\Delta U = -\beta\Delta T - R_s\Delta I \tag{21}$$

$$U_{new}\left(U_{ref}\right) = U_{ref} + \Delta U \tag{22}$$

$$I_{new}\left(I_{ref}\right) = I_{ref} + \Delta I\ , \tag{23}$$

where: α and β are the temperature change coefficients, respectively, of temperature T and radiation E.

These temperature coefficients for the studied module type *ASE-250-DG-FT/MC* are, α = 0,00515[A/^{0}C] and β = 0,28[V/^{0}C], and R_s = 1,5[Ω], respectively.

The effect of solar radiation on current-voltage and power-voltage characteristics of *ASE-250-DG-FT/MC* PV module is shown in Fig.12 and Figure 13, respectively. Modelling has been performed at temperature T_{ref} = 25[^{0}C] (STC), U_{ref} = 0, 0,01…62[V] and solar radiation 1000[W/m^2] (STC), 800[W/m^2] and 600[W/m^2].

The effect of temperature on current-voltage and power-voltage characteristics of *ASE-250-DG-FT/MC* PV module is shown in Figs. 14 and 15, respectively. Modelling has been performed in solar radiation E_{ref} = 1000[W/m^2], in conformity with STC, U_{ref} = 0, 0,01…62[V] at temperatures: 25[^{0}C] (STC), 70[^{0}C] and - 20[^{0}C]. In this case the effect of temperature on the characteristics in the open-circuit voltage area U_{oc} is less significant.

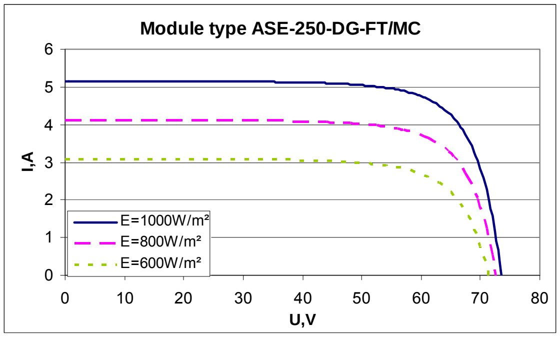

Figure 12. Modelled Current-Voltage Characteristics of Module Type ASE-250-DG-FT/MC under Different Solar Radiation

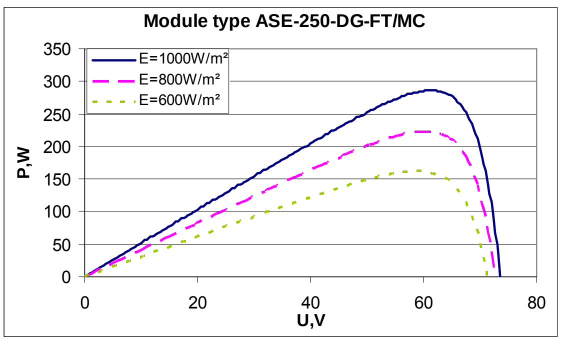

Figure 13. Modelled Power-Voltage Characteristics of Module Type ASE-250-DG-FT/MC under Different Solar Radiation

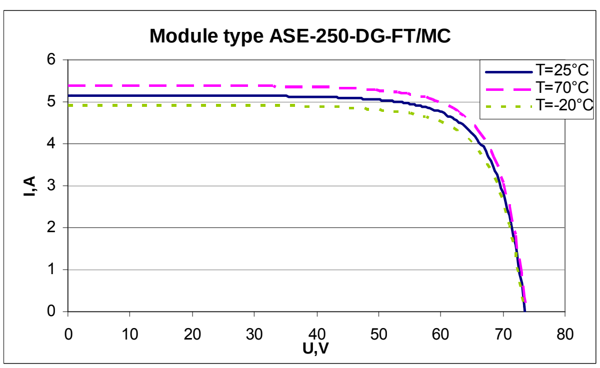

Figure 14. Modelled Current-Voltage Characteristics of Module Type ASE-250-DG-FT/MC at Different Temperatures

3.4. Comparison of Modelled and Measured Electrical Characteristics of PV Modules

A comparison between experimentally taken and modelled current-voltage and power-voltage characteristics of the solar module IBC80 can be made on the basis of Figs. 16 and 17, respectively.

The ratings of the IBC80 module of the stand-alone PV system operating in the Technical University of Gabrovo are as follows: P_{nom} = 80,0 [W], I_{sc} = 5,08 [A], U_{oc} = 21,0 [V], I_{mp} = 4,71 [A], U_{mp} = 17,0 [V]. The calculated fill factor for IBC80 module is 0,75. The greater difference between the measured and modelled characteristics is due to the fact that measurements have been taken in real outdoor conditions, where solar radiation and temperature cannot be kept constant, corresponding to STC.

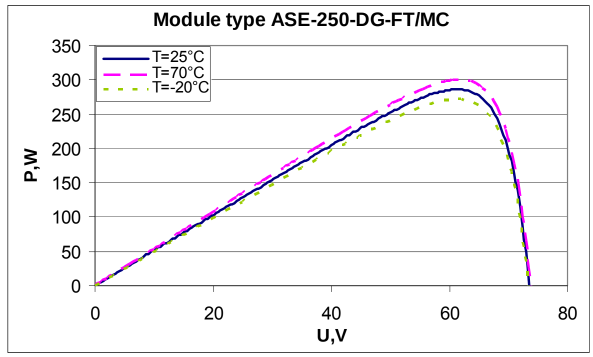

Figure 15. Modelled Power-Voltage Characteristics of Module Type ASE-250-DG-FT/MC at Different Temperatures

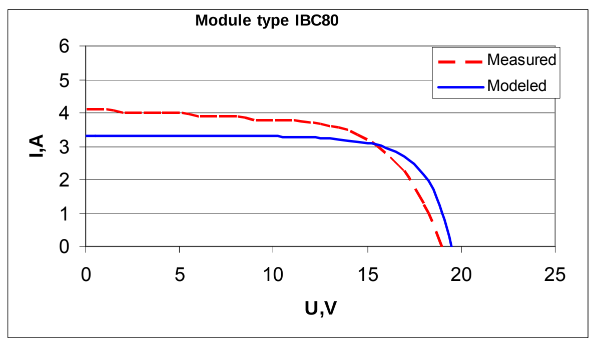

Figure 16. Modelled and Measured Current-Voltage Characteristics of IBC80 module type

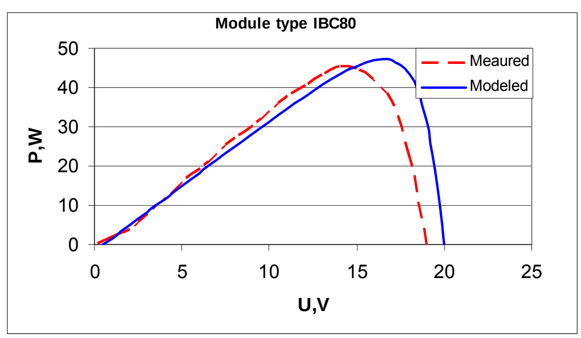

Figure 17. Modelled and Measured Power-Voltage Characteristics of IBC80 module type

4. CONCLUSION

The employment of classical and modified single-diode models for modelling the electrical characteristics of PV cells and PV modules, respectively, has been shown. Modelling has been performed both under standard test conditions, and with changes in temperature, solar radiation and shading. The model characteristics obtained reflect exactly the effect of these parameters. When the classical single-diode model was used a larger inaccuracy appears in the maximum power point area, than when using the modified one. The key electrical parameters of the PV cells studied, as well as the fill factor of the PV cells and PV modules modelled have been determined.

5. REFERENCES

[1] F. Iannone, G. Noviello, A. Sarno, *Monte Carlo Techniques to Analyse the Electrical Mismatch Losses in Large-Scale Photovoltaic Generators,* Solar Energy, 62 (1998) 85−92.

[2] Q. Folker, R. Hanitsch, *Numerical Simulation of Current-Voltage Characteristics of Photovoltaic Systems with Shaded Solar Cells,* Solar Energy, 56−6 (1996) 513−520.

[3] Ts. Izumi, K. Nozaki, K. Sakuta, T. Oshiro, K. Korukawa, *Simulation Results of Stand-Alone PV System under Various Load Conditions,* 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion (6-9 July), Viena, Austria 1998.

[4] M. S. Ziyada, B. Borowy, A. Amin, *Photovoltaic Module-Site Matching Based on the Capacity Factor,* IEEE Transactions on Energy Conversion, 10−2 (1995) 326−332.

[5] R. Lamoureux, D. Sadarnak, N. Buchheit, *Estimated Energy Gain Provided by an MPPT to Stand-Alone Photovoltaic System*, 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion (6-9 July), Vienna, Austria 1998.

МОДЕЛОВАЊЕ ЕЛЕКТРИЧНИХ КАРАКТЕРИСТИКА ФОТОНАПОНСКИХ НАПАЈАЊА ИЗВОРА

Сажетак: Фотонапонски (ФН) генератори главни су елемент ФН електросистема; карактерише их низак коефицијент конверзије. Ово оправдава потребу за изучавањем струјно-напонских и снага-напонске карактеристике ФН извора како би се добила максимална излазна снага када дође до промјена и у самим модулима и у окружењу у којем раде. У овом раду коришћени су класични и модификовани модели са једном диодом за моделовање електричних карактеристика ФН ћелија и модула. За моделовање је коришћен Mathcad софтверски пакет. Изучавани су утицај сунчевог зрачења, температуре и засјењавања на електричне карактеристике и на ефикасност ФН ћелија и модула.

Кључне ријечи: електричне карактеристике, модел са једном диодом, моделовање, ефикасност.