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Enhanced Photovoltaic Panel Model

for MATLAB-Simulink Environment Considering Solar Cell Junction Capacitance

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***Abstract*—Maximal energy harvesting of photovoltaic panels is possible only if the load of photovoltaic cell is consuming current that corresponds to the maximal power point for condition combination on a certain moment. Correct and detailed mathematical modeling of photovoltaic panels is able to help to develop control techniques for maximum power point tracking converters. In order to overcome the disadvantages of Simscape solar cell block, a model of photovoltaic cell has been developed during the research on photovoltaic energy sources. Equations that are used for control of equivalent scheme of photovoltaic cell, comparison of the proposed model to the model represented in Matlab 2009 Simscape library and modeling description parameter estimation have been done. The comparison of models is represented in a steady state I-V curve characteristics that are compared to the experimental data obtained with a real photovoltaic panel. The proposed model showed results that are closer to the experimental data than the ones presented by Simscape library model. The performance of models in dynamic processes was not verified, but significant differences in behavior of the models have been ascertained.**

***Keywords*— Modeling, Simulation, Matlab, Simulink, Simscape, Photovoltaic cell, Measurements**

I. INTRODUCTION

Solar energy conversion to electrical energy is one of the prospective energy sources due to its continuous incoming to Earth. Solar energy can be harvested in many ways; most popular nowadays is the use of photovoltaic cells. Use of small-power-rate solar-cells is very popular for small portable applications, but development of technology is making it possible to construct solar power plants of hundreds of kilowatts and this kind of energy sources are becoming more popular. The advantages of this kind of energy source are that it is renewable and it produces zero emissions to the atmosphere. This makes photovoltaics a good energy source for lighting systems [1] and renewable energy systems with hydrogen buffer [2], [3]. One of the most significant disadvantages of photovoltaic panels is the need for special energy converters or maximum power point tracking (MPPT) converters that are able to provide maximum energy yield, because of the non-linear V-I curve of the photovoltaic cell [4]

Modern virtual modeling software is able to provide cost-effective, fast and precise process modeling converters. Therefore the development of modern converters is closely related to the simulation software. Matlab is one of the most popular modeling and computational software packages in the world and this paper is related to the development of SimPowerSystems-based models of photovoltaic panels that are able to provide detailed prediction of the photovoltaic cell behavior under different conditions.

Matlab has Simscape block library that contains a model of the photovoltaic cell that in combination with other blocks of this kind can be interconnected according to the photovoltaic panel`s circuit structure. The model of the photovoltaic panel composed in this way considers the external conditions like solar irradiance and temperature, which have strong effects on the V-I curve and available maximum energy yield. Larger discussions on this topic are represented in [5], [6], [7]. As the less popular SimScape package library`s block has different signal coupling system than more popular Simulink and SimPowerSystems, the use of the mentioned photovoltaic cell is related to the compatibility solutions and therefore there is need for SimPowerSystems based model that has the same or maybe larger number of parameters and is closer to the real photovoltaic cells. The Matlab simulation models in [8] and [9] are close to the model proposed in this paper, but have no PN-junction capacitance that has a place in real world, a less precise model implemented in Simulink is described in [10]. In [11] authors are controlling photovoltaic cell using Matlab CMEX S-function. This can increase the correspondence of VI curves to the real world and make the development of the control system of the MPPT-converters more precise when the simulation codes get transferred to the control microprocessors and ICs. For example Simulink model in [4] can be considered acceptable but incomplete for precise simulation of PV-panel and MPPT technique because of few scheme parameters.

One of the main advantages of the proposed model is the absence of the coupling subsystems between the Simscape blocks and Simulink blocks (same as in the [9], [10], [11]), which are taking the calculation capacity of the computer and introducing inaccuracies in the calculations as well as possible convergence problems and other errors during simulation of different circuits.

II. CLASSIC PHOTOVOLTAIC CELL MODEL

The classic model of the photovoltaic cell consists of a diode (Fig. 1.) with anode on the positive pole side and cathode on the negative. The light-generated current is represented by a current source (I_L in Fig. 1.). The value of the current generated by this source is strongly related to the irradiation level. Classic photovoltaic cell model is shown in Fig.1.

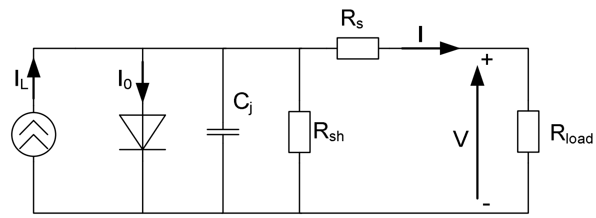

Fig. 1. Classic PV-cell model based on the current source and one diode

The model of the cell also contains the series and the shunt resistances that strongly impact the V-I curves and efficiency of the panel (or single cell). In order to improve the precision of the model during static, dynamic and transient processes PN-junction capacitance must be added (C_j in Fig.1).

The current of the cell is expressed in equation (1) [12]:

$$I = I_L - I_0\left[\exp\left(\frac{(V + IR_s)q}{nk_BT}\right) - 1\right] - \frac{V - IR_s}{R_{sh}}, \qquad (1)$$

where I stands for output current, I_L is light-generated current and is equal to the I_{SC} short-circuit current of the cell, I_0 stands for the diode saturation current (the diode leakage current density in the absence of light), V is the voltage of the photovoltaic cell, R_s and R_{sh} are series and shunt resistances of the model, q is the charge of electron (equal to 1.6×10-19), k_B is Boltzmann`s constant (1.38×10-23), n is the diode quality factor, that was found by method of selection (calculation of the parameters to fit the maximum power of the panel at nominal conditions), T is the temperature of the cell in Kelvin scale.

The diode saturation current can be calculated by equation (2) (V_{OC} is cell`s open circuit voltage):

$$I_0 = \frac{I_L}{\exp\left(\frac{V_{OC}q}{nk_BT}\right)} \qquad (2)$$

The photovoltaic cell can also be described as the function of voltage. In this case the equation expressing V-I curve is shown in (3) [13].

$$V = \frac{nk_BT}{q}\ln\left(\frac{I_L - I}{I_0}\right) - IR_s \qquad (3)$$

This makes possible the compositon of voltage-source-based model, but a significant disadvantage of this kind of mathematical approach is if for some reason the natural logarithm argument gets a zero or becomes negative, the solution of equation is (invalid for this case) a complex number. The model based on the equation (3) is not fail-safe for differential equation solvers used in the modeling software like Matlab.

III. SIMSCAPE MATLAB PV-CELL MODEL

Matlab has Simscape library of SPICE compatible blocks. The main disadvantage of these models including the solar cell model is their relatively complicated integration in the simulations with blocks of widely used Simulink and SimPowerSystems libraries. Matlab 2009 SimScape model of the solar cell has 3 variants of model structure. One of the model variants considers model parameterization through data available from datasheets (data like short-circuit current, open circuit voltage etc.) and is based on a single diode model (Fig. 1). This way of modeling the photovoltaic cell is chosen due to the availability of non-specific parameters like dark saturation current etc. Scientific papers [15] and [16] describe research on photovoltaics with Simscape models. The imprecision of simulation comparing to the experimental results in [16] can be explained by the absence of voltage change coefficient in the Simscape solar cell model. The authors explained it as a difference of the real illumination to the measured one.

IV. THE PROPOSED PHOTOVOLTAIC CELL MODEL

The advantage of the proposed model is is the inclusion of significant voltage change coefficient to the temperature and an included PV-panel capacitance. The proposed model is composed of the SimPowerSystems blocks in contradistinction to Simscape model. Equation (2) is used to control the current source of the photovoltaic model current source shown in Fig. 2. Element Ro (on Fig. 4) is the output resistance of PV-cell model that helps to avoid convergence problems at low load and open-circuit simulations. The value of Ro is 1 MΩ.

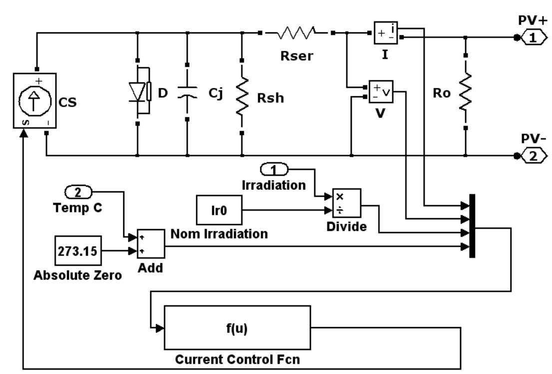

Fig. 2. Proposed model of PV-cell based on the equivalent circuit and composed of SimPowerSystems and Simulink blocks

The model composed for this article has a reference of voltage and current (Fig. 2) in order to control output characteristics of the model. The model considers the change of V-I curve in respect to the temperature (Simscape model has only current change ratio in respect to the temperature).

Both proposed and Simscape models are composed of 32 photovoltaic cell models connected in series and divided to two sub-strings reflecting the circuit diagram of a real PV-panel SPR-90-WHT-I produced by SunPower Corporation.

V. Estimation of Photovolataic Panel Parameters

The estimation of correct parameters is very important for proper modeling of the photovoltaic cell as there is a large number of factors that have strong influence on the performance. The experimental data for model verification was estimated using SPR-90WHT-I solar panel. The 90Wphotovoltaic panel has the following parameters available on datasheet and listed in Table1.

TABLE I. Parameters of the PV-panel

Parameter Description	***Abbreviation***	***Value***
Maximum Power at 1000W/m^2 and 25ºC, AM1.5 (W)	P_{MPP}	90
Open Circuit Voltage (V)	V_{OC}	21.2
Short Circuit Current (A)	I_{SC}	5.5
Maximum Power Voltage (V)	V_{MPP}	17.7
Maximum Power Current (A)	I_{MPP}	5.1
Voltage change by temperature increase (mV/ºC)		-60.8
Current change by temperature increase (mV/ºC)		2.2

Datasheets provided by PV-panel producers contain most of the significant parameters, but not enough to implement the model that corresponds to a real photovoltaic panel. For this reason the values of series resistance, shunt resistance and PN-junction capacitance should be found experimentally. Classic photovoltaic cell model is shown in Fig.1. [12]. A series of 7 experiments was done for the estimation of parameter: two with no shading, two times with shading by large plastic mesh, one with a small plastic mesh and two with both of meshes.

A. Series Resistance Estimation

Series resistance can be found by dividing the voltage drop on the photovoltaic panel terminals by the current that flows through the PV panel during transient state of load connection by step-function of one of the measurements done during the research. The voltage drop on internal series resistance is the difference between open circuit voltage (V_{OC}=19.2 V, watch Fig. 3) and voltage after connecting to load (V_{1R}=14.5 V). The current in the beginning of transient is equal to 6.24 A(I_1) [13].

$$R_s = \frac{V_{OC} - V_{1R}}{I_1} = \frac{19.2 - 16.9}{7.16} = 0.321\Omega \tag{4}$$

Fig. 4 shows the oscillogram with a graphic illustration of equation (4). Open circuit voltage in the example equation is different from the nominal, because the test was done in conditions different from the nominal (different temperature, the panel was evenly shadowed by a plastic mesh during several of 7 tests).

A series of 7 experiments under different lighting conditions were done for series resistance estimation. The average value of results (0.321 Ω, 0.323 Ω, 0.345 Ω, 0.319 Ω, 0.298 Ω, 0.318 Ω, 0.318 Ω) is 0.321Ω.

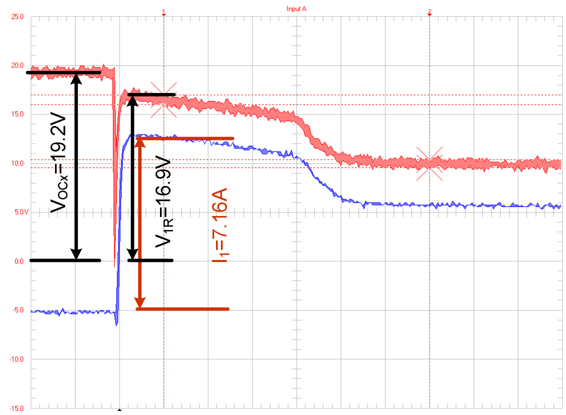

Fig. 3. Transient of the PV-panel current and voltage (illustration of series resistance calculation)

The series resistance of photovoltaic panel can also be estimated by calculating voltage and current differences at maximum power points for different irradiation levels and then by investigating the slopes of voltage and current regions of I-V curve.

B. Shunt Resistance Estimation

Shunt resistance for the simulations was calculated from datasheet values analytically. Paper [14] contains a formula for the estimation of shunt resistance.

The shunt resistance value calculated according to [14] is equal to 4.5 Ω for each cell with diode ideality factor of 1.45.

C. PN-Junction Capacitance Estimation

Voltage on the terminals of the panel remains at almost the same value after the instantaneous load connection for 188 microseconds (Δt). This can be explained by PN-junction capacitance that is keeping the voltage at almost the same level and after discharge of the inner capacitance the voltage drops to the load steady-state value (the difference of voltages ΔV in (5)).

The capacitance of the photovoltaic panel can be calculated by equation (5) [13].

$$C_j = \frac{\Delta t \cdot I_{C\_a}}{\Delta V} \tag{5}$$

where C_j is PV-panel capacitance, I_{C_a} is mean current that will flow through capacitor during transient. Fig. 4. shows the same transient process with illustrations for photovoltaic panel capacitance estimation. Values illustrated in Fig. 3. are not mentioned. The voltage of the PN-junction capacitor in the moment of output voltage V_{1R} is assumed equal to the open-circuit voltage. For more precise calculation the value of capacitor voltage can be calculated in the same manner as the V_{2C}.

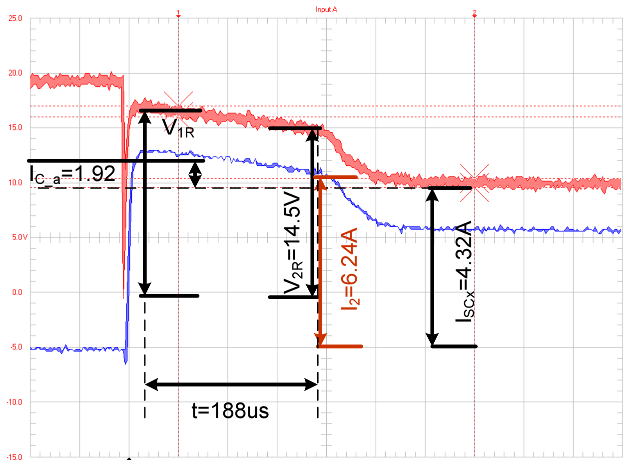

Fig. 4. Transient of the PV-panel current and voltage(illustration of PN-junction calculation)

The voltage of PN-junction capacitance (V_{2C}) in time of I_2 and V_{2R} is equal to (watch Fig. 4) (6).

$$V_{2C} = V_{2R} + I_2 R_S = 14.5 + 6.24 \cdot 0.32 = 16.5V \tag{6}$$

The capacitance of the photovoltaic panel can be estimated in following way:

$$\Delta V = V_{OCx} - V_{2C} = 19.2V - 16.5V = 2.7V \tag{7}$$

$$I_{C\_a} = I_a - I_{SCx} = \frac{7.16 + 6.24}{2} A - 4.32A = 2.38A \tag{8}$$

$$C_j = \frac{188 \cdot 10^{-6} \cdot 2.38}{2.7} = 165.7 \mu F \tag{9}$$

where ΔV is voltage difference between steady-state charged PN-junction capacitance C_j and voltage of almost discharged PN-junction capacitance. The average value of estimated capacitance in 7 experiments (166 µF, 162.9 µF, 145.5 µF, 151.5 µF, 154 µF, 194.6 µF, 177.5 µF) is equal to 164.6 µF. The dependence between solar irradiation and capacitance should be investigated in order to implement more precise model.

VI. Comparison of Photovoltaic Simscape and Proposed Panel Models

I-V curves for experimental data got estimated in the territory of The Power and Electrical Engineering Faculty of Riga Technical University. The photovoltaic panel was set to the optimal angle and corrected in respect to sun position. Electronic load in constant current mode was used for the V-I curve estimation. Two kinds of plastering meshes were used to get V-I curve at different irradiation levels. First V-I curve were obtained at direct sunlight. Two measurements were done with meshes (of different thread densities) set at the distance of 25 cm from the panel in the way shadowing of the panel was even. The last V-I characteristic was done with both plastering meshes set one over other. Due to the absence of a device which is able to measure irradiance in W/m^2 the irradiance was calculated from the short-circuit current in relation to the test-condition irradiance and short-circuit current. The experimental results were compared with the proposed model and the model based on the Simscape solar cell model block in Figures 5 to 8. The experimental data obtained during the test is shown in Fig.5-8 as green curve with circles, proposed model`s curve is shown as solid red and Simscape model as dashed blue line.

The parameters of panels for Simscape and the proposed Simulink model are absolutely the same. The parameters used for simulations are the same as in Table I and estimated in the chapter "V. Estimation of Photovoltaic Panel Parameters" (except junction capacitance applied only to the proposed model).

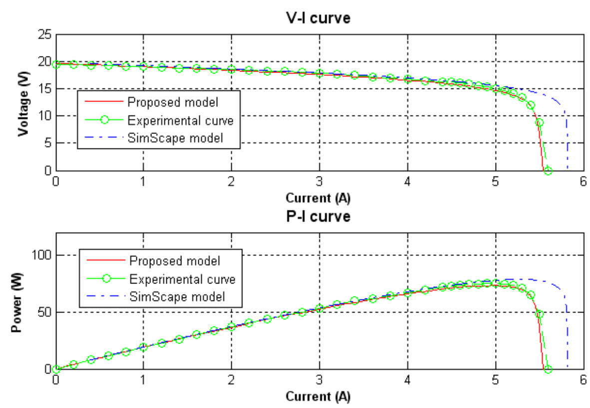

Fig. 5. Comparison of PV-panel`s experemental, proposed model`s and constructed of Simscape blocks model`s I-V and P-V curves with irradiation 1000 W/m^2, and temperature of 51ºC

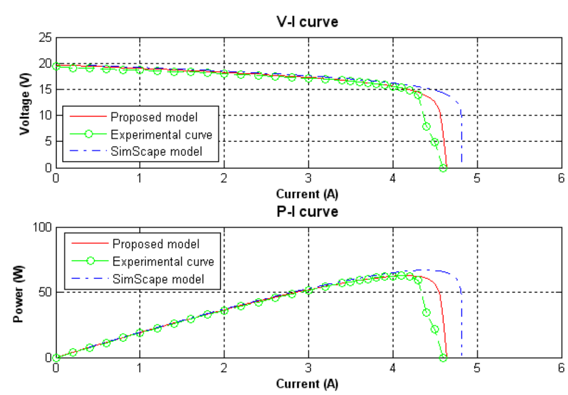

Fig. 6. Comparison of PV-panel`s experemental, proposed model`s and constructed of Simscape blocks model`s I-V and P-V curves with irradiation 838 W/m^2, and temperature of 46ºC

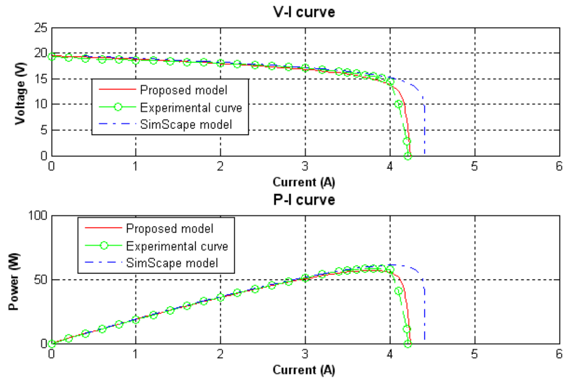

Fig. 7. Comparison of PV-panel`s experimental, proposed model`s and constructed of Simscape blocks model`s I-V and P-V curves with irradiation 765 W/m^2 and temperature of 47ºC

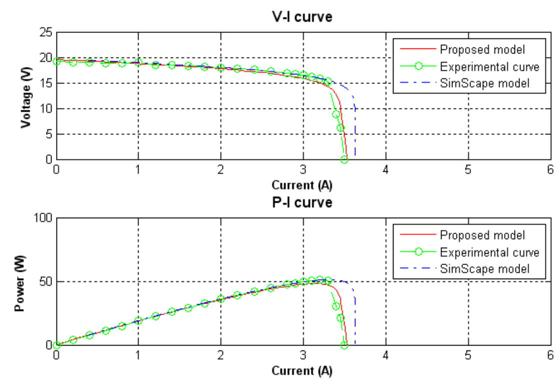

Fig. 8. Comparison of PV-panel`s experimental, proposed model`s and constructed of Simscape blocks model`s I-V and P-V curves with irradiation 636 W/m^2 and temperature of 42ºC

As follows from the illustrations above, the proposed model is a little bit closer to the experimental V-I curve than Simscape model variant at modeled conditions and using the same parameters of the PV-panel model.

VII. Photovoltaic Panel Model Performance in Combination With Switching Converters

A model with included PN-junction capacitance is able to provide more precise and closer to the reality simulations of transient processes. The PV-panel voltage ripple and offset from the maximum power point can take place during transient and steady-states with constant current waveform, especially if output current of the panel is discontinuous (for example classic buck converter and buck-boost converter). A simulation with PN-junction capacitance is able to decrease voltage ripple and predict processes related to the photovoltaic cells before they get tested on real application. A correct simulation is very important for maximum power point tracking control design. Fig. 9 and Fig. 10 show the difference of simulated input voltage and current of a buck converter for Simscape and SimPowerSystems based simulations. Both simulations of dynamic processes have the same buck converter working with the same duty ratio and the load is a resistances with the same value. The buck converter is modeled with SimPowerSystems simulation blocks and connected to the Simscape-based PV-panel model via a special coupling subsystem.

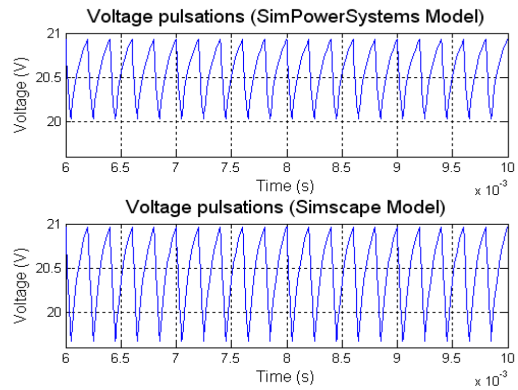

Fig. 9. Voltage pulsation comparison for SimPowerSystems based model and Simscape based model.

As seen from the Fig. 9 and Fig. 10 behavior of the models is different. The simulation with the Simscape-based PV-panel model and the proposed one has approximately same mean current. Smaller voltage pulsations and a little bit higher current pulsations in the proposed model can be explained by the presence of PN-junction capacitance that provides better voltage filtration because of R-C circuit of PN-junction capacitance and series resistance of the panel. These pulsation levels are significant in case of selection of the filtering elements for the design.

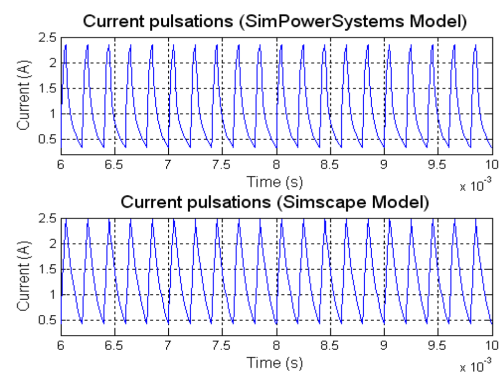

Fig. 10. Current pulsation comparison for SimPowerSystems based model and Simscape based model

The dynamics of the models and performance of the steady-state for switching converters should be verified in future research.

As follows from the experience of using the Simscape model, its weak place is current-temperature coefficient that makes significant shift of the V-I curve.

One more significant difference can be found if comparing the calculation speed of the models based on the different libraries. As the Simscape model is represented by block with debugged encapsulated code the performance of Simscape based model was higher. The simulation of the same time value takes in average about 38 seconds using ode23t (mod. stiff/Trapezoidal) solver. In contrast a simulation of SimPowerSystems based model (with the same structure except Simscape to SimPowerSystems coupling subsystem) takes up to 500 seconds. SimPowerSystems based model is constructed of common library blocks of capacitors, controlled current sources, etc. Simulation time test was done on a PC, using Matlab 2009. Other solvers showed smaller difference between the calculation times, but both of the models showed too slow speed to consider them as recommended for use.

This means that more precise simulation takes more time and must be run on computers with high calculation speed. Another solution is composing SimPowerSystem code-based block (for example embedded Matlab function, C-code S-functions) and debugging it for calculation speed increase and to avoid convergence errors.

VIII. Conclusions

In this work a photovoltaic cell model is composed for more precise simulation of PV-panels. Experimental I-V curve of the panel was compared to the steady current-voltage characteristics of the proposed Simulink based model and a model based on the Simscape solar cell model. Both models are able to simulate performance of PV-panels at different temperatures and irradiance conditions. Both models are using parameters that can be found in producer's datasheets except the series and shunt resistances that must be estimated experimentally and/or analytically. I-V curve of the proposed model is closer to the experimental data than the solar-cell block that can be found in the library. A test of models during dynamic processes showed difference in voltage and current pulsation levels. This is explained by ht addition of PN-junction capacitance in the model that has strong effect on the behavior of the model. Verification of the model performance must be done experimentally in the future.

Simulations with models in combination with switching converters shows that the speed performance of the Simscape based model is much better using only one of the solvers available in Matlab2009, while both of the models are slow if other solvers are used.

The topics of future research and tasks:

- Verify the behavior of the PV-panel loaded with a switching converter
- Optimize the photovoltaic cell model
- Improve, systemize and compare photovoltaic panel parameter estimation methods
- Make more precise model that considers junction capacitance variation by the change of conditions

IX. Acknowledgements

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