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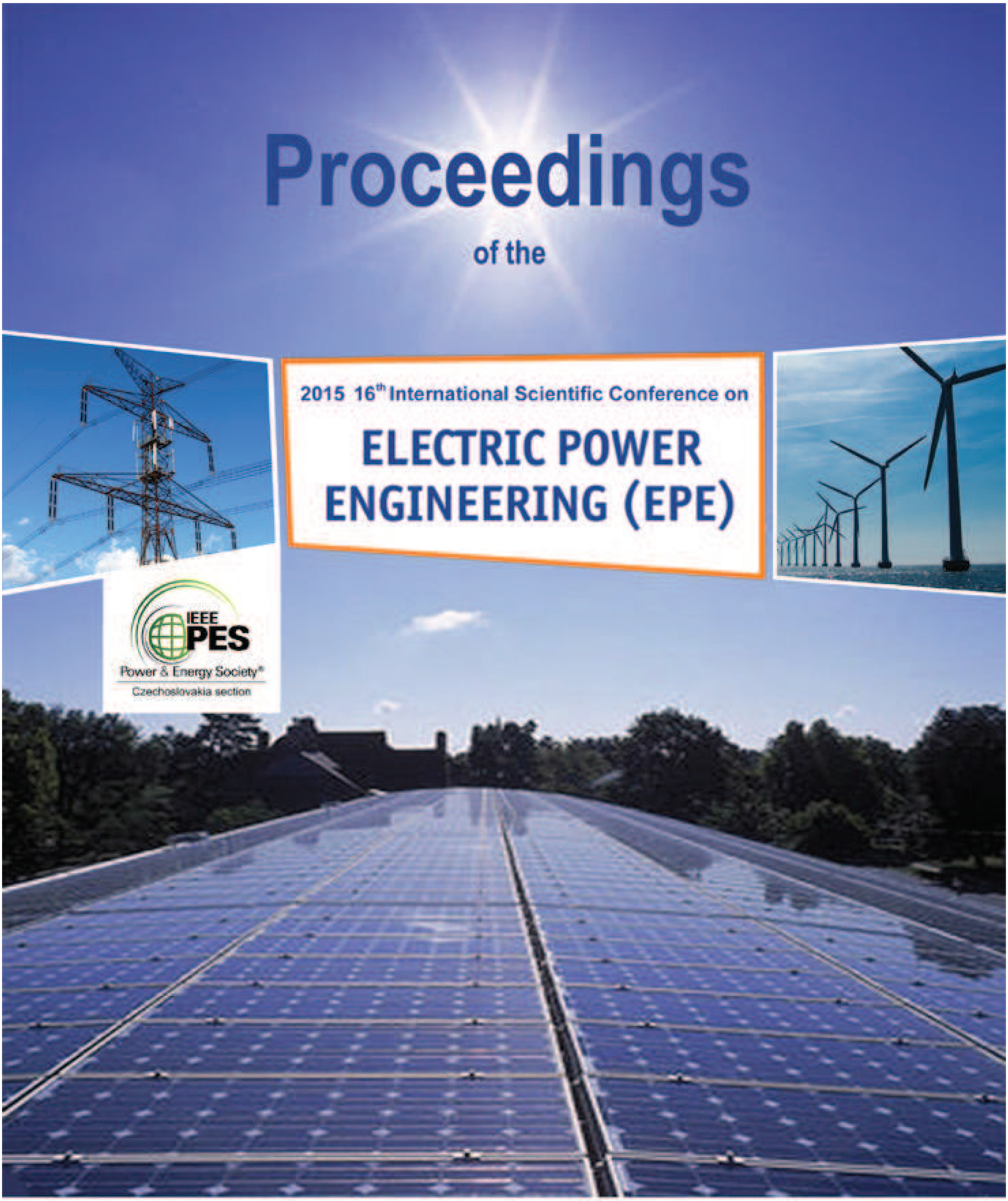

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EPE 2015

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Modeling of a DC boost converter behavior in PV system using finite state machines

Martina Látková, Peter Braciník, Michal Baherník, Filip Suško
Department of Power Electrical Systems
Faculty of Electrical Engineering, University of Žilina
Žilina, Slovak Republic
martina.latkova@kves.uniza.sk

***Abstract*— This paper presents an approach to the modeling of a DC boost converter used in a small photovoltaic system, whose operation is controlled by the maximum power point tracking controller. The presented simulation model is capable of representing converter's dynamic operation during the changes of solar irradiance as well as speeding-up the simulation during a steady state converter's operation, when there is no change of solar irradiance. In order to achieve this functionality, a finite state machines model of the photovoltaic system was created. Used mathematical formulas and simulation results showing model's functionality are presented as well.**

Keywords— photovoltaic, DC boost converter, finite state machines, dynamic modeling, MPPT

I. Introduction

The directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources has put EU member states under an obligation to increase the amount of electricity produced in renewable energy sources (RES). Due to the fact that an electricity generation in some types of RES is quite intermittent, it is necessary to study their influence on power system operation at all voltage levels. Unfortunately, most of these studies are oriented only on the analysis and definition of how many uncontrolled RESs could be added to existing power systems without harming its reliable and secure operation. Therefore meeting goals defined by the directive 2009/28/EC usually means to calculate how much power of conventional energy sources can be spent on auxiliary services, from technical as well as economic point of view, in order to eliminate negative influences of RES operation on power system.

Moreover, it seems that there is no will to take RESs as normal energy sources, which can control their generated output and can cooperate with other sources, conventional or renewable ones, on the covering of local demand. If we assume that the future development of electric networks will lead to the application of the Smart Grid concept, where the local demand should be covered by distributed generation, partially also covered by RESs, it is necessary to study the operation of RES from the longer period point of view and with respect to their future ways of operation, when they will have to cooperate with the network and other sources with different dynamics. Therefore it seems to be very useful to create such simulation models that will be able to represent RESs' steady state as well as dynamic operation correctly and to switch between these two simulation modes whenever it is needed during the simulation.

Because the biggest part of the required RES installed capacity in Slovak Republic is covered by photovoltaic (PV) power plants (537 MWp), not counting big hydro power plants, the authors have decided to focus on the creation of a simulation model with above mentioned capabilities for PV systems. As the model should represent different operation states of PV systems, the decision was made to use finite state machines for modeling [1]. Such approach was already tried by [2] and [3]. The next text will present partial results achieved by authors in this field.

II. Finite State Machines

Finite state machines are used to model system behavior in many types of engineering applications. Intuitively, a state of a system is its condition at a particular point in time. A state machine is a system whose outputs depend not only on the current inputs, but also on the current state of the system. A finite state machine (FSM) is a state machine where the set of possible states is finite. A graphical notation for FSMs can be drawn like in Fig. 1 [1], [4].

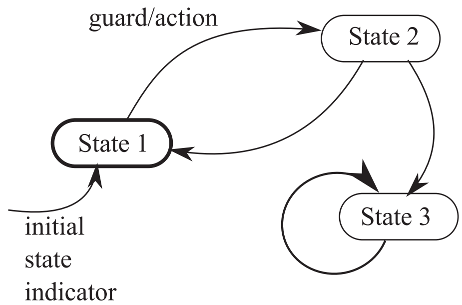

Fig. 1. A graphical notation for FSM.

The transitions between states are represented as a curved arrow (Fig. 1), going from one state to another. Transition may also start and end at the same state (*State 3*) and then it is called a self-transition. Transition is governed by the rule set in a guard. The guard determines whether the transition may be taken on a reaction. The guard is a boolean-valued expression

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that evaluates to true when the transition should be taken, changing the state from that at the beginning of the transition to that at the end [1].

III. FSM Model of a DC Boost Converter

Typically, photovoltaic systems employ a DC boost converter, which is a class of switching power regulator that provides operation of a PV array in its maximum power point (MPP) even during variation of solar irradiance and temperature [5].

A. Mathematical Model of a DC Boost Converter with MPP tracking controller

A topology of the ideal DC boost converter loaded by resistive load is shown in Fig. 2. The converter operates in continuous conduction mode (CCM) and it works in two modes of operation, which are given by the operation state of the switch. The output variables are inductor current i_L and the capacitor voltage v_C [3], [5].

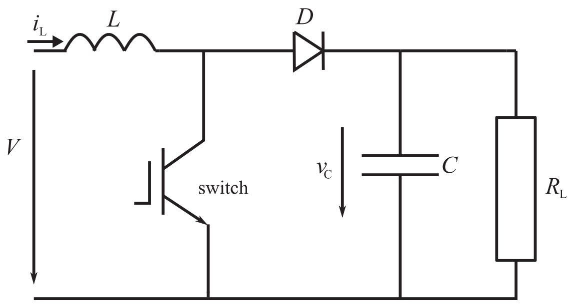

Fig. 2. Topology of a DC boost converter.

When the switch is ON (closed), the inductor stores the energy from the PV array and the load is supplied only by the energy stored in the capacitor (Fig. 3) [6].

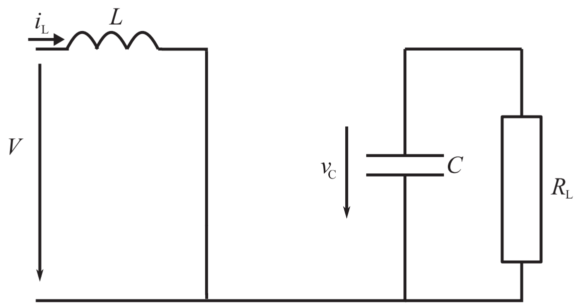

Fig. 3. ON operation mode of a converter.

This state can be described by following differential equations [6]:

$$V = L \cdot \frac{di_L}{dt}, \tag{4}$$

$$\frac{v_C}{R_L} = -C \cdot \frac{dv_C}{dt}. \tag{5}$$

When the switch is OFF (open), the inductor current flows to the load and the stored energy of the inductor is transferred to the capacitor and the load (Fig. 4) [6].

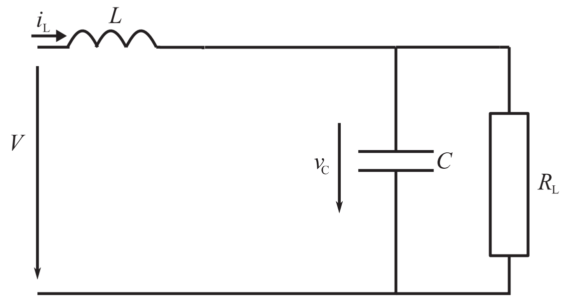

Fig. 4. OFF operation mode of a converter.

This state can be described by following differential equations [6]:

$$V = L \cdot \frac{di_L}{dt} + v_C, \tag{6}$$

$$i_L = C \cdot \frac{dv_C}{dt} + \frac{v_C}{R_L}. \tag{7}$$

Time when the converter is in ON or OFF state is defined by the duty cycle D of the converter. Duty cycle represents the fraction of the commutation period during which the switch is ON. Therefore D ranges between 0 (switch is never ON) and 1 (switch is always ON).

The switch of a DC boost converter is controlled by a maximum power point tracking (MPPT) controller to achieve the maximum power point of a PV array. The controller changes duty cycle D of the converter to achieve a voltage at the maximum power point and so the maximum power [7].

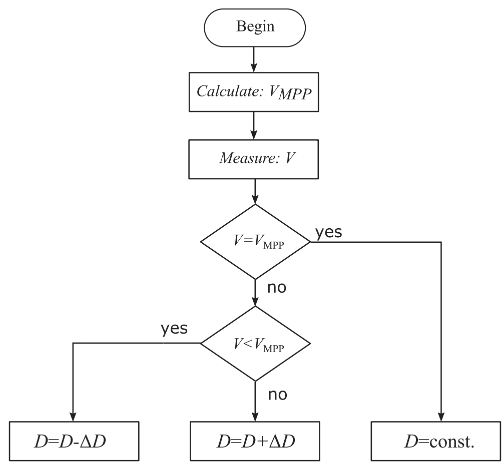

Fig. 5. Flowchart of the constant voltage method.

There are many methods for the MPPT, such as perturb and observe method, incremental conductance method or constant voltage, etc. A constant voltage method was chosen for the use in our model, due to its simple implementation and ability to find the point of maximum power very fast. The constant voltage algorithm is based on an assumption that the ratio of the array's maximum power voltage V_{MPP} to its open-circuit voltage V_{OC} is approximately constant. This ratio has been empirically determined between 70 and 80 % [7].

The controller firstly calculates the open-circuit voltage and 80 % of its value (in our case) and this value is set as V_{MPP}. Then, if the voltage of the PV array is lower than the calculated value, the controller decreases duty cycle, what in consequences decreases current in the converter and therefore increases the voltage according to V-I curve of the PV panel and vice versa. Flowchart of this method is shown in Fig. 5.

B. *Modelling of a DC Boost Converter*

According to previously presented theoretical description, a DC boost converter operates in two basic states – ON and OFF. The change of one state to the other is caused by the switching impulses generated by MPPT controller. Each state is described by different set of differential equations representing its dynamics, (4) and (5) or (6) and (7), respectively. For such cases, the use of finite state machine model is very suitable, because it enables to combine different representations of model's object dynamic operation very easily, just by defining appropriate number of states and transitions between them. Therefore a FSM domain in the software Ptolemy II [1] was used to create the model of DC boost converter. The created model is shown in Fig. 6. There are parameters iL representing inductor current i_L and vC representing voltage at capacitance v_C. The guards in this model are defined by the switching impulses from MPPT controller. When the value of impulse is 1, it means it is time when the converter should be in state ON and so the transition from state OFF to state ON is made and vice versa.

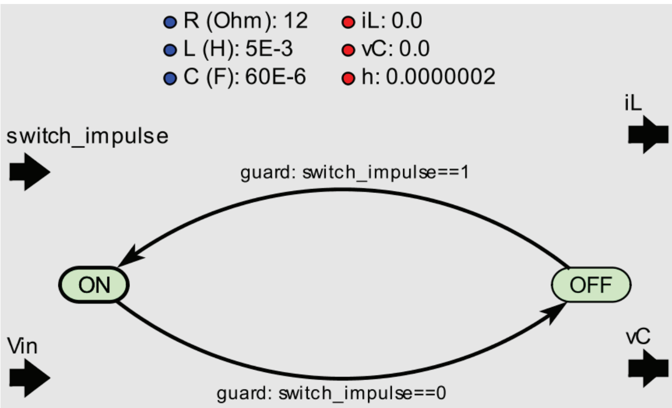

Fig. 6. FSM model of a DC boost converter.

The set of differential equations in each state was calculated by the fourth order Runge – Kutta method [8]. The equations used for the computation in state ON are presented in Fig. 7. The equations used for the computation in state OFF are presented in Fig. 8. In both states, the variables i_L and v_C are calculated and saved in parameters iL and vC for the use in the next iteration, either in the state ON or OFF.

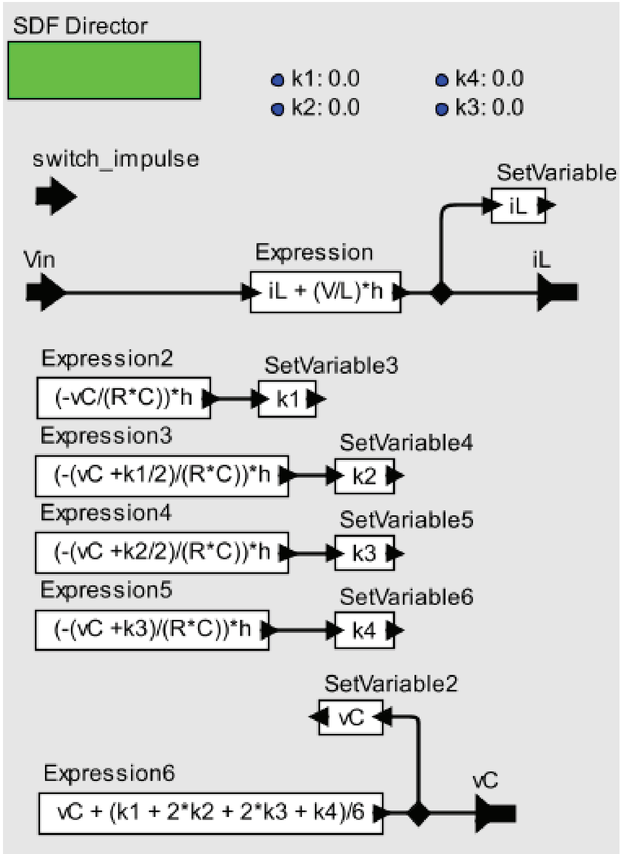

Fig. 7. ON state of the converter.

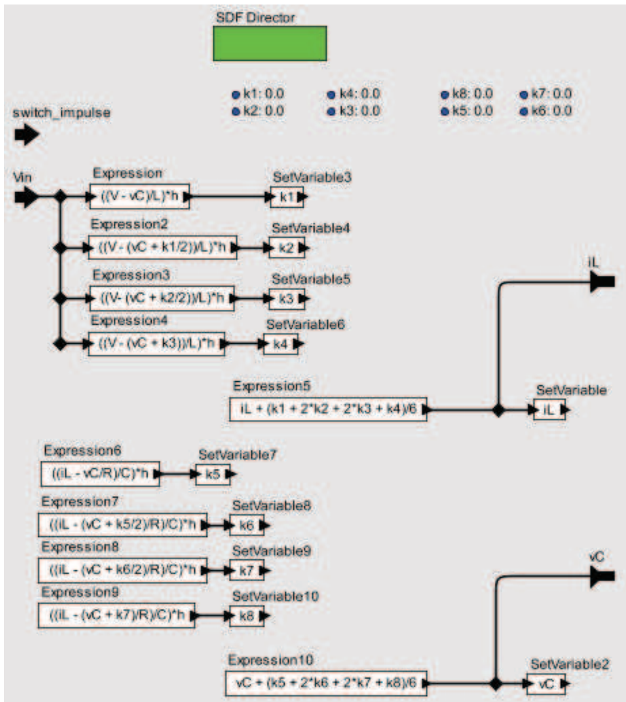

Fig. 8. OFF state of the converter.

The presented FSM model can be also used with more complicated and exact mathematical models of a DC boost converter operation. It is only necessary to put correct differential equations in ON and OFF state of the FSM model.

C. Operation of a DC Boost converter

The created model of the DC boost converter was implemented in the model of simple PV system consisting also of a PV array and MPPT controller (Fig. 9). A constant resistance was use as a load of the PV system. All models were created and simulated in Ptolemy II software.

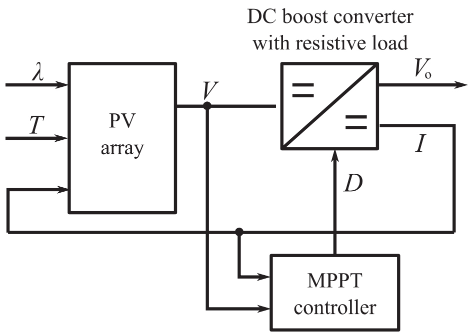

Fig. 9. A block diagram of PV system.

The model of PV array, more described in [9], was parametrized to represent a real installation of 8 PV panels having the total peak power 1960 Wp. Installation's P-V curves for selected values of a solar irradiance are shown in Fig. 10. Table I presents panels' parameters used in simulations.

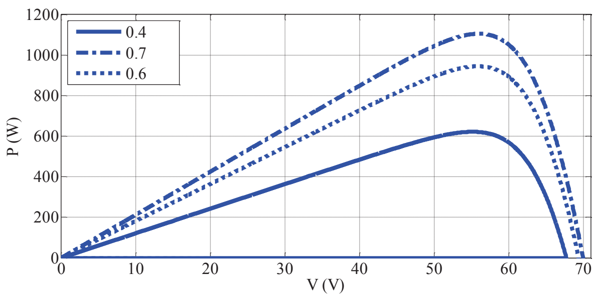

Fig. 10. P-V curve of the PV array.

TABLE I. TECHNICAL PARAMETERS OF USED PV PANELS

Parameter	Parameter name	Parameter value
I_{sc}	Short-circuit current	7.71 [A]
K_I	Cell temperature coefficient	0.11 [mA/C]
K	Boltzmann's constant	$1.38065 \cdot 10^{-23}$ [J/K]
T_r	Thermodynamic reference temperature	298.15 [K]
q	Electron charge	$1.6 \cdot 10^{-19}$ [C]
E_g	Bandgap voltage for silicon	1.11 [eV]
A	Ideality factor	1.3 [-]
V_{oc}	Open-circuit voltage	0.589 [V]
R_s	Serial resistance	0.01136 [Ω]
R_{sh}	Parallel resistance	116.8415 [Ω]

The model of PV system from Fig. 9 is shown in Fig. 11. Model inputs are the solar irradiance λ and temperature of the PV array T, which are used to calculate PV array output current, voltage, power and open-circuit voltage. The calculated values of PV array voltage and open-circuit voltage are used in the model of the MPPT controller, where the boost converter duty cycle D is set according to the flowchart presented in Fig. 5 and switching impulses controlling the DC boost converter operation are generated. The converter works according to previously presented theoretical description. Table II presents used parameters of the converter. The load was set to 12 Ω. Parameters Im, Vm and Pm in Fig. 11 represent PV array current, voltage and power at the MPP and the parameter Vo represents output voltage of the converter.

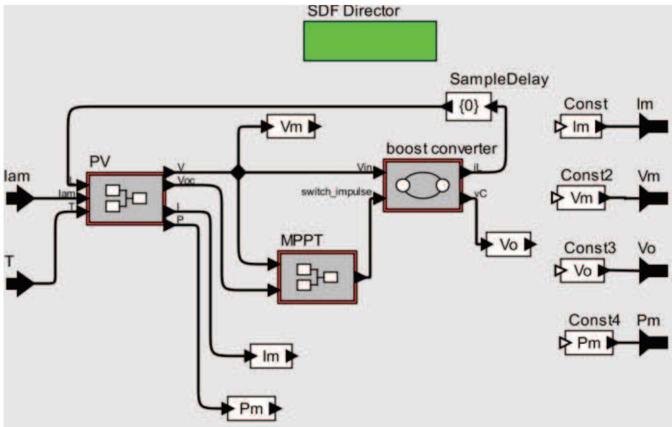

Fig. 11. Model of PV system.

TABLE II. TECHNICAL PARAMETERS OF THE DC BOOST CONVERTER

Parameter	Parameter name	Parameter value
f_S	Switching frequency	50 [kHz]
L	Inductance	5 [mH]
C	Capacitance	60 [μF]

A simulation case was used to verify model functionality. The value of solar irradiance λ, at the constant temperature of 25 °C, was set to 400 W·m^{-2}, then it was raised to 700 W·m^{-2} and afterwards it was decreased back to the 600 W·m^{-2}. This procedure was chosen to test model's ability to calculate correct PV array output power and to represent correctly the dynamics of the DC boost converter. Obtained simulation results are presented in Fig. 12 to Fig. 16.

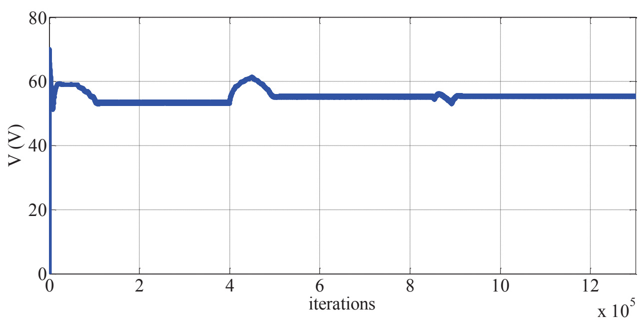

Fig. 12. PV array output voltage feeding the converter for different solar irradiances.

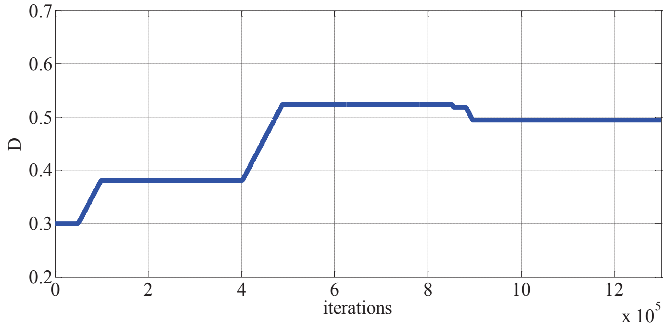

Fig. 13. Changes of duty cycle of the converter for different solar irradiances.

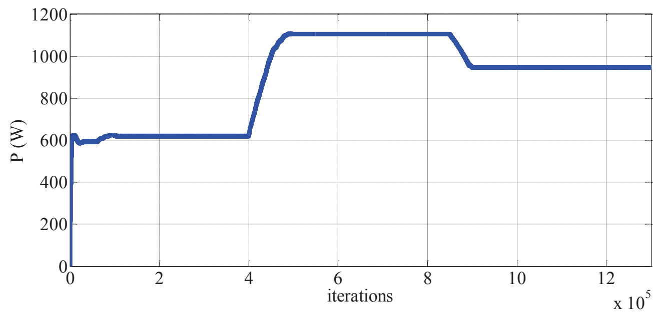

Fig. 14. PV array output power for different solar irradiances.

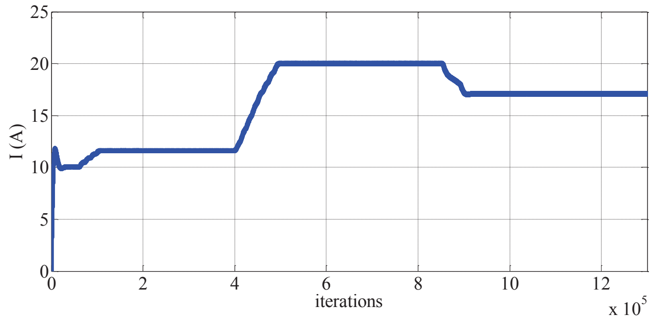

Fig. 15. PV array output current for different solar irradiances.

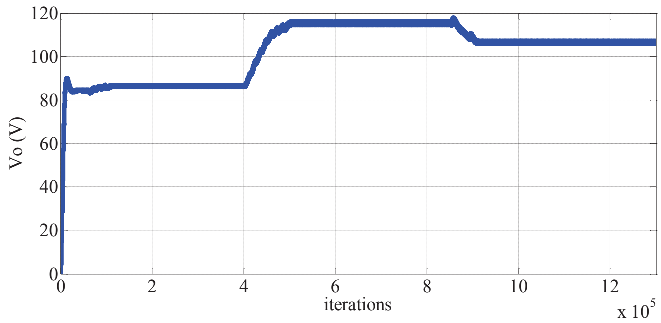

Fig. 16. DC boost converter output voltage for different solar irradiances.

The MPPT controller was able to hold a constant value of the PV array output voltage (Fig. 12), through the changes of converter duty cycle D (Fig. 13), which were necessary for finding PV array maximum output power (Fig. 14) due to the changes of its output current (Fig. 15) caused by the changes of solar irradiance.

As it could be seen from Fig. 14, the calculated values of PV array generated power are the same as in Fig. 10. The dynamic behavior of DC boost converter can be seen from the transients of its output voltage presented in Fig. 16. But the system dynamics can be observed in other presented figures as well.

IV. FSM Model of PV System

The first simulation case proved the model's ability to represent PV system dynamics correctly. However, all values were calculated through the solving of differential equations, what had a significant influence on the length of simulation time. But if we look at presented figures, it is obvious that the differential equations have to be used only during the transients caused by the changes of solar irradiance. Before and after these transients the values remain the same.

It could be very efficiently used to reduce the simulation time, if a FSM approach is applied also on a whole model of PV system. Its operation can be described by two states, steady state and transient state. The *transient state* describes the dynamics of the systems by calculating the changes of output parameters at each change of the solar irradiance or the temperature. If there is no change of these parameters, the FSM model can go to the *steady state*, in which the steady state operation of PV system is simply simulated through the repeating of the last calculated values of output parameters (in *transient state*) to the model output ports.

A FSM model of PV system with two above described states, created in Ptolemy II software, is shown in Fig. 17. The *transient state* consists of model illustrated in Fig. 11.

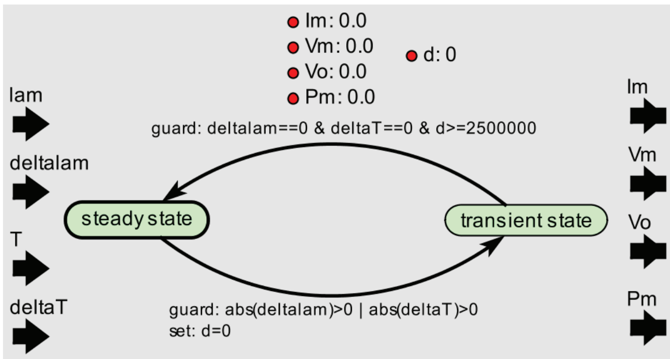

Fig. 17. FSM model of PV system.

A simulation case, where the value of solar irradiance, at constant temperature 25 °C, was increased from 0 to 1 000 W·m^{-2}, with the step 200 W·m^{-2}, was used to verify the model functionality.

Obtained simulations results are shown in Fig. 18 to Fig. 21. They show the curves of PV array output voltage (Fig. 18), changes of converter's duty cycle D (Fig. 19), PV system output power (Fig. 20) and the DC boost converter output voltage (Fig. 21).

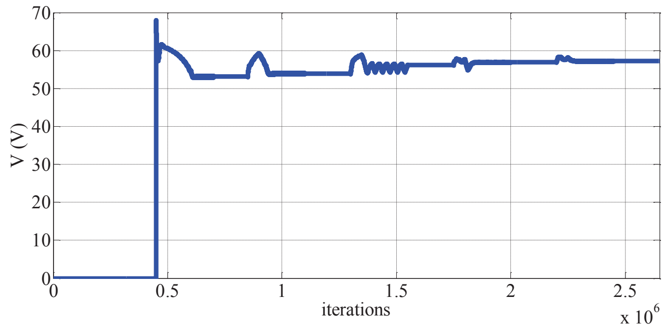

Fig. 18. PV array output voltage calculated by FSM model of PV system.

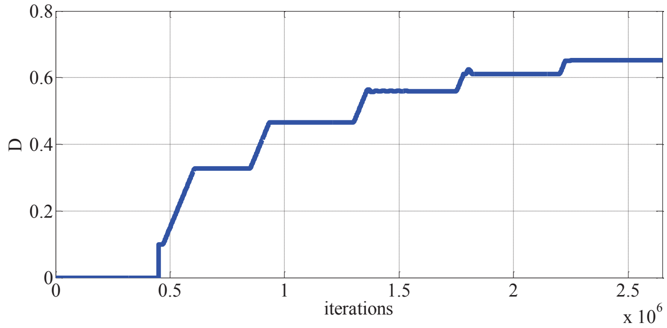

Fig. 19. Changes of duty cycle in FSM model of PV system.

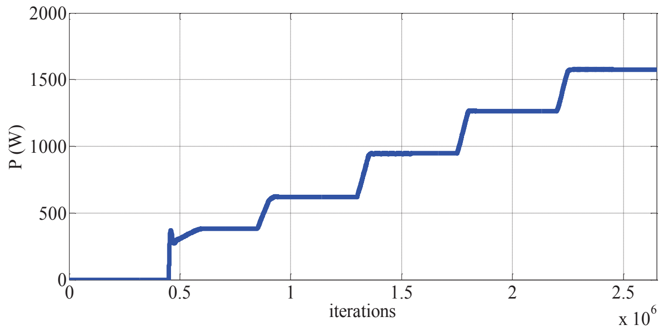

Fig. 20. PV system's power curve calculated by FSM model of PV system.

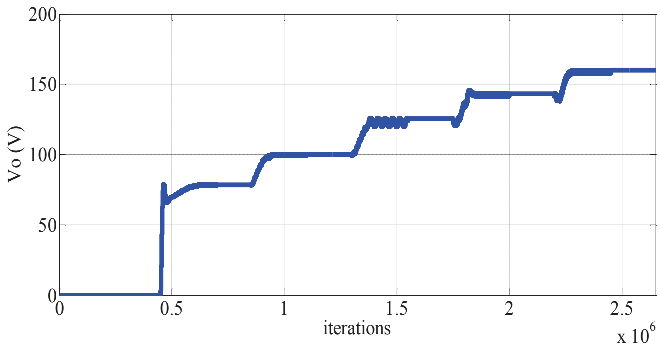

Fig. 21. DC boost converter output voltage calculated by FSM model of PV system.

Despite the fact that a simplified steady state was used to speed up the simulation, the character of these curves is the same as in the first simulation case, when all values were calculated through differential equations. Their shape is given by the increasing value of solar irradiance, but their clearly show the model's ability to represent dynamics of PV system operation.

V. Conclusion

A finite state machine model of a simple photovoltaic system consisting of photovoltaic array, DC boost converter and MPPT controller was created in Ptolemy II software. The model is able to represent both steady state and dynamic operation of PV system. The model uses both states during the simulation and chose them for calculation according to changes of model input parameters, which are solar irradiance and panel's temperature. Such arrangement can significantly reduce simulation time, but still simulate correctly the dynamics of PV system operation. The future work will be oriented on the specification of third state of FSM model, in which small changes of input parameters will be processed with simplified mathematical description, which will sufficiently represent the PV system dynamics for small changes of input parameters, but will further decrease the simulation time.

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