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The Use of a Finite State Machine Approach for a Simple Photovoltaic System Dynamics Modelling

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Abstract — **This paper presents a FSM model of a PV system consisting of a PV array and a DC boost converter with MPPT. The FSM approach is used to represent different operation conditions caused by the change of input parameters – a solar irradiance and a temperature. Presented model consists of three states. The first state represents a steady state operation, the second one a dynamic operation during big changes of input parameters and the last one uses fill factor to model their small changes. Such arrangement enables to reduce a simulation time, but it is still capable to simulate correctly the dynamics of PV system operation.**

Keywords: photovoltaic system; finite state machine; fill factor; modelling

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. Because the biggest part of the required RES installed capacity in Slovak Republic is covered by photovoltaic (PV) power plants (537 MWp), without considering the big hydro power plants, the authors have decided to focus on the creation of a simulation model for PV systems, which will represent dynamic operation of these systems.

The problem of PV systems is in the strong dependency of their output power on weather conditions, such as a solar irradiance or a temperature. Therefore it is useful to create an appropriate model to represent their operation during different operating conditions. The model representing dynamics of a simple PV system consisting of a PV array and loaded DC boost converter with maximum power point (MPP) tracking algorithm is presented in this paper. The dynamics of MPP regulation can be neglected in some cases and the maximum power is then calculated using simple equation as in [1]. However, the authors have decided to focus on dynamics of this regulation, because such a small PV systems, when used in islanded Smart Regions, can be source of voltage mitigations that can significantly influence an operation of other devices. The differential and nonlinear equations are commonly used for modelling of such system as in [2], [3], [4]. As the model should represent different operation state of PV systems, an approach based on finite state machines (FSMs) was used in order to simplify these simulations [5]. This method is also used in [6] and [7].The model representing both steady states and dynamic operation of the PV system had been already created in [8]. The model uses these two states during the simulation and applies them for calculation according to changes of model's input parameters, which are solar irradiance and panel's temperature. Such arrangement has significantly reduced simulation time, but has still simulated correctly the dynamics of PV system operation. Some researchers calculate maximum power just using a fill factor, as in [9], [10]. As shown in [9], the fill factor changes slightly with changes of solar irradiance and temperature. Based on this assumption the authors decide to specify the third state for the model in [8], in which the maximum power point is calculated using the fill factor in cases of small changes of input parameters.

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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 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 [5], [11].

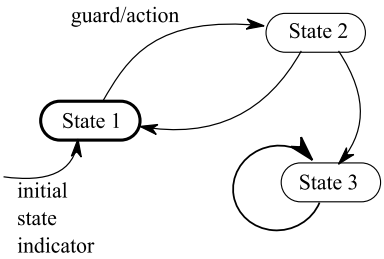

Figure 1. A graphical notation for FSM.

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

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 [5].

III. Mathematical Model of a PV System

The model of PV system consists of mathematical models of a PV array, a DC boost converter loaded by constant resistive load and a maximum power point tracking (MPPT) controller (Fig. 2).

The inputs of the PV array model are solar irradiance λ (kW·m^{-2}), temperature T (K) and load current I (A). They are used to calculate the PV array voltage V that is used as an input for the model of DC boost converter. Converter calculates the increased output voltage V_o and the load current I.

The switching of the DC boost converter is controlled by MPPT controller, which changes the duty cycle D of the converter according to the voltage from PV array and load current. The MPPT controller´s algorithm determines the duty cycle needed to operate the PV array in a point of its maximum power.

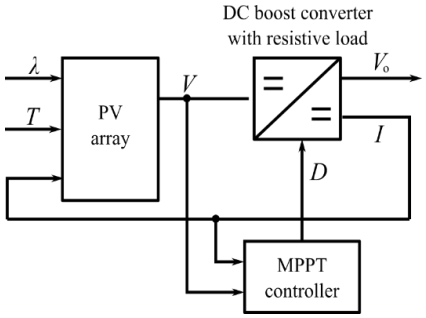

Figure 2. A block diagram of a PV system.

The model of PV array, more described in [12], was parametrized to represent a real installation of 8 PV panels having total peak power 1960 Wp. Table I presents panels' parameters used in simulation.

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]

An ideal DC boost converter is modelled in two modes of operation, which are given by the operation state of the switch. Detailed description of the mathematical model of the converter can be found in [8]. Parameters of the converter used for simulation are presented in Table II.

TABLE II. Technical Parameters Of the DC Converter

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

The DC boost converter is controlled by MPPT controller to achieve maximum power point of the PV array. There are many methods for the MPPT, such as perturb and observe method, incremental conductance method or constant voltage, etc. Controller changes duty cycle D of the converter to achieve voltage at maximum power point and so the maximum power in all of these techniques [13].

We use constant voltage method in our system, as the simplest and fastest method. The basis for the constant voltage (CV) algorithm is assumption that the ratio of the array's maximum power voltage V_M to its open-circuit voltage V_{OC} is approximately constant. This ratio has been empirically determined between 70 and 80 % [13]. The mathematical model is described more in [12] and the flowchart of the constant voltage method for MPP tracking is shown in Fig. 3.

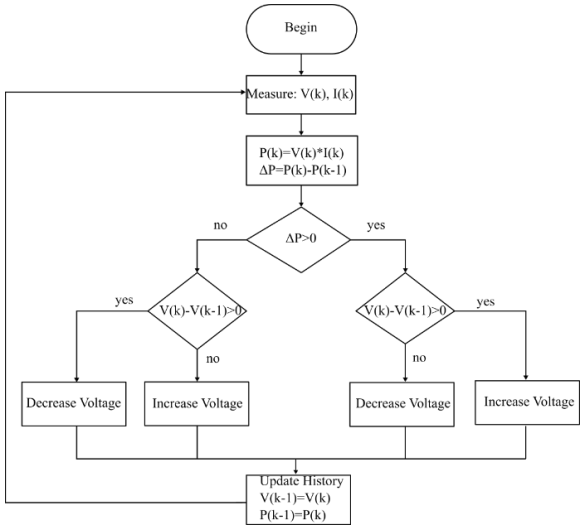

Figure 3. Flowchart of the constant voltage method.

IV. FSM Model of PV System

A. *Two-states FSM Model*

FSM model of PV system had been already created in [8]. The model consists of the two states, transient and steady state. The *transient state* describes the dynamics of the systems by calculating changes of output parameters at each change of the solar irradiance or the temperature, according to the previous description. Because before and after these changes the values remain the same, the *steady state* had been created, in which the operation of PV system is simply simulated through the repeating of the last values of output parameters calculated in transient state to the model output ports. Described model, created in Ptolemy II software, is shown in Fig. 4.

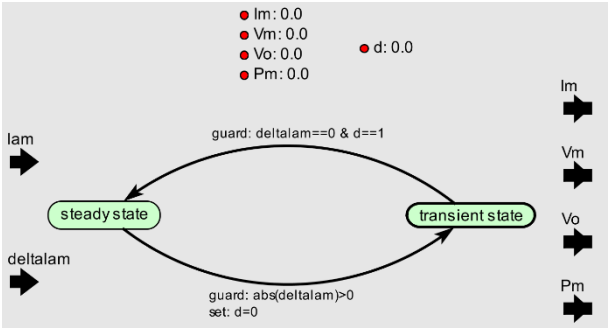

Figure 4. Two states FSM model of PV system.

B. *FSM Model of PV System with Fill Factor*

Fill factor (FF) is a parameter, which in conjunction with the open circuit voltage (V_{oc}) and the short-circuit current (I_{sc}), determines the maximum power of a solar cell. The FF is defined as the ratio of the maximum power to the product of the open circuit voltage and the short-circuit current [14].

As mentioned above, the FF changes slightly with changes of solar irradiance and temperature [9]. For these small changes of input parameters, the decision was made to simplify the boost converter model. Instead of using the before mentioned MPPT algorithm and differential equations describing the converter operation, the direct calculation of the current (I_M) and the voltage (V_M) at the point of maximum power using a fill factor of PV array was applied. It of course influences the model's dynamic, but the model is still able to represent the small changes in PV system operation. The model for this state is shown in Fig. 5.

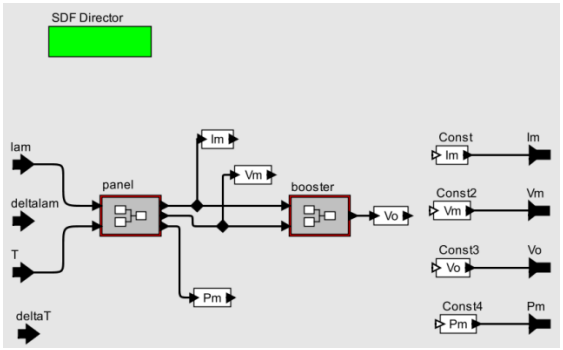

Figure 5. The model of the state using FF for maximum power determination.

The maximum power is calculated as a multiplication of the fill factor, the short-circuit current obtained and the open circuit voltage [12]. Then a set of equations, consisting of following equation for maximum power:

$$P_M = V_M \cdot I_M \tag{1}$$

and the generalized equation for solar array [12], are used to calculate PV array voltage (V_M) and current (I_M) in MPP.

The model of DC boost converter in Fig. 5 represents an ideal DC boost converter and its mathematical representation consists of following equations:

$$I_M = \frac{V_M}{R \cdot \left(1 - D^2\right)}, \tag{2}$$

$$V_o = \frac{V_M}{1 - D}. \tag{3}$$

The duty cycle D is derived from (2) and then used in (3) to calculate the converter's output voltage V_o.

The FSM model with this approach is shown in Fig. 6. The transient state is the same as in the previous FSM model. The only difference is that the fill factor is calculated from maximum power achieved by the MPP algorithm. In case that there are no changes of input parameters, the model passes to the steady state, where the operation of PV system is simply simulated through the repeating of the last values of output parameters calculated in transient state to the model output ports, as before.

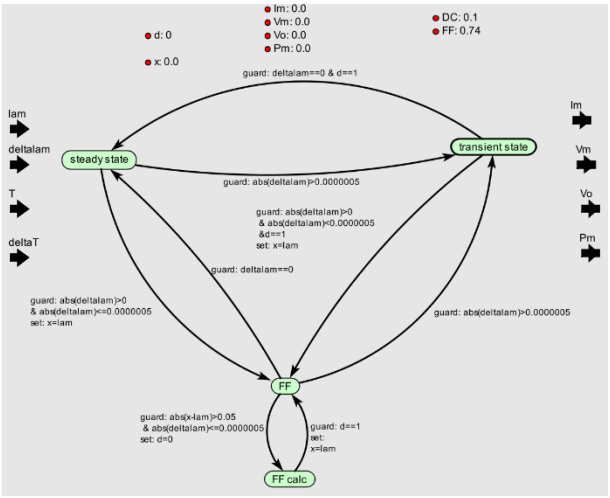

Figure 6. Extended FSM model.

In the case of small changes of input parameters, the model can pass to the next state (labeled as *FF*), where the maximum power is determined using value of fill factor calculated in transient state. For the case of the several following small changes of input parameters, the state labeled as *FF calc* has been complemented, where the maximum power is calculated using MPP algorithm for the short time and the fill factor for the following calculation of the maximum power is consequently determined.

V. Comparison of the Created Models

A simulation case was used for a comparison with previously created models as well as to verify model functionality. The curve of solar irradiance changes, at the constant temperature of 25 °C, is shown in Fig. 7.

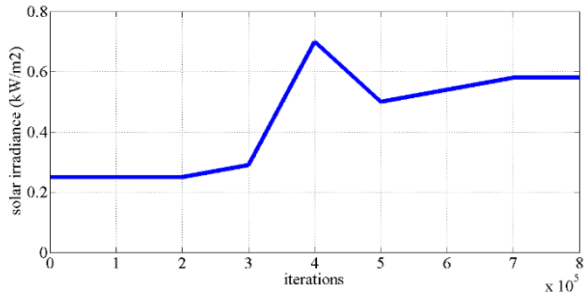

Figure 7. Solar irradiance curve.

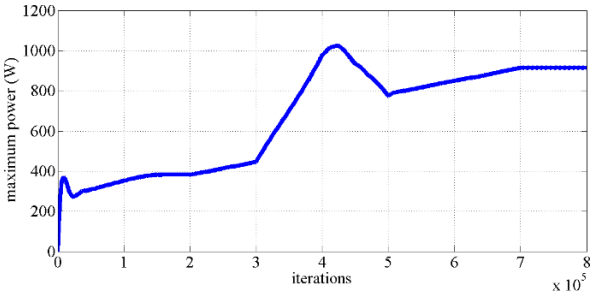

Figure 8. PV array output power of the first model for different solar irradiances.

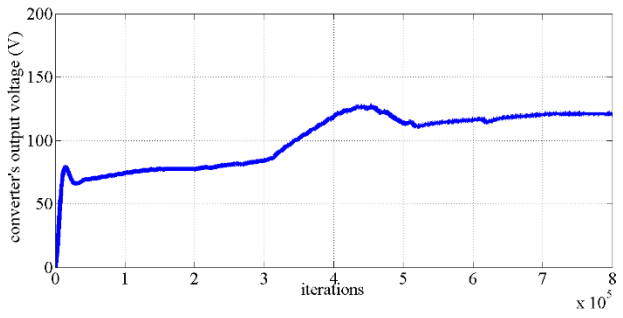

Figure 9. DC boost converter ouput voltage of the first model for different solar irradiances.

This procedure was chosen to test model's ability to calculate correct PV array output power. Obtained results for the first FSM model are shown in Fig. 8 and Fig. 9. It can be seen in Fig. 7 and Fig. 8 that there are small changes in output power of PV array caused by small changes of solar irradiance. Nevertheless, the output power is calculated using differential and nonlinear equation, what takes a lot of execution time. So the extended model with *FF* state was used for the same simulation case. As it can be seen from Fig. 10 and Fig. 11, the obtained simulation results were the same. The maximal error of the simplified (extended) model was only 5 % and the average error was only 2.16 %.

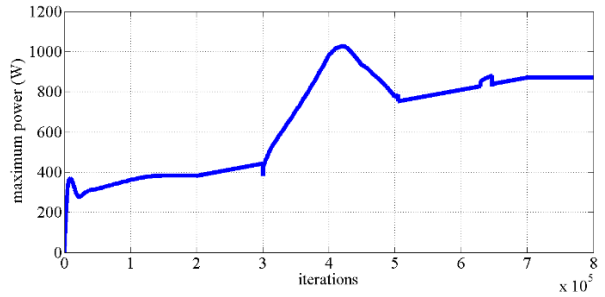

Figure 10. PV array output power of extended model for different solar irradiances.

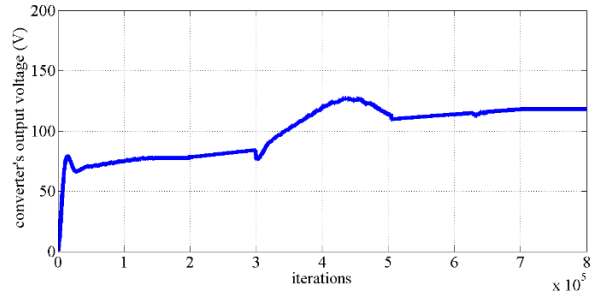

Figure 11. DC boost converter output voltage of extended model for different solar irradiances.

VI. Conclusion

The implementation of renewable energy sources to electric power system, especially those with an intermittent generation, requires a deep study of their operation in different operation conditions. It is even more important, if we consider them as the main energy sources for planned Smart Regions. To optimize future investments, it is necessary to create such models that will enable these studies. Therefore this paper describes the FSM model of a small PV system, which should, after its finishing, meet these requirements. The FSM approach was used to build a model capable of representing steady state as well as dynamic operation of a PV system.

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