Realistic Modeling and Simulation of The PV System - Converter Interface

Miona Andrejević Stošović, Duško Lukač, and Vančo Litovski

Abstract — In this paper we will present main problems and existing solutions concerning photovoltaic (PV) cells modeling and simulation. After several experiments performed by simulation we come to the conclusion that dynamic model of the PV cell is needed in order to get a realistic picture of its working conditions.

Keywords — modeling, photovoltaic cells, circuit simulation.

I. Introduction

In our recent proceedings [1] we made an overview of the existing applications of the photovoltaic (PV) cell models and the corresponding PV panel models. Our main interest was to search for application of dynamic modeling of the PV system. A large set of published results was consulted, to mention only a few of them [2-14], and we came to a conclusion that no dynamic circuit modeling was exercised at all. In fact, under dynamic modeling of PV systems thermal transient analysis was understood.

The reasons for such a situation, in our opinion, are several. First, the changes of the excitation to the PV system i.e. the light intensity are incomparably slower than the transients (local time constants) in it. Second, in existing applications, parallel to the PV system a capacitor with large capacitance is connected. It is assumed that its capacitance is at least by order of magnitude larger than the output capacitance of the PV system so suppressing any oscillations. Finally, it is a common practice to separately design the PV system and the DC to AC electronic conversion chain. In that way the interaction between the input of the converter and the output of the PV system is overlooked.

It is our intention here to put some more light to the electrical interface between the PV system and the DC/DC converter that is first encountered in the conversion chain. It will be shown by simulation that, due to the commutations within the converter, the output voltage of the PV system by no means is as simple as a DC voltage. In addition the properties of large capacitors will be exposed to show that inductive behavior may be expected at the harmonic frequencies of the controlling signal of the converter. Finally, sudden faults and especially intermittent ones are expected to seriously disturb the DC levels within the PV panel which, we expect, will give rise to transients in which the dynamic properties of the PV cells come to the fore.

The paper is organized as follows. The common model of a solar cell will be introduced first. An equivalent Norton source will be extracted in order to simplify the proceedings. Then, a DC/DC converter simulation results will be given to show the signals at its inputs. A simplified model of the interface will be created and simulation results will be given to show the output voltage of the PV system (input voltage of the DC/DC converter) in different situation. After introducing the so called link (electrolytic) capacitor and its model final conclusions will be drawn related to the need of modeling the dynamic properties of PV cells.

II. PV Cell Models

A function of a PV cell is simple: it absorbs photons from sunlight and releases electrons, so when there is a load connected to the cell, electric current will flow. PV cells are based on a variety of light-absorbing materials, including mono-crystalline silicon, polycrystalline silicon, amorphous silicon, thin films such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) materials, and organic/polymer-based materials.

A PV cell is usually represented by a light-induced current source in parallel with a diode, as shown in Figure 1. The output of the current source is proportional to the light flux falling on the cell. The diode determines the I-V characteristics of the cell.

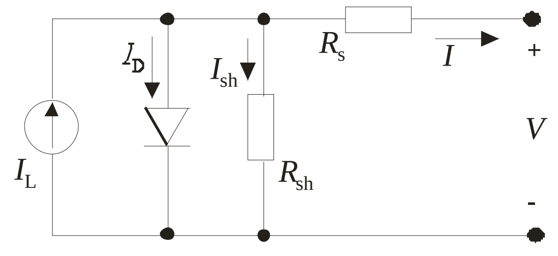

Figure 1. Circuit model of PV solar cell

Because of material defects and ohmic losses in the cell substrate material as well as in its metal conductors, surface, and contacts, the PV cell model also must include

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series resistance (R_s) and shunt resistance (R_{sh}), respectively, to account for these losses. R_s is a key parameter because it limits the maximum available power (P_{max}) and the short-circuit current (I_{sc}) of the PV cell.

The R_s of the PV cell may be due to the resistance of the metal contacts on the cell, ohmic losses in the front surface of the cell, impurity concentrations, or junction depth. Under ideal conditions, R_s would be 0 Ω. The R_{sh} represents the loss due to surface leakage along the edge of the cell or crystal defects. Under ideal conditions, it would have an infinite value and in most of the literature it is neglected in order to simplify the electrical model. But, in [15] it is shown that at very low irradiances, its value increases dramatically, i.e. the contribution of the apparent shunt resistance is only significant for cell voltages below about 0.45 V, and depends on irradiance.

The equations describing I-V characteristics of the PV cell based on equivalent circuit shown in Fig. 1, are usually expressed in the form given below,

$$I = I_L - I_0\left(e^{\frac{q(V+I\cdot R_S)}{k\cdot T}} - 1\right) - \frac{V + I\cdot R_s}{R_{sh}} \qquad (1)$$

$$I_D = I_0\left(e^{\frac{q(V+I\cdot R_S)}{k\cdot T}} - 1\right) \qquad (2)$$

where I is the cell current; q is the charge of electron; k is the Boltzmann constant; T is the cell temperature; I_L is the light generated current; I_0 is the diode saturation current; R_S and R_{sh} are the cell series and shunt resistances, V is the cell output voltage.

The electrical properties of the cell as a function of the ambient irradiance are captured within the expression of I_L while the cell temperature influence is mainly expressed through (2).

The suitability of this way of expressing of the I-V characteristic of the PV cell was discussed in [1] and alternative expressions were suggested allowing for circuit simulation of the PV cell in a complex electronic surroundings. Such an expression asks for a new variable to be introduced in the model, namely, the cell`s internal voltage V_i. If so, having in mind the notation of Fig. 2, the following nodal equations may be written

$$\begin{aligned} &I_D + I_{sh} + I = I_L \\ &-I + I_{out} = 0. \end{aligned} \qquad (3)$$

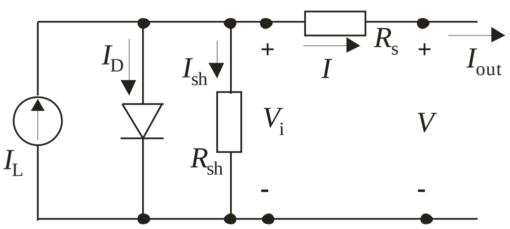

Figure 2. Modified interpretation of the PV cell model

All, I_D, I_{sh}, and I may represent models of nonlinear voltage controlled elements as does I_D in Equ. (2). I_L is here considered as voltage independent. In the case, however, when some voltage dependent light emitting element is in the electronic circuit and it illuminates the PV cell, I_L may become voltage dependent and will be shifted to the left-hand side of the nodal equation.

For the most frequent case, when linear R_s and R_{sh} are expected, one may use the following nodal equations

$$\begin{aligned} &\frac{1}{R_s}(V_i - V) + \frac{V_i}{R_{sh}} + I_D = I_L \\ &\frac{1}{R_s}(V - V_i) + I_{out} = 0 \end{aligned} \qquad (4)$$

where

$$I_D = I_0\left(e^{\frac{q\cdot V_i}{n\cdot k\cdot T}} - 1\right), \qquad (2)$$

and: I_{out} is the load current (Most frequently $I_{out} = V/R_{load}$, where R_{load} is the load resistance), n is the p-n junction`s ideality factor.

Introduction of the cell`s nonlinear capacitances in the model is a straightforward task as shown in Fig. 3.

Using this concept, if model parameters available, simulation of photovoltaic systems containing virtually unlimited number of PV cells and electronic circuitry of any complexity may be simulated using standard electronic circuits analysis methods [15].

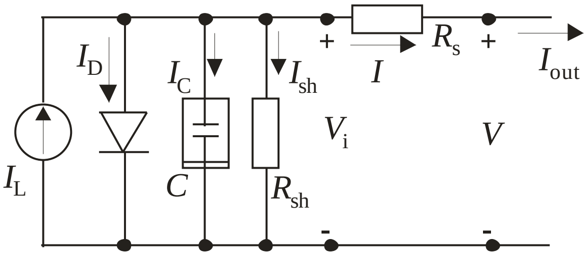

Figure 3. Modified interpretation of the PV cell model

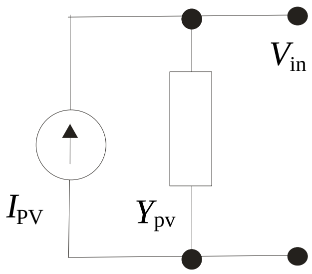

Figure 4. A nonlinear model of the PV system

III. THE CONVERTER

The output circuitry of a PV system, as complex as it can be [16], may be modeled as a current source I_{pv} (equivalent Norton) with internal admittance Y_{pv} as shown in Fig. 4. Note the admitance is to be nonlinear since it represents the nonlinearities of the diode(s), the junction capacitance(s) and the resistances. Here, however, the purpose of modeling is to get a rough picture of the PV system-converter interface and no details will be given about the PV-model parts.

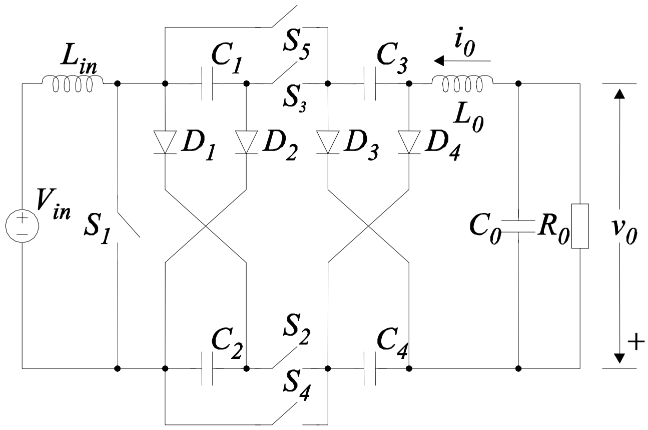

Figure 5. The Ćuk converter

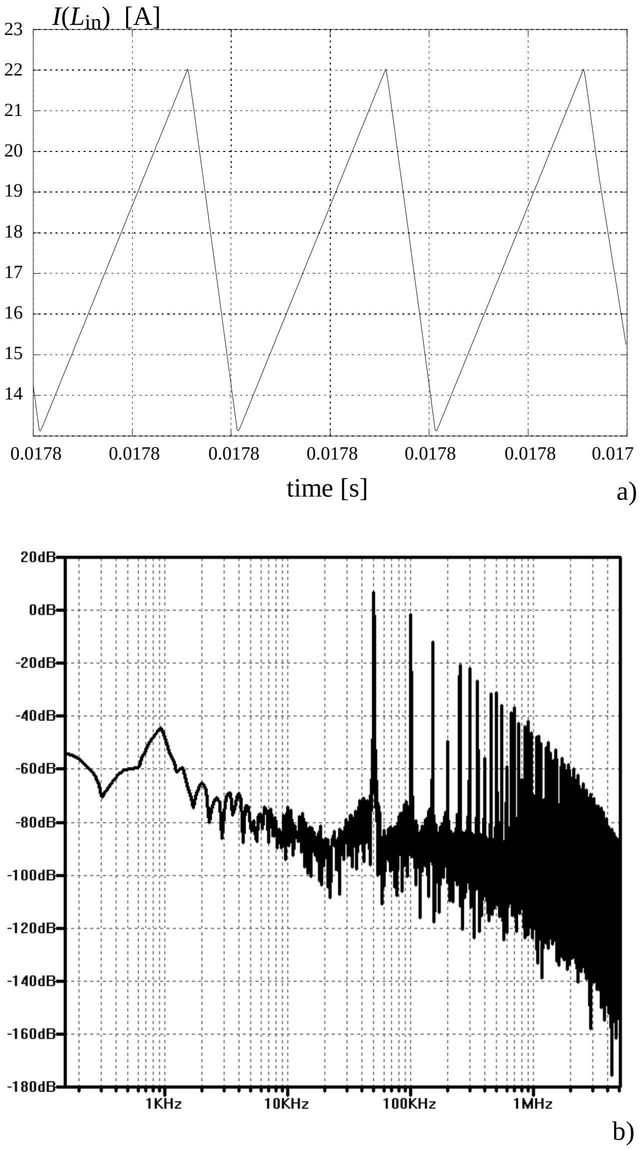

Figure 6. The input current of the Ćuk inverter after steady state (a) and its spectrum (b)

This circuit in most cases is driving a DC to DC converter. One, among many, variant of the DC/DC converter is the Ćuk converter shown in Fig. 5. Here constant voltage excitation of 12 V is assumed while the switching frequency is 50 kHz. For this proceedings the input current trough the coil (L_{in}=20 μH) is of interest. It was obtained by simulation and part of the response is shown in Fig. 6a. The corresponding spectrum is depicted in Fig. 6b.

It may be observed that the input current, in addition to the DC component, has an AC component reach of harmonics. Accordingly, when connected to the PV system such a converter will draw alternating current in addition to the DC power which was targeted.

IV. MODELING THE COMPLETE SYSTEM

The simplified schematic of the complete system is depicted in Fig. 7 which is considered self-explanatory. Fig. 8 represents a model of the whole system where the PV system, as modeled in Fig. 4, is loaded by the input resistance (R_{in}) of the converter and excited by alternating current (depicted in Fig. 6) labeled by J_{AC}.

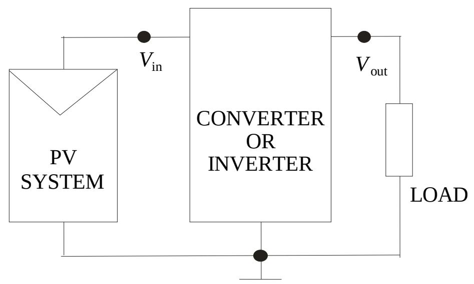

Figure 7. A simplified representation of the PV system to load connection

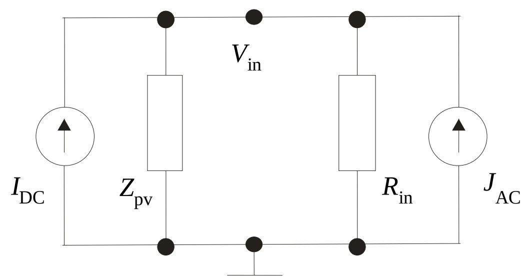

Figure 8. A simplified model of the PV system - converter interface

Since J_{AC} may be considered as a form of feed-back to the PV system, stability is becoming an important concern. Namely, a question arises as to whether the oscillations may persist and influence the quiescent working point of the PV system. To check for that an additional experiment was performed.

A new circuit was created consisting of the Ćuk converter [17] and a capacitor charged by 12 V. The capacitor is considered as a substitution to the constant voltage source. Relatively small capacitance was used to simulate the PV system output capacitance. As expected, oscillatory discharge of the capacitor was observed as shown in Fig. 10. Having in mind the DC power comming from the PV system, in more realistic situations, one may expect sustained oscillations at high frequencies at the PV system to converter interface.

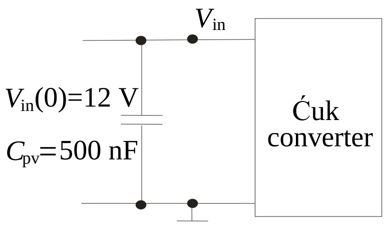

Figure 9. Experiment to check for oscillations

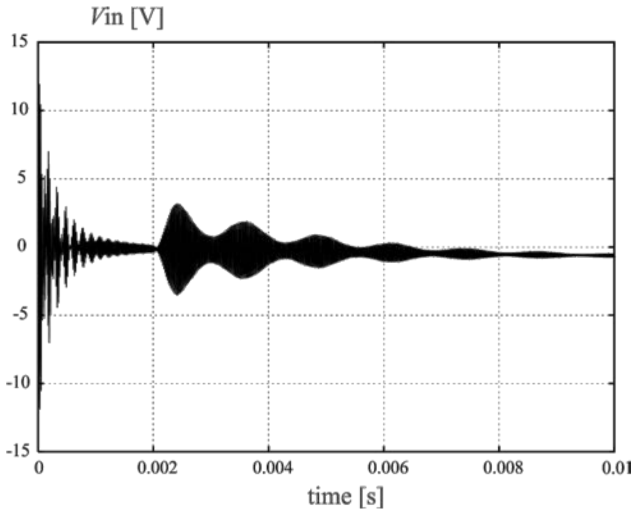

Figure 10. The input voltage as a function of time for the circuit of Fig. 9.

To avoid such oscillations a capacitor of large capacitance is usally inserted at the interface as shown in Fig.11.

To verify whether this is a solution to the oscillations problem we performed an additional simulation in which the PV system was modeled by a single DC current source as shown in Fig.12. The simulation results are shown in Fig. 13. As can be seen, alternating current of large amplitude may arise at the input of the converter. That current, in the circuit of Fig. 12, flows through the capacitor only since here no realistic model of the PV system was implemented. That however does not affect the conclusion that the capacitor is not a solution to the oscillation problem at the input of the converter. Namely, even in this case, the capacitor voltage still contains a significant AC component (about 2Vpp) that is driving backwards to the PV system. One is to add to these considerations the fact that real electrolytic capacitors of large capacitances suffer of relatively large series resistance and inductance which may becomes dominant at high frequencies i.e. at the frequencies of the harmonics depicted in Fig. 6b.

V. COMMENTS ON THE PV MODELING

Summarizing the analysis of the PV system to converter interface we may draw a general conclusion that in any case oscillations will remain at the interface. The amplitude of the time varying voltage at the output of the PV system will depend on several factors such as the switching frequency of the converter, the type and structure of the converter, the capacitance value, quality, age, and temperature of the electrolytic line capacitor, and the output capacitance of the PV system.

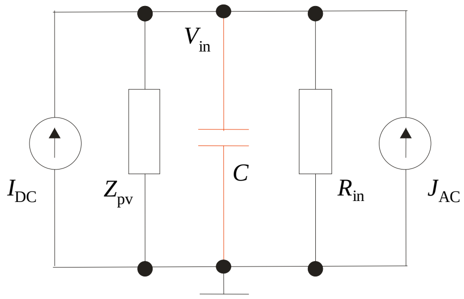

Figure 11. Model of the interface with a capacitor inserted

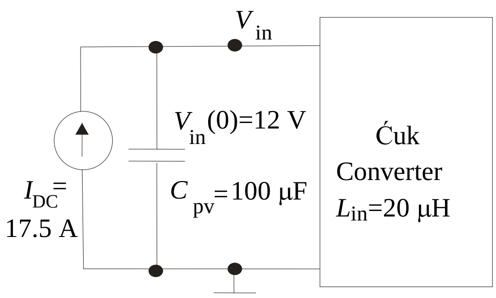

Figure 12. Simplified model of the PV system used to excite the Ćuk converter with large capacitance in between

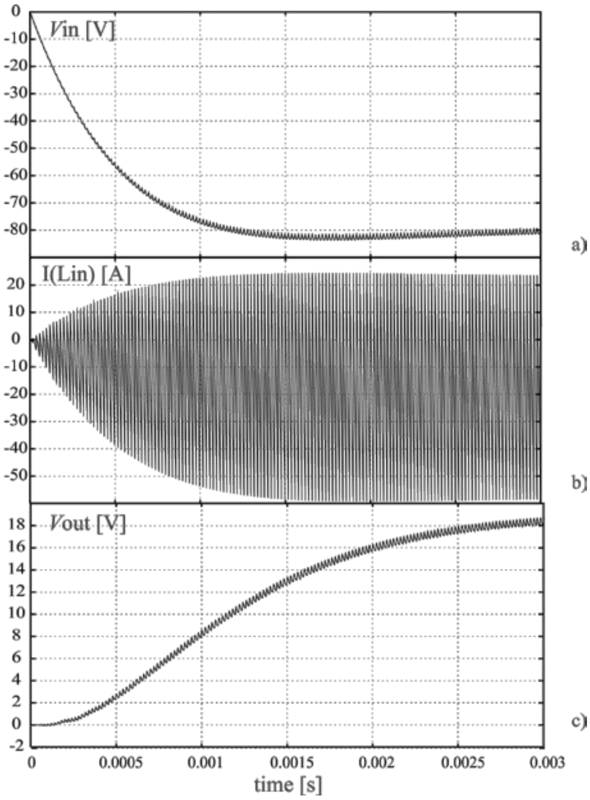

Figure 13. Simulation results for the circuit of Fig. 12. a) input voltage, b) input current and c) output voltage of the converter

The last claim is not as obvious as other ones. Namely, one may expect that the output capacitance of the PV system being equivalent of the PV cell`s junction capacitance, is much smaller than the line capacitance so being of no influence. That however is to be taken with caution since in between these two capacitances we meet several circuit elements such as the (nonlinear) diode, the shunt and series resistance of the PV cell and the parasitic elements of the line capacitor.

In any case the alternating component of the PV system output voltage is distributed downwards to all cells affecting all quiescent working points. If one wants to get realistic picture of the working condition of the PV cell one needs to take into account that component which implicitly means that one needs to use a model of the PV cell that exhibits dynamic behavior like the one of Fig. 3.

VI. Conclusion

The state-of-the-art in modeling PV cells was investigated. Properties of the existing models and simulation concepts were established. It was concluded that, based on the presumption that the output of the PV system may be characterized as a DC circuit, no dynamic simulations were performed and reported in the literature.

After a set of simulations on simplified models of the PV system to converter interface a conclusion was drawn that the output voltage of the PV system that is driving the converter contains a significant time varying component that is due to the switching in the converter. That alternating component is reduced but not suppressed by the line capacitor.

Accordingly, the main result of these investigations was the conclusion that one needs a realistic dynamic model of the PV cell in order to establish knowledge on its real working conditions. Simulations based on such a model including more realistic model of the electrolytic capacitor will shed clearer light on the working conditions of the PV system and the PV cell itself.

Acknowledgement

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