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DYNAMIC PROPERTIES OF SOLAR CELLS

Miona Andrejević Stošović, *University of Niš, Faculty of Electronic Engineering, miona@elfak.ni.ac.rs*
Duško Lukač, Rheinische Fachhochschule Köln, *lukac@rfh-koeln.de*
Vančo Litovski, *University of Niš, Faculty of Electronic Engineering, vanco@elfak.ni.ac.rs*
Dragiša Milovanović, *University of Niš, Faculty of Electronic Engineering, dragisa.milovanovic@elfak.ni.ac.rs*

Abstract – *The importance of investigation the dynamic properties of solar cells is stressed first. Using existing models simulations were performed in order to show that if the solar cell is seen from the load side as a nonlinear dynamic component its dynamic behavior is necessary to be taken into account when designing PV systems.*

1. 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 [2-7], 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 was our intention in [8] 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 was 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 were exposed to show that inductive behavior may be expected at the harmonic frequencies of the controlling signal of the converter. Finally, having in mind that 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), the dynamic properties of the PV cells come undoubtedly to the fore.

There are, however, no investigations on the behavior of a PV cell as part of a nonlinear dynamic circuit in the literature. That is why here for the first time we are trying to get some fundamental ideas on the responses of the PV cell embedded in simple circuits and to get information about its properties in the time domain.

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. A simplified model of the interface between the PV panel and the DC/DC converter will be created in which the so called link (electrolytic) capacitor and its model will be inserted. Simulation will be performed with a reduced resistive model of the PV panel to get the notion on the voltage waveform at the interface.

The main new contribution of the paper will be presented in Paragraph 5. where transients will be given for a PV cell in a circuit containing resistors and switches only.

2. 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, I_P, in parallel with a diode, as shown in Figure 1. The output of the current source is proportional to the light flux falling onto the cell. The diode determines the I-V characteristics of the 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 series (R_s) and shunt (R_{sh}) resistance, 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.

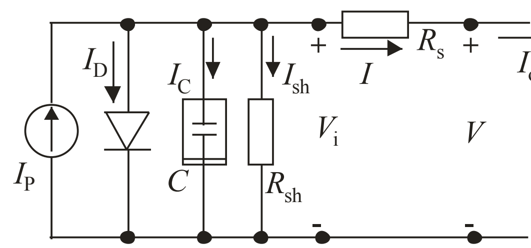


Figure 1. The PV cell model

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. Hence its nonlinearity. 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 [7] 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 electrical properties of the cell as a function of the ambient irradiance are captured within the expression of I_P while the cell temperature influence is mainly expressed through temperature dependence of the diode current.

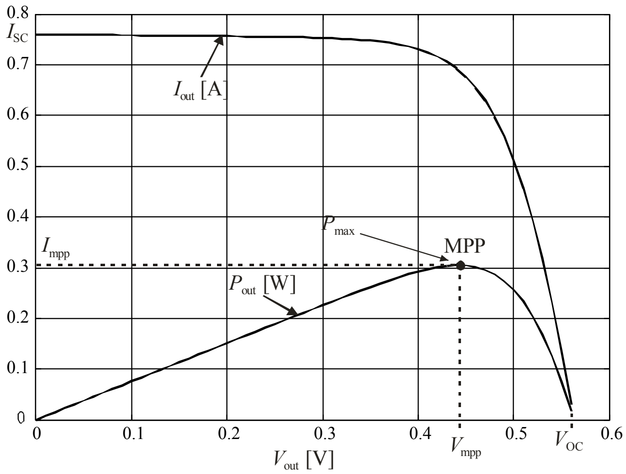


Figure 2. The steady state characteristics of a PV cell

The PV cell characteristics under steady state conditions are depicted in Fig. 2. Two diagrams are shown: the I-V and the P-V characteristic. Based on these the main parameters of the PV cell e.g. I_{SC} (the short-circuit current), V_{OC} (the open-circuit voltage), V_{mpp} (the voltage at maximum power), and I_{mpp} (the current at maximum power), may be recognized.

The dynamic properties of the PV cell are related to the capacitances of the diode. These are the junction capacitance that is dominant at voltages below and about MPP, and the diffusion capacitance that takes over at high diode currents.

So, having in mind the notation of Fig. 1, the following nodal equations may be written

$$\begin{aligned} &I_D + I_{sh} + I + I_C = I_P \\ &-I + I_{out} = 0. \end{aligned} \tag{1}$$

All, I_D, I_{sh}, I_C, and I may represent models of nonlinear voltage controlled elements. I_P is here considered as voltage independent. In some cases however, it may be voltage dependent as shown in [9].

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

$$\begin{aligned} &\frac{1}{R_s}(V_i - V) + \frac{V_i}{R_{sh}} + I_D + I_C = I_L \\ &\frac{1}{R_s}(V - V_i) + I_{out} = 0 \end{aligned} \tag{2}$$

where

$$I_D = I_0(e^{\frac{q \cdot V_i}{n \cdot k \cdot T}} - 1), \tag{3}$$

$$I_C = \frac{\mathbf{d}Q_C}{\mathbf{d}t} = (C_t + C_d) \cdot \frac{\mathbf{d}V_i}{\mathbf{d}t} \tag{4}$$

and: q is the charge of electron; k is the Boltzmann constant; T is the cell temperature; I_0 is the diode saturation current; I_{out} is the load current (Most frequently $I_{out} = V/R_L$, where R_L is the load resistance); and n is the p-n junction`s ideality factor. C_t stands for the junction capacitance while C_d represents the diffusion capacitance.

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 [10].

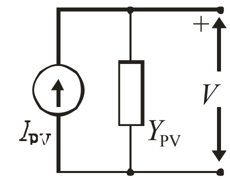


Figure 3. A nonlinear model of the PV system

The output circuitry of a PV system (and PV cell), as complex as it can be [11], may be modeled as a current source I_{PV} (equivalent Norton) with internal admittance Y_{pv} as shown in Fig. 3. Note the admittance 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.

3. THE CONVERTER

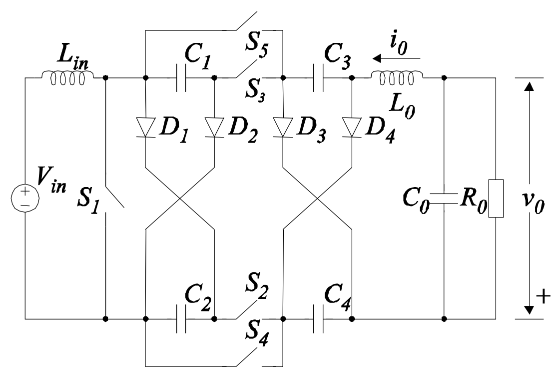
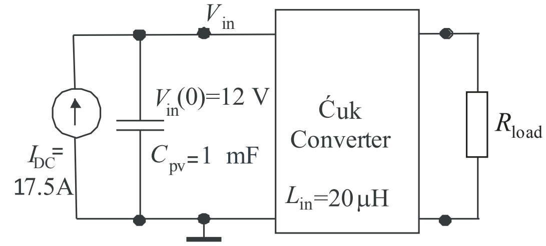


Figure 4. The Ćuk converter

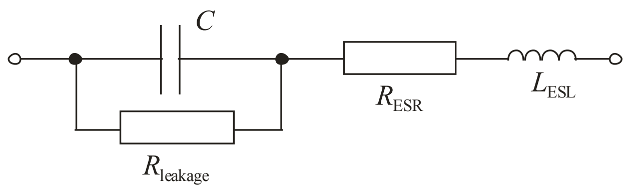
The PV panel, in most cases, is driving a DC to DC converter. One, among many, variant of the DC/DC converter is the Ćuk converter [12] shown in Fig. 4. Here constant voltage excitation is assumed while the switching frequency is 50 kHz. For these proceedings, however, since the converter is excited by a PV panel, the input voltage V_{in} of the converter is unknown.

4. MODELING THE COMPLETE SYSTEM

The simplified schematic of the complete system is depicted in Fig. 5a. Here for simplicity Y_{pv} is neglected and I_{PV}=17.5 A is used. A link capacitor C_{pv}=1mF is inserted at the interface. Its model is depicted in Fig. 5b.



a)



b)

Figure 5. a) Simplified model of the PV system used to excite the Ćuk converter with large capacitance in between. b) Model of the electrolytic capacitor (C_{pv}): C=1mF, $R_{leakage}$=1 MΩ, R_{ESR}=0.5 Ω, and L_{ESL}=3 nH.

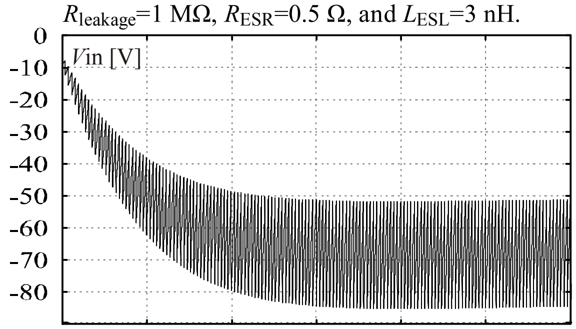


Figure 6.The input voltage of the circuit of Fig. 5a

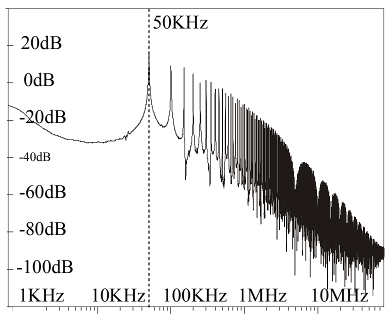


Figure 7. Spectrum of the input voltage

The switching frequency, the line capacitance and the inductor value are to be selected for the best performance considering conversion efficiency, cost and power consumption. For example, the higher the switching frequency, the lower the inductor and the capacitance size, but also the tracker power consumption and losses are higher. On the other hand, larger capacitances decrease the responsiveness of the harvester to fast variations of environmental irradiance.

The simulation results are shown in Fig. 6. As can be seen, alternating component of amplitude larger than 20% of the DC voltage value is obtained. The spectrum of the input voltage is depicted in Fig. 7. It shows presence of significant amount of harmonics giving rise to capacitances of the order of nF. These simulation results were motivation to search for the transient behavior of the PV cell.

5. SIMULATION OF SOLAR CELLS AS NONLINEAR DYNAMIC ELEMENTS

The investigation of the dynamic behavior of the PV cell will be based on an experiment. Namely, a PV cell loaded by a resistance (See Fig. 8) equal to the one leading to maximum power (R_{Lopt}) was taken as a reference. Then, the load resistance was switched to values twice and half of the R_{Lopt}. In the case when the load resistance was risen, as can be seen from Fig. 8, the diode gets more direct biased giving rise to both the diffusion and the junction capacitance.

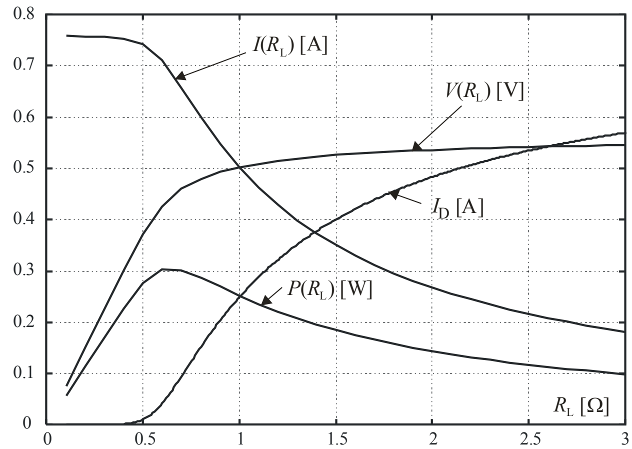


Figure 8. PV cell loaded by resistor R_L. Reference Fig. 1.

When the load resistance is diminished the diode bias is reduced under the diode threshold and only junction capacitance is active. To facilitate the understanding of this behavior the value of I_D is depicted in Fig. 8 to remind to the fact that the capacitances are related to it. In that way, we expected, complete information of the dynamic behavior of the load was to be extracted. The schematic of the experimental circuit is depicted in Fig. 9.

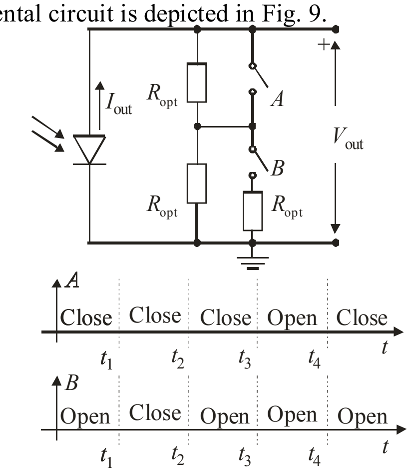


Figure 9. The test circuit

Numerical data for the simulation were taken from [13] and [14]. The following was used: I_0=0.3223 μA, n=1.4837, R_s= 0.0364 Ω, R_{sh}=53.76 Ω, C_{t0}=354 nF, V_0=0.73, and C_{d0}= $2.43 \cdot 10^{-15}$ F.

The simulation results are shown in Fig. 9. Here the load resistance was first switched from R_{Lopt} to $R_{Lopt}/2$ and back in a total time interval of 4 μs. Then the load was switched from R_{Lopt} to $2 \cdot R_{Lopt}$ and back with the same time interval. The whole experiment took 8 μs what is equivalent to 125 kHz. The time intervals were chosen as a minimum time needed to allow for full establishment of the voltage level after change of the load. In that way the value of 125 kHz may be accepted as the highest frequency at which full reproduction of the exiting pulses may be expected. That is the frequency below which one is not expected to consider the PV cell as a short circuit for time varying signals.

The difference between the negative and positive pulses comes from the nonlinearity of the I-V characteristic of the PV cell.

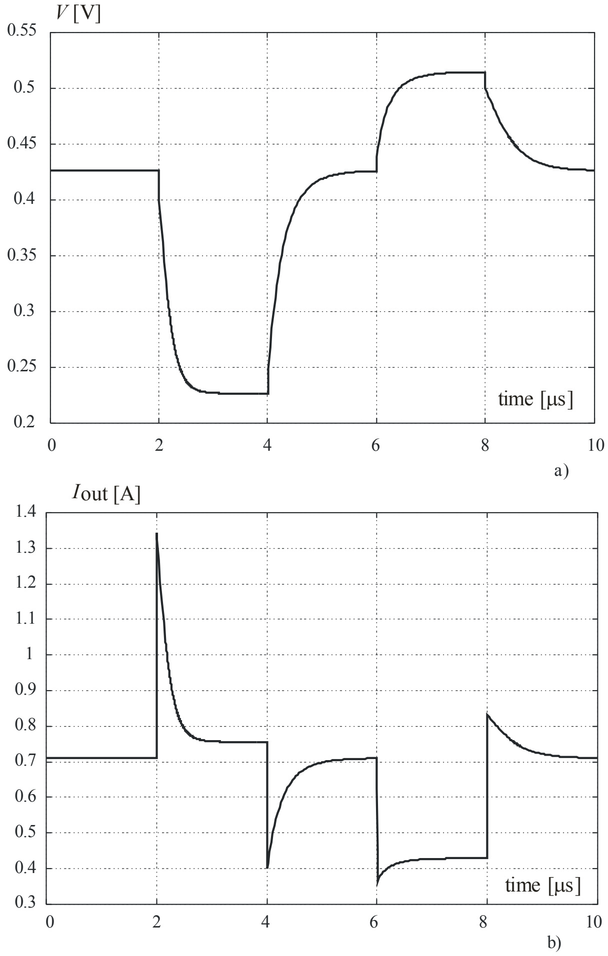


Figure 10. Responses of the circuit of Fig.9.

6. CONCLUSION

The photovoltaic system being always built of a PV source (panel) and a converter (or inverter) has its own specific properties that are frequently overlooked leading to unrealistic designs. We showed here that at the PV-converter interface the signal is far from DC asking for knowledge of the dynamic properties of the PV side. A simple test circuit was used to identify the dynamic properties of a PV cell. It was shown that it represents a recognizable impedance at frequencies belonging to the main and higher harmonics of the current incoming from the converter.

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