Comparison of Solar Panel Models for Grid Integrations Studies: Harmonics and Voltage Disturbances

M. H. de Souza, A. F. Cupertino, L. P. Carlette, F. H. de Oliveira and H. A. Pereira, *Member IEEE*

Abstract–**The photovoltaic systems are extremely dependents on the climatic conditions in which they are submitted. For to represent this influence, there are in the literature three models of the solar photovoltaic panel: the equivalent circuit, the mathematical model and the multi-physical model. This paper compares these models using a grid connected photovoltaic system. Simulations of grid disturbances, like harmonics and voltage sags are made for observed the behavior of each model.**

***Keywords* - Photovoltaic Panel, Modeling, Grid disturbances.**

I. Introduction

DAILY an enormous amount of energy enters our world in a free and clean way. The solar rays that focus on Earth can be used to generate electric energy. In order to do this, are used solar cells consisting of two layers of semiconductor materials. The power generated by these cells is direct current and can be directly used or stored in batteries. The photovoltaic panel is formed by solar cells and suffers the panel's temperature influence besides the influence of the solar irradiance incident on the generated power [1].

Despite these favorable conditions, the use of solar energy has not been considered in the National Energy Plan 2030 and only 8 Central Generating Solar Photovoltaic appeared in the database of the Nation Electric Energy Agency (ANEEL) until February 2012. "Over the past 10 years, photovoltaic technology has shown potential to become one of the predominant sources of electricity in the world - with robust growth and continued even in times of financial and economic crisis. It is expected that this growth will continue in the following years, backed by awareness of the advantages of photovoltaic energy. At the end of 2009, the cumulative installed capacity of PV systems was approximately 23 GW. A year later was 40GW. In 2011, over 69 GW are installed in the world and can produce 85 TWh of electricity each year. This volume of energy is sufficient to supply the annual need for more than 20 million homes."

For purpose of analysis, system's comprehension and research development, there are representative models to the photovoltaic panel, making possible the simulation in computational environment. Photovoltaic panels have an intermediary behave between a current and a voltage source.

Moreover, variations in the incident solar irradiance and temperature have a great impact on the generated power. Some parameters used in the modeling are informed by manufactures and they are in TABLE I [2].

In literature there are three main models: the equivalent circuit in which the parameters of the model are calculated according to the electrical characteristics of the photovoltaic panel but the temperature is not a parameter and consequently the PV curve does not change when variations on temperature happen; the mathematical model that consider the equations from the power generated by the panel; the multi-physics model that represents the influence of various phenomena in which a real system is subjected. It takes into account 16 parameters and also contains two diodes which better represent the non-linear characteristic of each cell.

Although they represent the same panel, there are differences between the obtained results for each model and the parameters supplied by the manufacturers. In [3] the three models were compared and it was possible to see that although their behavior is similar there are some differences. In this work the goal is to compare the model's behavior, applied to a photovoltaic system connected to the power grid in the situation closer to reality as possible.

The proposed system contains an algorithm that extracts the maximum power of the PV array. Variations in solar irradiance and temperature of the panels during the day were considered and were simulated disturbances in the power grid such as voltage sags and presence of harmonics.

TABLE I PARAMETERS OF A KYOCERA SM-48KSM SOLAR PANEL FOR 1000 W/M² AND 25 ºC.

Parameter	Symbol	Value
Maximum Power (W)	P_{max_e}	48 W
Maximum Power Voltage (V)	V_{mp}	18.6 V
Maximum power current (A)	I_{mp}	2.59 A
Open circuit voltage (V)	V_{oc_n}	22,1 V
Short circuit current (A)	I_{sc_n}	2.89 A
Temperature coefficient of V_{oc_n} (V/K)	K_v	$-0.070\ V/K$
Temperature coefficient of I_{sc_n} (A/K)	K_i	1.66 mA/K

II. Methodology

A. Models

The photovoltaic panel is constituted by many photovoltaic cells connected to each other that are responsible for the transformation of photons emitted by the sun into electricity through the photovoltaic effect [2], [4]. Separately each photovoltaic cell produces little power and generates a very low voltage. In order to be able to generate more energy, photovoltaic cells are connected in series and parallel forming the photovoltaic panels.

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I. Equivalent Circuit:

The equivalent circuit is represented in Figure 1. The simplified equivalent circuit contains two resistances: one in series representing the voltage drop when the charge migrates from the electrical contacts and one resistance in parallel representing the reverse leakage current of the diode. V_{oc} is the open circuit voltage and I_{pv} is a constant continuous current source. The temperature is not a parameter. The PV curve does not change when variations on temperature happen. Where R_s, R_p and I_{pv} are calculated by (1), (2) and (3):

$$R_s = \frac{V_{oc_n} - V_{mp}}{I_{mp}} \qquad (1)$$

$$R_p = \frac{V_{oc_n}}{I_{sc_n} - I_{mp}} \qquad (2)$$

$$I_{pv} = I_{sc_n} \frac{G}{G_{ref}} \qquad (3)$$

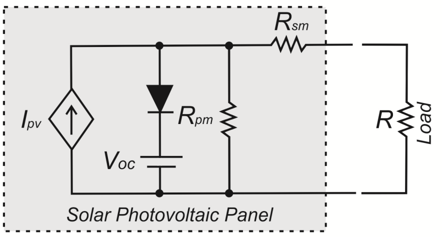

Fig. 1: Equivalent circuit of a photovoltaic panel

II. Mathematical Model

The equation of the current in the solar panel is:

$$I = I_{pv} - I_0 \left(e^{\frac{V + I\,R_s}{a\,V_t}} - 1 \right) - \frac{V + I\,R_s}{R_p} \qquad (4)$$

The variable I_{pv} is calculated by (5):

$$I_{pv} = \left(I_{pv_n} + K_i\,\Delta T \right) \frac{G}{G_{ref}} \qquad (5)$$

Where I_{pv_n} is the current in the nominal conditions, calculated by equation(6); $\Delta T = T - T_n$ (T is the solar panel temperature and T_n is the nominal solar panel temperature); G e G_{ref} are the values of incident solar irradiance and the reference irradiance (W/m^2), respectively. The variable K_i is the temperature coefficient of the short circuit current (A/K).

$$I_{pv_n} = \frac{R_p + R_s}{R_p} I_{sc_n} \qquad (6)$$

The reverse leakage current in the diode,I_0 is:

$$I_0 = \frac{I_{sc_n} + K_i\,\Delta T}{e^{\left(\left(V_{oc_n} + K_v\,\Delta T \right) / a\,V_t \right)} - 1} \qquad (7)$$

I_{sc_n} is the nominal short-circuit current, V_{oc_n} is the nominal open circuit voltage and K_v is the coefficient of the open circuit voltage (V/K). The variable $a$is the ideality constant of the diode, contained in the range$1 \leq a \leq 1.5$. $I_0$is strongly dependent on temperature and equation (7) is an alternative way to express this dependency showing a linear variation in open circuit voltage due to K_v. This equation also simplifies the model canceling the errors around the open circuit voltage points and consequently in other points of the IxV curve. Finally, V_t is calculated by (8):

$$V_t = \frac{k\,T}{e} \qquad (8)$$

Where k is the Boltzmann's constant, T is the temperature of the panel (K) and e is the electron charge.

In [5] and [6] it is proposed an algorithm for adjusting R_s and R_p. The method is based on the fact that there is an only pair $\{R_s, R_p\}$ in which the maximum power calculated by the I-V model P_{max_m} is equal to the maximum experimental power from the datasheet P_{max_e}. Using $P_{max_m} = P_{max_e}$ in equation (4), it will be obtained [5]:

$$R_p = \frac{V_{mp}\left(V_{mp} + I_{mp} R_s \right)}{V_{mp} I_{pv} - V_{mp} I_0 \left[e^{\left(\frac{V_{mp} + I_{mp} R_s}{a\,V_t} \right)} - 1 \right] - P_{max_e}} \qquad (9)$$

The interactive process is shown in Fig. 2. The initial values of R_s and R_p are [5]:

$$\begin{cases} R_{s_{min}} = 0 \\ R_{p_{min}} = \dfrac{V_{mp}}{I_{sc_n} - I_{mp}} - \dfrac{V_{oc_n} - V_{mp}}{I_{mp}} \end{cases} \qquad (10)$$

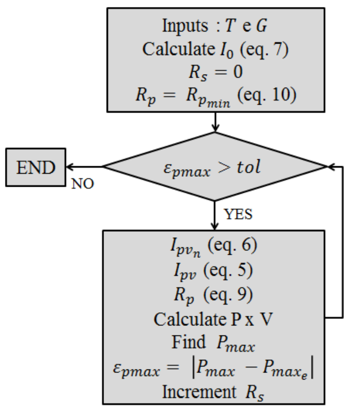

Fig. 2: Algorithm of the method used to adjust the I x V[5].

III. Solar Cell Multi Physical Model

The multi-physics modeling represents the influence of various phenomena in which a real system is subjected. There is in Matlab 7.10.0/Simulink®, in Simscape library, a multi physical model of a solar cell defined by 16. This model also contains two diodes which better represent the non-linear characteristic of the cell. Moreover, it is possible to observe the change in the series and parallel resistances with temperature.

The equation of the current in the solar panel is:

$$I = I_{pv} - I_{s1}\left(e^{\frac{V+I R_s}{a V_t}} - 1\right) - \\ -I_{s2}\left(e^{\frac{V+I R_s}{a V_t}} - 1\right) - \frac{V + I R_s}{R_p} \tag{11}$$

I_{pv} is calculated by (5), I_{s1} and I_{s2} are the reverse leakage current in each diode that are equal, in this case, and calculated by (12) and (13), where $\frac{TXIS1}{a} = 3$, as a default value.

$$I_{s1}(t) = I_{s2}(t) = I_{s1,n}\left(\frac{T}{T_n}\right)^{\frac{TXIS1}{a}} exp\left[\frac{qEg}{ak}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \tag{12}$$

$$I_{s1,n} = \frac{I_{sc_n} + K_i\,\Delta T}{exp\left({V_{oc_n}}/{a\,V_t}\right) - 1} \tag{13}$$

$$R_p(t) = R_p\left(\frac{T}{T_n}\right)^{TRP1} \tag{14}$$

$TRS1$ and $TRP1$ are zero in this work, because these parameters are not informed in the datasheets.

Comparing equations (7) and (13) it is possible to see the main difference between Model 2 and 3. In Model 2 there is one more coefficient for temperature influence, K_v.

Simulations were performed in Matlab/Simulink environment for a 1,2kW system. The three models were simulated according the parameters given by the manufacturers. The connection is made by a PWM three-phase controlled inverter in current mode.

B. Inverter connected to the grid

For the three models it is used a three phase inverter, Voltage Source Inverter – VSI, with IGBT switching. Fig. 3shows a schematic of the grid connected photovoltaic system through a controlled inverter. The control of the inverter keeps the voltage at the panel's terminal in a fixed value equal to the maximum power point (provided by the manufacturer) and it injects the generated power in the grid with the power factor close to the unity.

The controlled variables were written in direct and quadrature axis. The control loops of the inverter are shown in Fig. 4, there is the reactive power loop that controls the power factor and a loop for regulate the DC bus voltage. The current control loops use proportional controllers and the external loops use proportional-integral controllers [7]. The controller's gains were adjusted by the poles allocation method.

A Synchronous Reference Frame – PLL (SRF-PLL) circuit is used as synchronism technique to connect the system to the grid. This structure estimates the grid voltage angle for the control of the inverter. To reduce the harmonics generated by IGBT's switching a LCL filter was used. The designer of this component is in [8].

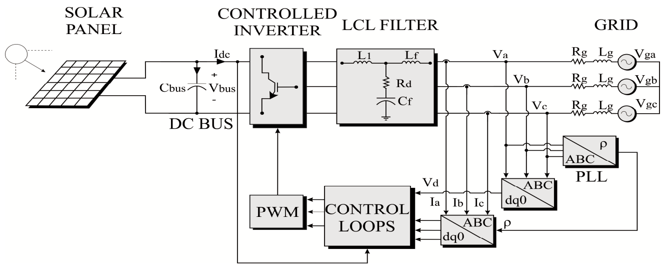

Fig. 3: Simulated grid-connected photovoltaic system

In order to do the maximum power point tracker of the solar photovoltaic panel an incremental conductance algorithm was used. This method computes the maximum power point by comparison of the incremental conductance to the array conductance. When the incremental conductance is zero, the output voltage is the maximum power point (MPP) voltage. The controller maintains this voltage until the irradiation changes and the process is repeated [9].

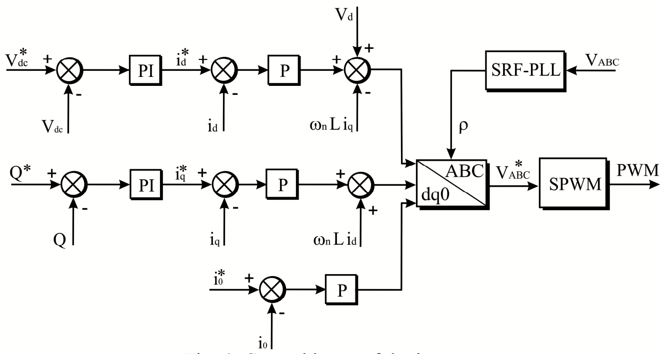

Fig. 4: Control loops of the inverter

C. Inserting Disturbances

The electrical energy is subjected to many disturbances as harmonics and voltage sags [10].

Harmonics are waves of multiple frequencies of the fundamental and decreasing amplitude produced by any distorted sine wave, so, any device connected to the grid that can distort the sine wave will be producing harmonics [11].

In this work the behavior of the three models was tested by inserting harmonics and voltage sags. The parameters of the simulations are shown in TABLE II.

TABLE II
Parameters of the system

Parameter	Value
V_{DC} (DC Bus Voltage)	465 V
C_{barr} (Capacitance of DC Bus)	93.91µF
R_{grid} (Resistance of the grid)	4.03 µΩ
L_{grid} (Inductance of the grid)	107 nF
V_{rms}(Grid voltage)	127 V
G (Irradiance on panel)	1000 W/m^2
T_c (Temperature on panel)	25 ºC
L_1 (Inductance of theLCLfilter)	28.81 mH

L_f (Inductance of theLCLfilter)	576.2 µH
R_D (Resistance of the LCL filter)	26.21 Ω
C_f (Capacitance of the LCL filter)	3.29 µF

III. RESULTS

The first simulation submits the system to a voltage sag of 0.2 p.u. that lasts 0.1s, Fig. 5. The results for each Model are shown in Fig. 6. It is possible to observe that when the system suffers extreme voltage sag the current value rises and the control acts in order to maintain the power value before the sag. In this work it is not consider the current limit of the converter. We could see that the three models respond to it returning to their MPP value and the Mathematical Model is the fastest one to reach it.

The MPP of each model is associated to a different voltage point where its power is the greatest possible. This point is different for each model because the models are not the same, Fig. 7.Consequently in Fig. 8the DC bus stabilizes in different voltage values. This discrepancy is small when analyzing only one panel [3] but when associated it results in a considerable value.

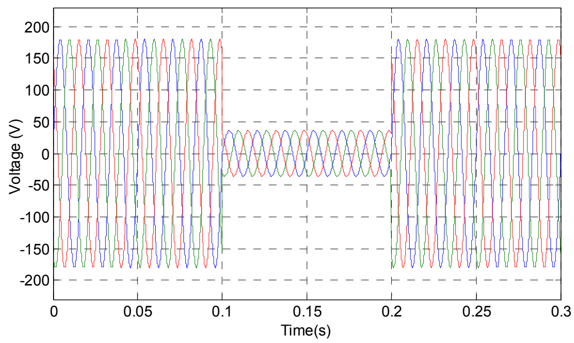

Fig. 5: Voltage on the grid

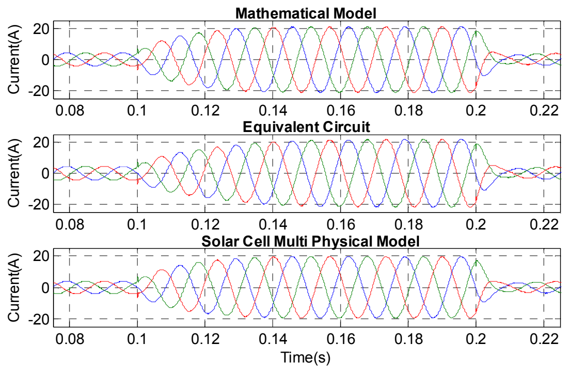

Fig. 6: Current for each panel during the voltage sag

The difference presented in the MPPT curve of the three models is due to its different dynamics and number of parameters each one considers.

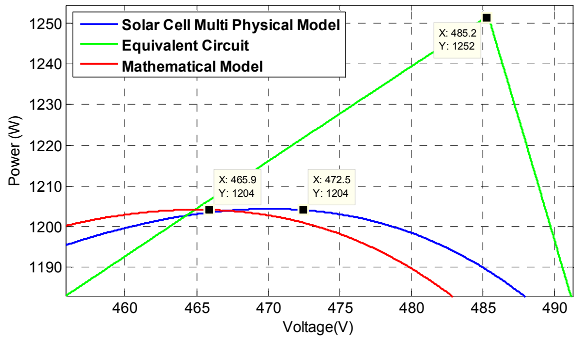

Fig. 7: Panel Curve for its Maximum Power Point

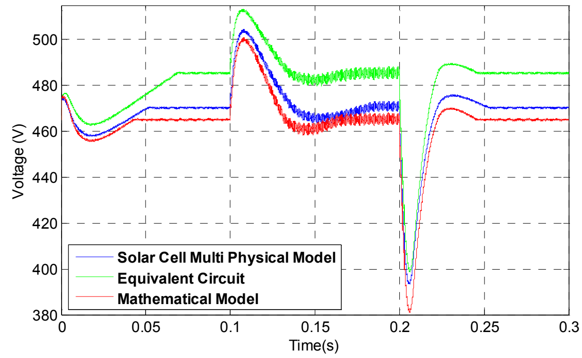

Fig. 8: Voltage on the DC Bus during the voltage sag

As regards the insertion of harmonics, the simulations showed that the three models behave in a very similar way but as we can see in TABLE IV and TABLE V, for some harmonic orders, the variation rate was smaller.

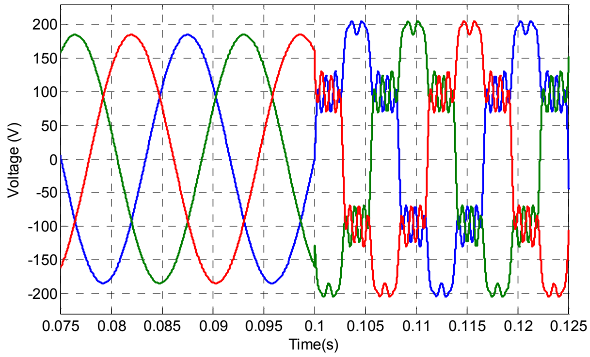

Fig. 9: Voltage on the grid during harmonics insertion

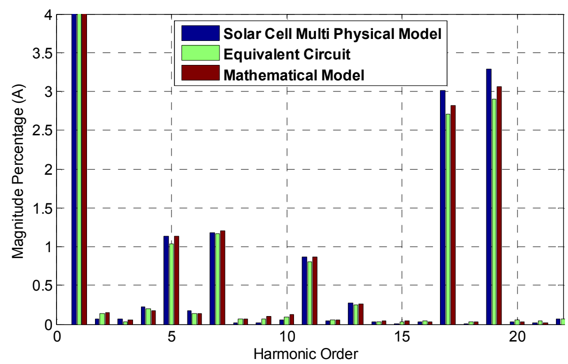

Fig. 10: Current Spectrogram

The Mathematical Model overcomes the Equivalent circuit Model once that it has the temperature as one of its parameters and also spent the same simulation time independent of the panel's number. Nevertheless, the Multi-Physical Model overlaps the previous models considering each cell's characteristics and all the other variations on the panel, generating a PxV curve really close to the one provided by the manufacturer. Its disadvantage consists in presenting a simulation time relatively high when compared to the other models.

TABLE III
Comparison between simulation time for the models in each disturbance

Models	Disturbances	Simulation Time (s)
Model 1	Voltage SEG	56.02
	Harmonic Distortion	57.90
Model 2	Voltage SEG	50.89
	Harmonic Distortion	55.84
Model 3	Voltage SEG	6,828
	Harmonic Distortion	6,929

TABLE IV
Individual harmonics

Model	Harmonic (Percentage of fundamental)				
	5th	7th	11th	17th	19th
Equivalent Circuit	1.04	1.16	0.81	2.71	2.91
Solar Cell Multi Physical Model	1.14	1.18	0.87	3.01	3.29
Mathematical Model	1.13	1.21	0.87	2.81	3.06

TABLE V
Comparison between non-distorted and distorted current

Model	Non-Distorted Grid	Distorted Grid
	THD (%)	THD (%)
Equivalent Circuit	0.56	4.37
Solar Cell Multi Physical Model	0.49	4.85
Mathematical Model	0.53	4.58

IV. Conclusions

In this paper, three models of solar panel have been explained. These models were simulated for voltage variation and harmonic voltage on the grid.

Both of the panels were connected to the grid through the same three phase inverter. But each model presented a different voltage in the maximum power point. This way, the reference of outer loop control of each panel is different. The presence of voltage harmonics on the grid affects the performance of these three models.

Future works will compare experimental results with the models results.

V. References

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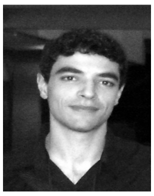
VI. Biographies

Marina Hassen de Souza was born in Belo Horizonte, Brazil. She is a student of Electrical Engineering at Federal University of Viçosa, Viçosa, Brazil. She is currently working at GESEP with microcontrolled systems and photovoltaic energy applied on power electronics.



Allan Fagner Cupertino was born in Visconde do Rio Branco, Brazil. He is student of Electrical Engineering at Federal University of Viçosa, Viçosa, Brazil. Currently is integrant of GESEP, where develop works about power electronics applied in renewable energy systems. His research interests include solar photovoltaic, wind energy, control applied on power electronics and grid integration of dispersed generation.

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