A Dynamic Maximum Power Point Tracker using Sliding Mode Control

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***Abstract*-This paper presents a maximum power point tracker method using sliding mode control for a photovoltaic module to produce and maintain the maximum power possible for a configuration of the array and the environmental variables. This is obtained using a variable structure control system to control the duty cycle of a DC-DC converter. The variable structure control system is a sliding mode control that will detect the maximum power that is available at a time and will force the PV array to work at this point. This method has the advantage that it will guarantee the maximum power output possible by the array configuration taking into considerations its dynamics parameters as temperature and solar irradiance. The procedure of designing the control law and results are presented in the paper.**

I. Introduction

A photovoltaic system is the technology that uses solar cells or an array of them to convert solar light directly into electricity. The power produced by these arrays depends directly from factors that are not controlled by the human being as the cell's temperature and solar irradiance. Photovoltaic cells have a single operating point where the values of the current and voltage of the cell result in a maximum power output. Each optimal operation point corresponds to particular resistance which is equal to the division of the maximum voltage and maximum current. Since this operating point depends on factors that are not constant and cannot be controlled, as temperature and solar irradiance, a device capable of tracking that point and force it to operate at that point is required. A maximum power point tracker is a device capable of search for the point of maximum power and, using DC-DC converters, extracts the maximum power available by the cell. A DC-DC converter is an electrical circuit that converts a DC source from one level of voltage to another level of voltage. It goes from one level to another by modifications of the switching duty cycle. By controlling the duty cycle of the switching frequency of the converter we can change the equivalent voltage of the cell and by that, its equivalent resistance into the one in which the PVM is in the maximum power operating point. In this work we present an implementation of a maximum power point tracker using a sliding mode controller as a pulse width modulator to control the switching frequency of a buck-boost converter in order to force the PVM to operate at its maximum power under dynamics factors.

II. System Description

In the Fig. 1, we can see the proposed scheme for the maximum power point tracker. This system use a PV system composed of N in series cells and P in parallel cells. It is connected to a converter in order to increase or decrease the desired voltage. After that, is connected directly to the load. The switching frequency is controlled by a sliding mode controller.

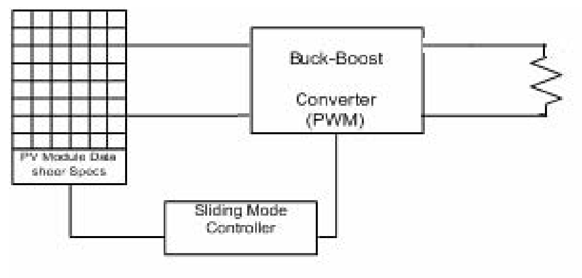

Figure 1. Proposed system scheme

A. *PV model*

In the past, there have been different types of models to estimate the non linear equations of the photovoltaic module. Models like Anderson's, Blesser and the most common the one diode model. All these models present a good approach into estimating the solar cell voltage and currents but most of them need too much computational power or need information not available in the manufacturer's sheet. A more suitable equation will be used where all the information needed can be found in the manufacturer's sheet. The PVM model is the following four equations.

$$I(V) = \frac{Ix}{1-\exp\left(\frac{-1}{b}\right)} \cdot \left[1-\exp\left(\frac{V}{b \cdot Vx} - \frac{1}{b}\right)\right] \quad (1)$$

$$P(V) = \frac{I_x}{1-\exp(-1/b)} \cdot \left[1-\exp\left(\frac{V}{b \cdot V_x} - \frac{1}{b}\right)\right] \quad (2)$$

$$Vx = s \cdot \frac{Ei}{Ei_N} \cdot TCV \cdot (T - T_N) + s \cdot V_{max} - s(V_{max} - V_{min})\exp\left(\frac{E_i}{E_{iN}} \ln\left(\frac{V_{max} - V_{op}}{V_{max} - V_{min}}\right)\right) \quad (3)$$

$$Ix = p \cdot \frac{E_i}{E_{iN}} \cdot [I_{sc} + TC_i \cdot (T - T_N)] \quad (4)$$

The first two equations (1) and (2) describe the relationship of the current and power with respect to the voltage. The PVM model takes into consideration the

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temperature, T, and effective irradiance, E_i, over the PVM and the Standard Test Conditions, STC, i.e. T_N is 25 °C and E_{iN} is 1000 W/m^2. The manufacturer data sheet will provide the temperature constant for the voltage, TCV, the temperature constant for the current, TCi, the open circuit voltage under STC, V_{oc}, short circuit current under STC, I_{sc}, and the PVM characteristic constant, b. Also, most of the manufacturers will provide the open circuit voltage, V_{max}, when E_i is more than 1200 W/m^2 and T is 25 °C and the open circuit voltage, V_{min}, when E_i is less than 200 W/m^2 and T is 25 °C[1] V_{max} is approximately $1.03 \cdot V_{oc}$ and V_{min} is approximately $0.85 \cdot V_{oc}$. This model considers the useful data given by the manufacturer while no additional parameters are required, i.e. thermal voltage, diode reverse saturation current, band gap for the material, etc. Also, the PVM model is continuous and differentiable with respect to the voltage. The open circuit voltage at any T or E_i, Vx is given by (3) and is calculated when the current of operation is zero. Ix, the short circuit current at any T or E_i, is calculated when the voltage of operation is zero and is given by (4).

B. DC-DC converter

In order to look for the point of maximum power we have to force the system to work at the optimal conditions. That means that it has to be working at the optimal voltage, Vop, and optimal current, Iop. Using a step-up converter (boost) will only guarantee that the maximum point of power will be found if the system is working in a point where the voltage is less than the optimal voltage. The same thing occurs for a step-down converter (buck) but when working in a point where the voltage is greater than the optimal voltage. In most of the cases you will need to be increase or decrease the values of voltages and current. The buck-boost converter let us step up or step down the voltage as we needed by controlling the frequency of switching of the switching devices composing them. For the buck-boost we are going to be using the following parameters:

C: 1000uF L: 100uH For the switch we are going to use an IGBT. The switching frequency will be generated by the sliding mode output.

III. SLIDING MODE CONTROLLER SURFACE

A sliding mode controller is a variable structure control where the dynamics of a non linear system is altered via the application of a high frequency switching control. In sliding mode control, the trajectories of the system are forced to reach a sliding manifold of surface, where it exhibit desirable features, in finite time and to stay on the manifold for all future time. It is achieved by suitable control strategy. To apply sliding mode control we have to know if the system can reach the sliding manifold. Once the systems reach the sliding manifold, the controller has to force the system to stay in the manifold for all future time. To design the sliding mode controller we have to select the desired surface. We want to obtain the maximum power that can be extracted from the PV module at the given factors. A typical P-V curve for a PVM is given by Fig. 3. The power of the PV module is given (2).

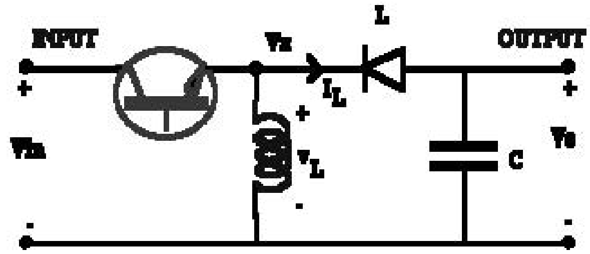

Figure 2. Buck-Boost Converter

A sliding mode controller is a variable structure control where the dynamics of a non linear system is altered via the application of a high frequency switching control. In sliding mode control, the trajectories of the system are forced to reach a sliding manifold of surface, where it exhibit desirable features, in finite time and to stay on the manifold for all future time.

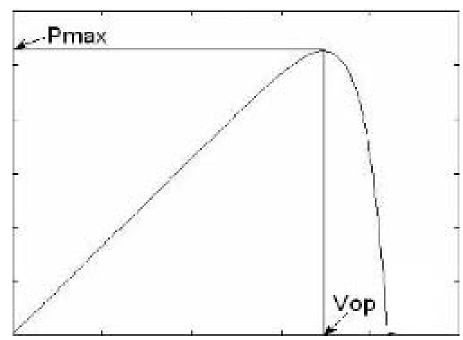

Figure 3. Power vs. Voltage

Clearly, Fig. 3 shows that the maximum power occurs at a given optimal voltage, Vop, which it smaller that the open circuit voltage, Vx. If we derivate the power with respect to the voltage we obtain the following equation [1]:

$$\frac{\partial P(V)}{\partial V} = \frac{Ix - Ix \cdot exp\left(\frac{V}{b \cdot Vx} - \frac{1}{b}\right)}{1 - exp\left(\frac{-1}{b}\right)} - V \cdot \frac{-Ix \cdot exp\left(\frac{V}{b \cdot Vx} - \frac{1}{b}\right)}{b \cdot Vx - b \cdot Vx \cdot exp\left(\frac{-1}{b}\right)} \quad (5)$$

At the knee of the P-V curve is the maximum power of the PVM. Also at the knee, the derivative of power with respect to voltage is zero. Solving (5) for V we obtain the optimal voltage, Vop. Unfortunately, (5) is a transcendental function that cannot be solve for V. To solve this problem the Linear Reoriented Coordinates Method will be used to approximate the optimal value for the voltage to obtain the maximum power as given by (6).

$$Vop = Vx + Vx * b * \ln(b - b * \exp(-1/b)) \quad (6)$$

Where Vx is the open circuit voltage, b is the characteristic constant for the PVM. To obtain the optimal current, Iop, (6) is substituted by (1). Finally, knowing that we can formulate our sliding manifold as the following:

$$S = 1/2 - 1/2 sign(Vop - V) \quad (7)$$

IV. SIMULATION

The system was simulated using Matlab's Simulink software with the power system toolbox. With this software we simulate and test the sliding mode controller and the proposed model. The Simulink model is shown at Fig. 3.

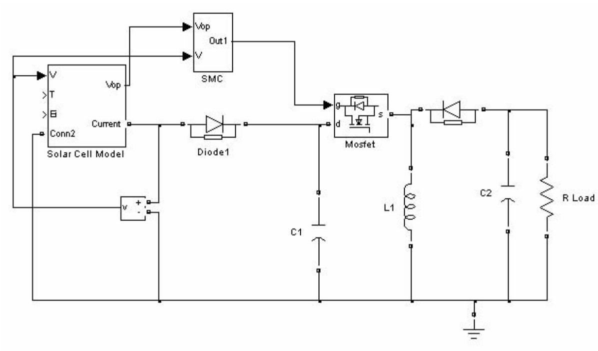

Figure 4. Simulation Scheme for the Proposed Model.

The photovoltaic module model was represented by a single block composed by a Matlab Embedded function containing the equations of a solar cell [1] [4]. The system was simulated under constant ambient temperature and solar irradiance and under varying ambient temperature and solar irradiance.

Appendix C shows the computer simulation results of the PV system for constant ambient conditions and without the sliding mode controlled Buck-Boost converter. Appendix D shows the computer simulations results of the PV system for constant ambient conditions but with the SMC buck-Boost converter. The simulation in Appendix E shows the results of the PV system for varying ambient conditions without SMC BB converter. Appendix F shows the results of the simulation with varying ambient conditions with SMC BB converter.

The results of the simulation validates the sliding mode controller and ensure that the PV operation point is in the knee point of the power vs. voltage graph were the PV operates at its maximum power even under varying ambient temperature and solar irradiation conditions.

V. CONCLUSIONS

This paper presents a dynamic maximum power point tracker sliding mode controller for a photovoltaic system capable of compute the maximum power point under varying ambient temperature and solar irradiation. The proposed controller is capable of change the switching frequency of the converter in order to move the operation point of the PV system to the optimal operation point and to maintain this operation point with time. The proposed algorithm to calculate the optimal voltage is capable of compute the corresponding value under different ambient temperature and solar irradiance with a very little error. The proposed controller only requires the array output voltage and the optimal voltage which is continuously computed. From the simulation results is evident that a maximum power is tracked and achieved by the proposed sliding mode controller under constant and varying ambient temperature and solar irradiance.

VI. APPENDICES

A. System value

C1: 5000uF C2:10,000uF L1:100mH R: 50 Ohms

B. Solar cell parameters

TABLE I
SPECIFICATIONS FOR A SIEMENS SP75

Voc (V)	Isc (A)	b	TCi (mA/C)	TCv (mV/C)	Vmin (V)	Vmax (V)
21.7	4.8	0.087	2.06	-77	18.45	22.243

TABLE II
SPECIFICATIONS AND PARAMETERS OF THE PV SYSTEM

Cell in Series	Cell in Parallel	Vop (at T=25$_o$C and Ei=1000W/m$_2$)	Pmax (at T=25$_o$C and Ei=1000W/m$_2$)
4	2	277V	2398 W

C. Simulation results for constant ambient conditions without sliding mode controlled buck-boost converter

TABLE III
SPECIFICATIONS AND PARAMETERS

T ($_o$C)	Ei (W/m$_2$)	Calculated Vop	Calculated Pmax
25	1000	281.5 V	2,394 W

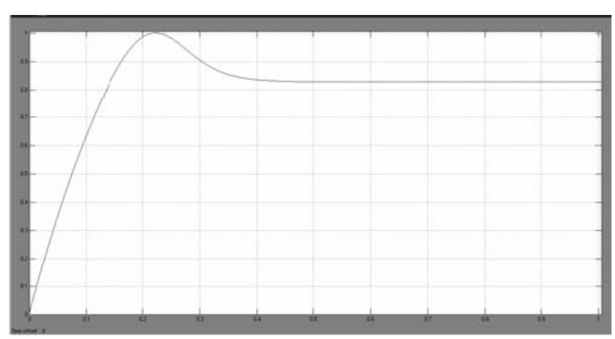

Figure 5. PV Output Power Vs Time

D. Simulations result for constant ambient conditions with sliding mode controlled buck-boost converter

TABLE IV
SIMULATION RESULTS FOR A CONSTANT AMBIENT CONDITIONS WITHOUT SLIDING MODE CONTROLLED BUCK-BOOST CONVERTER

T ($_{o}$C)	Ei (W/m$_{2}$)	Calculated Vop	Calculated Pmax
25	1000	281.5 V	2,394 W

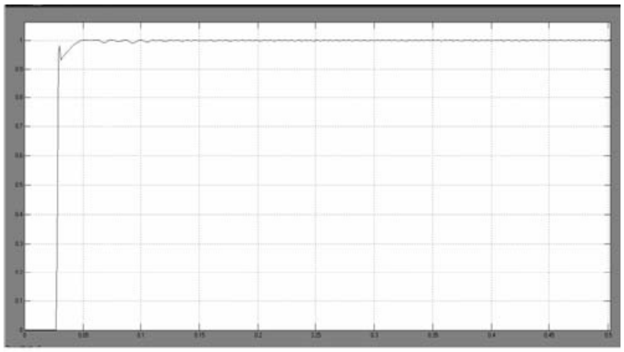

Figure 6. PV Output Power Vs Time

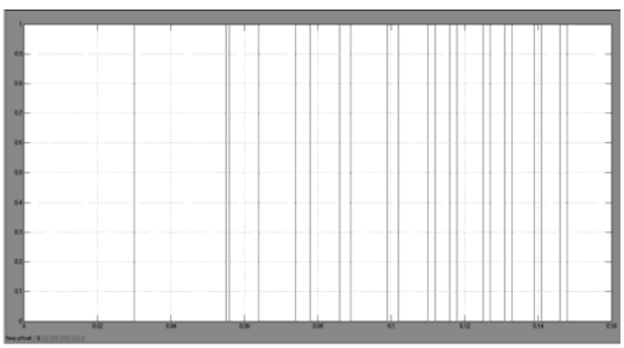

Figure 7. Sliding Mode Output Vs Time

E. Simulations result for varying ambient conditions without sliding mode controlled Buck-Boost converter.

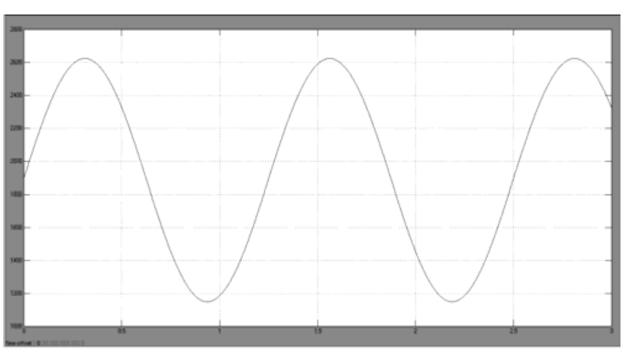

Figure 8. PV Maximum Power Available Vs Time(s)

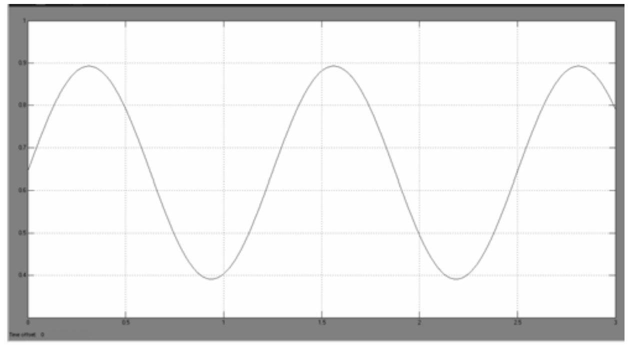

Figure 9. PV Output Power Vs Time(s)

F. Simulations result for varying ambient conditions with sliding mode controlled Buck-Boost converter.

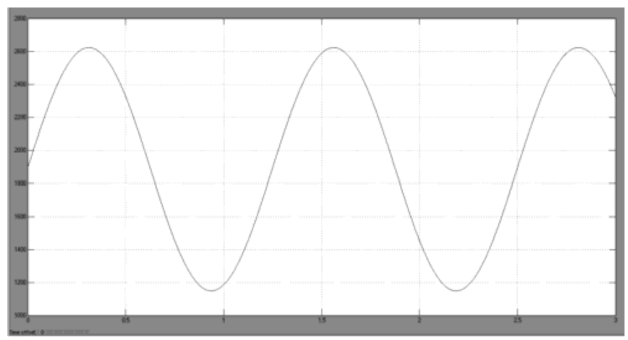

Figure 10. Dynamics of the PV Maximum Output Power vs Time

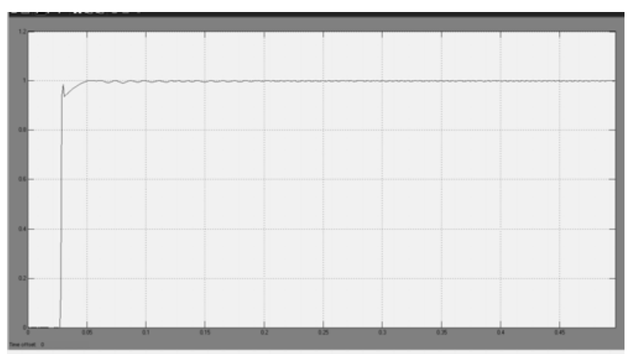

Figure 11. PV Output Power divided by maximum power vs Time

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