Simple Photovoltaic Solar Cell Dynamic Sliding Mode Controlled Maximum Power Point Tracker for Battery Charging Applications

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Abstract - **In this paper, we present a maximum power point tracker and estimator for a PV system to estimate the point of maximum power, to track this point and force it to reach this point in finite time and to stay there for all future time in order to provide the maximum power available to the load. The load will be composed of a battery bank. This is obtained by controlling the duty cycle of a DC-DC converter using sliding mode control. The sliding mode controller is given the estimated maximum power point as a reference for it to track that point and force the PV system to operate in this point. This method has the advantage that it will guarantee the maximum output power possible by the array configuration while considering the dynamic parameters temperature and solar irradiance and delivering more power to charge the battery. The procedure of designing, simulating and results are presented in this paper.**

I. Introduction

In the actuality a lot of research work has been conducted to improve the use of the sun's energy. The generation of electricity using photovoltaic solar cells has been one of the most researched and studied. Photovoltaic is the technology that uses solar cells or an array of them to convert solar light directly into electricity. The power produced by the array depends directly form factors that are not controlled by the human being as the cell's temperature and solar irradiance. Usually the energy generated by these solar cells is used to provide electricity to a load and the remaining energy is saved into batteries.

Photovoltaic cells have a single operating point where the values of the current and voltage of the cell result in a maximum power output. These values correspond to a particular resistance which is equal to the division of the maximum voltage and maximum current. By connecting the PV cell directly to a load or a battery, the output power can be severely reduced due to load mismatching or, in case of a battery, load voltage mismatching. Since this operating point depends on factors like temperature, solar irradiance and load impedance, a device capable of tracking the maximum power point and force the PVM to operate at that point is required. A maximum power point tracker (MPPT) 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. 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.

Several methods have been designed and implemented to search for this operation point. A common method is the Perturb and Observe (P&O) algorithm [1-2]. Classical P&O algorithms tend to measure the converter's output power in order to modify the input voltage by modifying the converter's duty cycle. Another common method is the hill climbing method [3-4].This method is based on a trial and error algorithm in where the voltage is increased until you reach such voltage where the PV exhibits maximum power. Other MPPT algorithms sample the open circuit voltage and operate the PV module at a fixed percent of this voltage. Incremental conductance algorithms are another method to track the MPP [5-7]. Other methods that have been used to obtain the maximum power are parameters estimations [9], neural networks [10] and linear reoriented method [12].

Some of the disadvantages with these methods are that some of them require doing a lot of iterations to calculate the optimal steady state duty ratio. Some of them use approximate values that do not guarantee near maximum power output. Some of them can be very complex, can be slow and can become instable if the MPP moves abruptly.

In this paper, we present an implementation of a maximum power point tracker, based in reaching a reference open circuit voltage, using a sliding mode controller to control the duty cycle of a DC-DC converter in order to force the PV module to operate at its maximum power point, for a given temperature and irradiance, to improve the utilization of the produced energy when connected to a load. For this case the load it's a battery and a resistance.

II. Proposed System

Figure 1 shows the proposed scheme for the MPPT.

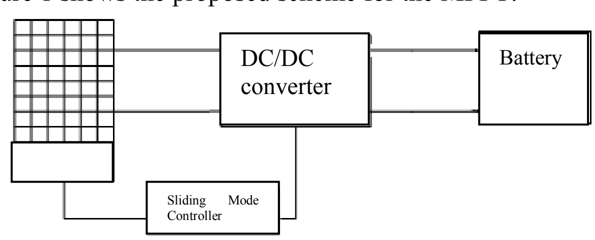

Figure 1: Proposed system scheme

This system use a PV array (*s* x *p*) composed of *s* in series cells and *p* in parallel cells. It is then connected to a

DC-DC converter in order to increase or decrease the desired voltage. It is then connected directly to the load, which is composed of a 12 V battery. The duty cycle of the converter is controlled by a sliding mode controller.

The proposed model will guarantee the extraction of the maximum power that can be produced by the PVM while regulating the load voltage to the battery's voltage. That way we can have a workable load voltage that can be connected to an inverter while matching the load resistance to the PV optimal resistance.

III. Mathematical Background

This section presents mathematical terms used in the paper.

- Re( ) Function - It extracts the real part *a* of a complex number written in the form *a+bi*. A complex number is a number which can be formally defined as an ordered pair of a real number
- Lambert's W Function, *lambertw(x)* - The Lambert's *W* function, which was named after Johann Heinrich Lambert, is defined to be the solution *W(x)* of the non linear equation, $W(x)\exp(W(x)) = x$.

IV. PV Model equations

In the past, there have been different types of models to estimate the non-linear equations of the photovoltaic module (PVM). Some of these models are the Anderson's, Bleasser 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 model to simulate a PV module is proposed by [13][15]. The PVM model is know as the Ortiz PVM model. In that work, a PV model was proposed where analytical equations relates the PV output current with the PV output voltage, temperature and solar irradiance over the PV module. It also shows experimental results validating the accuracy and effectiveness of the proposed model. An advantage of this model is that all the needed information can be found in the manufacturer's data sheet. Also it shows how the PV power is affected by changes in the temperature and solar irradiance. The equations are the followings:

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

$$P(V) = V\cdot I(V) = \frac{V\cdot Ix}{1-\exp\left(\frac{-1}{b}\right)}\left[1-\exp\left(\frac{V}{b\cdot Vx}-\frac{1}{b}\right)\right] \tag{2}$$

$$Vx = s\cdot\frac{E_i}{E_{in}}\cdot TCV\cdot(T-T_N)+s\cdot V\max - s\cdot(V_{\max}-V_{\min})\cdot\exp\left(\frac{E_i}{E_{in}}\cdot\ln\left(\frac{V_{\max}-V_{oc}}{V_{\max}-V_{\min}}\right)\right) \tag{3}$$

$$Ix = p\cdot\frac{E_i}{E_{in}}\cdot\left[I_{SC}+TCi\cdot(T-T_N)\right] \tag{4}$$

Ix and *Vx* represent the short circuit current and open circuit voltage at a given temperature and solar irradiance. *V* is the PVM output voltage, *T* is the PVM temperature, T_N is the standard conditions temperature, E_i is the effective solar irradiance at the PVM, E_{in} is the standard condition solar irradiance, *TCV* is the open circuit voltage temperature coefficient and *TCi* is the short circuit current temperature coefficient. V_{max} is the open-circuit voltage at 25°C and more than 1200W/m^2. V_{min} is the open-circuit voltage at 25°C and less than 1000W/m^2.

Figure 1 shows the non linear relation between the current and the voltage given by the (1). Figure 2 shows the non linear relation between the power and the voltage, given by (2) under standard conditions. We can see that the maximum power produced by the PVM occurs at a certain voltage level. Since the function of power depends only of the voltage and it is differentiable for all values of voltage, then maximum power that can be extracted from the PVM will occur when the partial derivate of the power with respect to the voltage is equal to cero. The partial derivate of the power against voltage is given in the following equation:

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

By equaling (5) to zero and solving by the voltage we can obtain the optimal voltage which is given by (6).

$$Vop = \mathrm{Re}\left(b\cdot Vx\left(lambertw\left(-0.36787944\ e^{\frac{1}{b}}\right)+1\right)\right) \tag{6}$$

From (6) we can obtain a very approximate estimate of PV cell's output voltage at which maximum power occurs. The advantage of this equation is its dynamic property. The only variant term is *Vx*. Given that we can express the equation as the following:

$$Vop = C\cdot Vx \tag{7}$$

$$C = \mathrm{Re}\left(b\cdot\left(lambertw\left(-0.36787944\ e^{\frac{1}{b}}\right)+1\right)\right) \tag{8}$$

Since it depends on *Vx* and *Vx* vary with respect to temperature and solar irradiance, the optimal voltage will vary with respect to the conditions of the temperature and irradiance, giving always an estimation of the required voltage necessary to extract the maximum power from the PV cell for all external conditions.

V. 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.

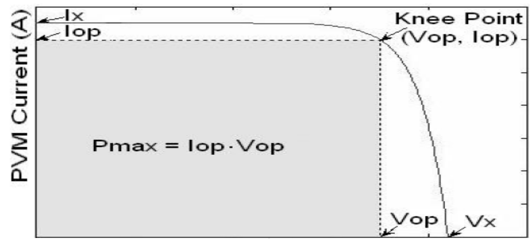

Figure 2: PV Output Power Vs Time

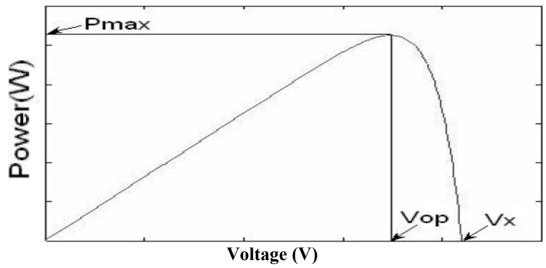

Figure 3: PV Output Power Vs Time

Sliding Mode Control is widely use for a lot of applications including control systems for DC/DC converters [8][14], power supply, electric grid connections[9], motors speed regulator[14], position control system, among others. 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 temperature and irradiance conditions. From (6) we can relate that maximum power to an optimal voltage. Since we know the output voltage we have to have in order to extract the maximum power from the PV system, we choose a surface that will force the system to reach that voltage in a finite time and stay there for infinite time. With that in mind, we chose the following sliding manifold:

$$\sigma = V - V_{op} \tag{9}$$

V is the output voltage of the PV cell and Vop is the optimal voltage. This sliding manifold will assure us to force all the trajectories of the system to reach the optimal voltage and to keep it in the optimal voltage for all future time. Since the optimal voltage is dynamic since it change when changes occur in the temperature and irradiance this sliding surface is also changing with respet to the temperature and irradiance giving us a dynamic sliding surface. The sliding mode will be controlling the duty cycle of a switching device. So the switchin device will have two operation state:

$$\begin{cases} On & V - V_{op} > 0 \\ Off & V - V_{op} < 0 \end{cases}$$

Now, the controller will behave in the following way:

$$u = \begin{cases} 1 & V - V_{op} > 0 \\ 0 & V - V_{op} < 0 \end{cases}$$

A control law that guarantees us that our controller will behave in that way is given by the following equation:

$$u = \tfrac{1}{2} + \tfrac{1}{2} \cdot sign\left(V - V_{op}\right) \tag{10}$$

This law of control also guarantees us that the system trajectories will reach the proposed manifold and will stay there for all future time. This can be explained in a practical way. At first, because the PVM is not connected, the PVM output voltage will be equal to its open circuit voltage. Since the open circuit voltage is greater than the optimal voltage the switching device will be on. When the switch is on, the PVM output voltage will begin to drop because of the load mismatching until it reaches below the optimal voltage. Then the switch will turn off creating an open circuit condition forcing the PVM output voltage to increase up to its open circuit voltage. When the output voltage passes the optimal voltage then the switch will turn off and the sequence will start again and will continue for all future time. This control law works for a variety of DC-DC converters like the Buck converter, SEPIC converter and Buck-Boost converter.

VI. 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 figure 4.

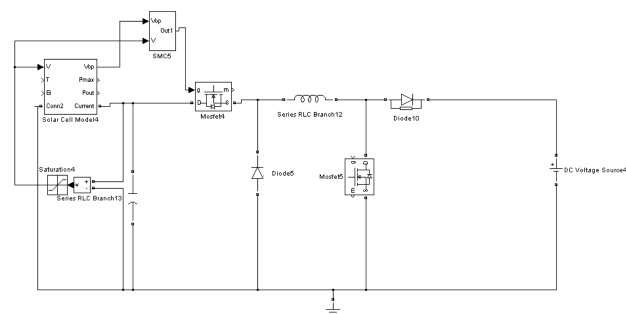

Fig 4: Simulation Scheme for the Proposed Model.

The solar Cell model was represented by a single block composed by a Matlab Embedded function containing the equations of a solar cell [13] [15]. The system was simulated under constant ambient temperature and solar irradiance and under varying ambient temperature and solar irradiance in order to validate the effectiveness of the controller. (1) and (6) were calculated and compare to the manufacturer's data sheet for several PV commercial models. The simulation results of the PV system, with constant ambient conditions, connected directly to the battery and connected to the battery by a non-inverting Buck-Boost converter, in Buck mode, are shown in figure 5 and 6. Simulations of the PV system, with varying ambient conditions, connected directly to the battery and connected to the battery by a non-inverting Buck-Boost converter, in Buck mode, were done. The converter in Buck mode only uses one Mosfet, the left one, and the second Mosfet is turn off. Finally, the simulations showed in figure 5, are for standard conditions for each PVM and figure 6, are for varying temperature and solar irradiance.

VII. Results

Table 1 and 2 shows the results of the estimated optimal voltage *Vop, Iop* and *Pmax* compared to the manufacturer's datasheet value. These tables validate (6) and (1) for the optimal voltage and optimal current estimation. The error percent for the voltage and current stays within acceptable values. Since the estimation are very near to the optimal values given by the manufacturer, by forcing the system to operate at the estimated voltage, guarantee us to be working in a near maximum power point. Figure 5 shows the temperature and irradiance over the PVM. Figures 6 and 7 validate 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 standard conditions(STC) and under varying ambient temperature and solar irradiation condition while supplying a higher power to the battery. Table 3 shows the percentage of increment in the power given to the battery. It can be seen that the proposed method increase significantly the available power delivered to the battery. Figures 8 and 9 show the simulation results of the power that is given to the battery for two different connection modes, directly to the battery and through a converter.

PV Model	Vop Datasheet	Vop Estimated	Error %	Iop Datasheet	Iop Estimated	Error %
SiemenSP75	17.0	17.593	3.49	4.40	4.2524	3.35
Shell SQ80	17.5	18.156	3.74	4.58	4.4305	3.27
SLK60M6	30.6	30.762	0.53	6.86	6.8193	0.59
Solare SX-5	16.5	16.673	1.05	0.27	0.2669	1.17
SolarxSX-10	16.8	17.098	1.774	0.59	0.5789	1.87

Table 1: Comparison of PV voltage and current estimated values vs. Datasheet values

PV Model	Pmax Datasheet	Pmax Estimated	Error %
Siemens SP75	74.8	74.815	0.02
Shell SQ80	80.15	80.44	0.36
SLK60M6	209.92	209.777	0.068
Solarex SX-5	4.455	4.449	0.135
Solarex SX-10	9.912	9.8989	0.132

Table 2: Comparison of PV Power estimated value vs. Datasheet value

PV Model	Power at battery connected directly (W)	Power at battery connected through converter (W)	Increment in Power %
Siemens SP75	57.26	71.61	25.06
Shell SQ80	58.12	76.96	32.24
SLK60M6	90.23	191	111.68
Solarex SX-5	3.573	4.43	32.98
Solare SX-10	7.753	9.815	26.59

Table 3: Comparison of the power supplied to the battery

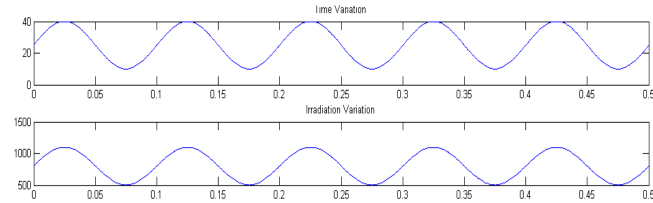

Fig 5: Temperature and irradiance variation over PVM

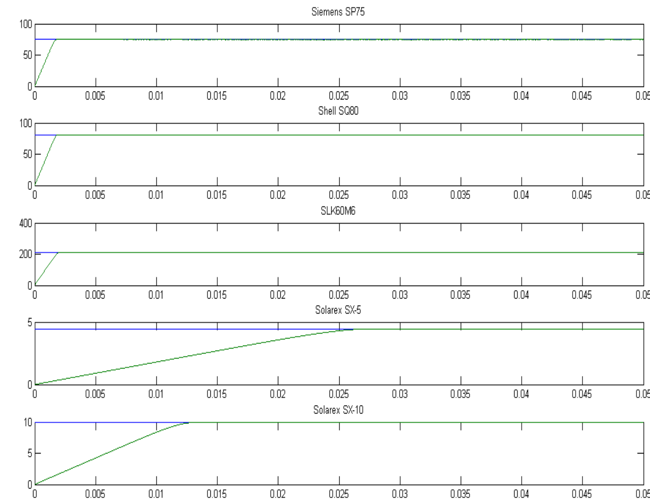

Fig 6: PV maximum possible output power (blue) vs actual PV Power when connected to proposed MPPT (green) at STC

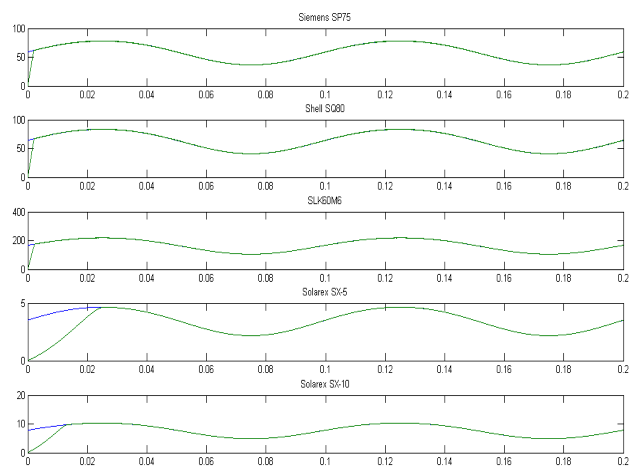

Fig 7: PV maximum possible output power (blue) vs actual PV Power when connected to proposed MPPT (green) at varying conditions

Those graphs reflects the importance of the use of a MPPT device since it can be seen that the power given to the battery is greater when connected through the MPPT converter than connected directly to the PV cell.

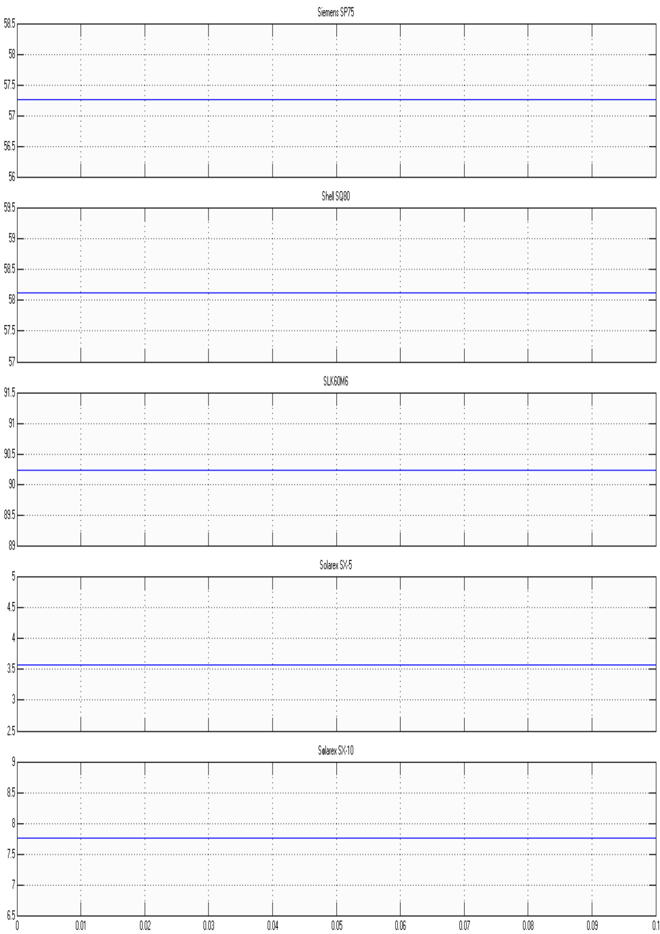

Fig 7: Power at the Battery for PV Modules connected directly to battery.

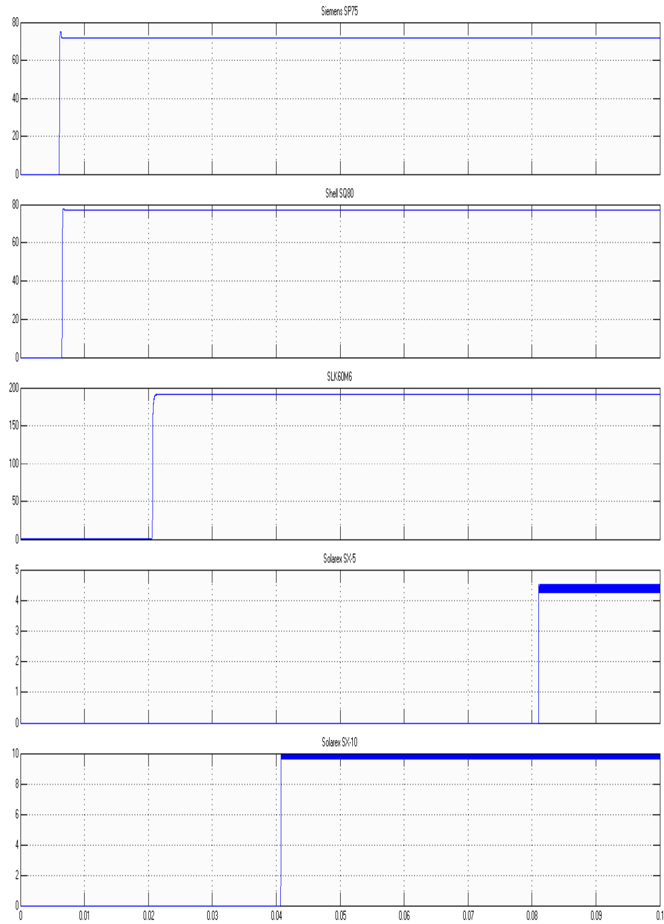

Fig 8: Power at the Battery for PV Modules connected to battery through DC/DC Converter.

VIII. Conclusion

This paper presents a simple photovoltaic solar cell dynamic sliding mode controlled maximum power point tracker for battery charging applications capable of compute the maximum power point under constant and varying ambient temperature and solar irradiation. The proposed controller is capable of changing the duty cycle of the Mosfet switch 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 uses a non inverting Buck-Boost converter in order to easily change the operation mode of the converter that can be necessary if the optimal voltage of the PV module is lower than the battery voltage. The proposed algorithm is capable of calculating the optimal voltage with 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 and delivered, with the losses in the converter, to the battery increasing the current that is charging the battery which, eventually, will reduce the charging time.

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