Design and performance analysis of a Maximum Power Point Tracking using Sliding Mode Controller for harvesting Photo Voltaic Power

S.Arun Sankar[1*], M.Willjuice Iruthayarajan[2]

[1*]Lecturer, Electrical and Electronics Engineering Department
P.A.C.Ramasamy Raja Polytechnic College, Rajapalayam, Tamilnadu-626108.
*arunsankar.memba@gmail.com
[2]Professor, Electrical and Electronics Engineering Department
National Engineering College, Kovilpatti, Tamilnadu-628503
m.willjuice@gmail.com

Abstract- In this paper the design and performance analysis of a Sliding Mode Controller (SMC) based Maximum Power Point Tracking (MPPT) in a Photo Voltaic system is reported. The proposed system uses the Positive Output Luo Converter (POLC) as the power converter. The performance of the SMC for the purpose of MPPT is analysed, contrasted and compared against the performance of the Perturb and Observe (P and O) algorithm. A MATLAB SIMULINK based simulation has been carried out and the proposed idea has been validated using simulation and a suitable experimental verification system.

Key Words: Photo Voltaic Power harvesting, Maximum Power point tracking, Perturb and Observe method of MPPT, Sliding Mode Controller, Positive Output Luo Converter.

1. Introduction

The fast depleting fossil fuels has triggered the exploration of putting into use all the available renewable energy sources primarily including the Photo Voltaic(PV) and the wind power [1]. The Photo Voltaic power generation is a better candidate by virtue of its ease of operation and maintenance. PV power generation is environment friendly and it does not incur running cost in the form of any fuel [2].

Unlike the conventional DC sources like the DC generators, the photo voltaic power generation using the solar panels demands the operation of the panels at an optimal load condition which is variable from time to time as the solar irradiation and temperature changes [3, 4]. Thus in order to maximise the power harvested from the PV panel, in the face of changing climatic or environmental conditions, the electrical load on the PV panel has to be adjusted appropriately. Thus enabling the maximum harvest of the power that is available at any given moment and this process is known as the Maximum Power Point Tracking (MPPT) [3, 4, 5].

Down the history, there had been many developments in the design of MPPT. The Perturb and Observe (P and O) [6], the incremental conductance (Inc) [7] and some modifications have also been reported in the literature. Besides soft computing has also been exploited in the attempt to develop MPPT systems which include the Fuzzy Logic Control (FLC) and the Artificial Neural Network (ANN) [8, 9, 10].

Heuristic algorithms have also been used for the implementation of MPPT. The Genetic Algorithm and the Particle Swarm Optimization (PSO) are the popular in this category [11, 12].

In the perspective of the converter used for harvesting the photo voltaic power both DC to DC and direct DC to AC converters have also been developed. Photo voltaic power generation schemes have been developed to cater to both DC and AC loads simultaneously as well like that used in a typical micro grid [13].

In the DC to DC conversion category the generic converters like the buck, the boost, the buck boost have been used along with the MPPT algorithms so as to derive the maximum power from the solar panel [14]. Each of the generic DC to DC converters suffers a certain drawback. Specifically the buck converter cannot be used in situations where the load needs a higher voltage than the available one. Similarly the boost converter cannot cater to a low voltage load that has to operate with a voltage less than the source voltage. The buck boost converter overcomes this drawback but the disadvantage is that it suffers from the polarity inversion problem [15]. The output and the input voltage polarities are inverted in the case of the buck boost converter. Although it is not a problem with stand alone loads it makes the circuit arrangement complex when it is required to measure the actual output voltage, feed it back and go ahead with a closed loop control system.

The polarity inversion problem can be solved by using the Positive Output Luo Converter (POLC).The POLC is therefore a suitable candidate to be used as a DC to DC converter with MPPT incorporated control system.

In this research the applicability of the POLC along with the Sliding Mode Controller (SMC) [17] is studied in detail. Sliding mode controller has two advantages. It requires only one parameter to be monitored and that it does not require any explicit carrier. The performance of the SMC based MPPT is validated using suitable simulations in the MATLAB SIMULINK environment. An experimental verification system has also been developed to validate the proposed sliding mode controller based MPPT and the results have been compared with the P&O method of MPPT.

2. A review of the Photo Voltaic Power generation

Photovoltaic power generation is based on the principle of the generation of the photovoltaic current from a solar cell when it is impacted by the photon. Many individual basic photovoltaic cells are cascaded in series and parallel and the final two terminals are brought out. The electrical equivalent circuit of the photovoltaic cell is given in Figure 1 and it depicts the single diode model of the PV cell when the two diode model and three diode model have also been studied in the literature.
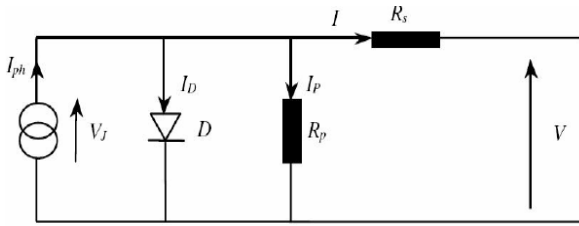
Figure 1.Single diode model of the PV

However the two important parameters of the photovoltaic panel that directly impacts its characteristics are the series resistance R_s and the parallel resistance R_p. The presence of the diode, the series and the parallel resistors make the analysis a little complex and especially this problem is more defined when the values of R_s and R_p are variable with respect to the operating conditions of the PV panel in respect of the available temperature, irradiation and the loading condition.

As such, in modelling the PV panel the challenge is the estimation of the values for R_s and R_p which is to be found on solving an exponential transcendental equation as shown in Equation(1) and that too has to be carried out in real time. The Newton Raphson method is a popular one used for this purpose. This paper does not model a PV cell and hence the details of the use of Newton Raphson or any other method used for estimating R_p and R_S are not discussed here. However it can be said that the complex characteristics of the PV panel can be attributed to the presence of the two dynamically varying resistances and the non linear nature of the internal diode.

$$I = I_{ph} - I_o \left\{ e^{\frac{q(V+R_SI)}{AKT}} - 1 \right\} - \frac{V+R_SI}{R_{sh}} \qquad (1)$$

where I is the PV array output current; I_{ph} is the cell photocurrent; I_o is the diode saturation current; q is the charge of the electron; v is the array output voltage; R_s is the series resistance; R_{sh} is the shunt resistance; A is the p-n junction ideality factor; K is Boltzmann's constant; T is the cell temperature.

The two typical characteristics of the Photovoltaic panel that are used in association with the design of a suitable converter incorporated with an MPPT algorithm are as shown in Figure 2.
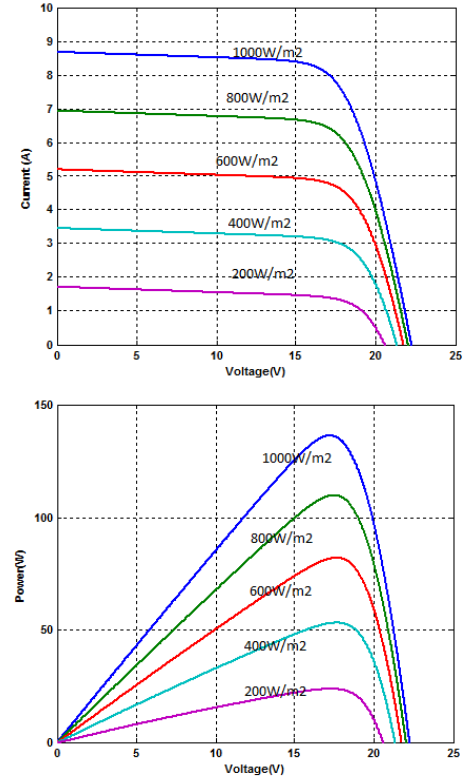

Figure 2. The Voltage Vs Current; Voltage Vs power family of Characteristics for different insolation levels.

3. The Positive Output Luo Converter

In Figure 3 the power control switch comes in series with the input DC power source. The Inductor L_1 is the shunt boost inductor and the inductor L_2 is the series filter inductor. The series inductor L_2 along with the output capacitor C_2 guarantees ripples free DC voltage across the load.
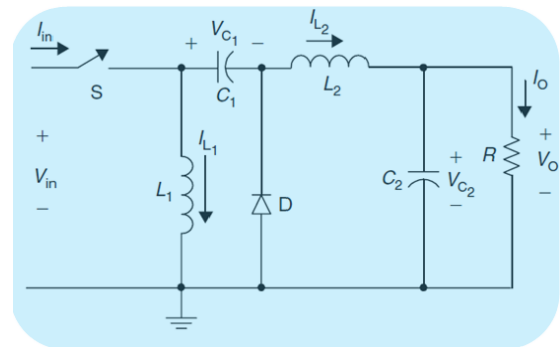

Figure 3. The schematic of the POLC used in this discussion

The output side and the input side are coupled through a series capacitor. When the converter is working the actual DC source voltage drops across the series capacitor and the voltage produced above the input voltage is passed on to the output. For example if the source voltage is 20V and the duty cycle is 0.6 then the steady state output voltage as given by the equation

$V_o = V_{in} * (d/(1 - d))$ and (Where V_{in} is the input voltage, V_o is the output voltage and d is the duty cycle). $V_o = 20 * (0.6/0.4)$ The output voltage will therefore be $V_o = 20 * 1.5 = 30V$.

In reality the actual voltage generated by the boost mechanism will be 50V and an equivalent of source voltage of 20V will drop across the series capacitor and the remaining will be 30V that will appear across the load.

Interestingly if the switch and the front end inductor or the boost inductor are just considered and if the relationship between the input voltage and the output voltage are related as a simple boost converter, the boosted voltage will be given by the relationship,

$$V_o = V_{in}/(1 - d) \qquad (2)$$

Substituting the input voltage Vin and the duty cycle 0.6 the boost voltage will be 20/(1-0.6) and Vo = 20/0.4 = 50V. Out of this 50V generated, the equivalent of the source voltage of 20V drops across the series capacitor and the remaining 30V appears across the load. This happens in compliance with the steady state equation for the output voltage of the POLC as given by,

$$V_o = V_{in} * (d/(1 - d)) \qquad (3)$$

The components that could incur power losses in the POLC are the power switch, the inductors and the series and the parallel capacitors. In this discussion we assume that the components are ideal and incur no losses and however in the simulation and in the experimental verification these losses will be exhibited.

3.1 The transfer function of the POLC

Before arriving the transfer function of the POLC when viewed between the input voltage V_{IN} and the output voltage V_O the following component specifications are considered [15].
$L_1 = 1$ mH
$L_2 = 1$ mH
$C_1 = 20$ μF
$C_2 = 20$ μF
R (the load resistance) = 10 Ohms.

The power electronic switch S and the diode D are considered to be ideal. This relaxation lets us treat the POLC under consideration a loss less entity with efficiency equal to 1. The switching frequency is 20 KHz and the duty cycle is denoted as d.

With values of components shown and considering the duty cycle of 0.6, the steady state of the system will be

$$V_O = V_{IN} * (d/(1 - d))$$
$$= 30V$$

The load current will be 30/10 = 3 Amps. By the principle of power balance with a conversion efficiency of unity the average input current will be,

$$I_{IN} = P_{IN}/V_{IN} \qquad (4)$$
$$= 90/20$$
$$= 4.5\ A$$

In view of the modern power electronic considerations the following lines are drawn out.
The pumping energy,

$$PE = V_{IN} * I_{IN} * T \qquad (5)$$
$$= 4.5\ mJ$$

The energy stored in the capacitor C_1 will be

$$W_{c_1} = 0.5 * C_1 * (V_{c_1})^2 \qquad (6)$$
$$= 4\ mJ$$

The energy stored in the capacitor C_2 will be,

$$W_{c_2} = 0.5 * C_2 * (V_{c_2})^2 \qquad (7)$$
$$= 9\ mJ$$

Energy stored in the inductor L_1 will be,

$$W_{L_1} = 0.5 * L_1 * (I_{in})^2 \qquad (8)$$
$$= 10.125\ mJ$$

Energy stored in the inductor L_2 will be,

$$W_{L_2} = 0.5 * L_2 * (I_0)^2 \qquad (9)$$
$$= 4.5\ mJ$$

Total stored energy $SE = (4 + 9 + 10.125 + 4.5)\ mJ$
$$= 27.63\ mJ$$
The Energy Factor $EF = SE/PE$
$$= 6.14$$
The ratio of energy stored in capacitor and inductor

$$CIR = W_c/W_L \qquad (10)$$
$$= 0.89$$

To arrive at the transfer function of the converter both the time constant τ and the damping time constant τ_d are required to be arrived at.

$$\tau = \left(\frac{2*T*EF}{1+CIR}\right) * (1 + CIR\frac{1-eff}{eff}) \qquad (11)$$

Where *eff* is the efficiency and it has been assumed to be 1

$$\tau = \left(\frac{2*T*EF}{1+CIR}\right) * (1 + 0)$$
$$= 324.86\ \mu s$$
$$\tau_d = \left(\frac{2*T*EF}{1+CIR}\right) * (CIR)$$
$$= 289.13\ \mu s$$

This results in the transfer function of the POLC as viewed between V_{in} and V_{out}.

$$G(s) = M/(1 + s\tau + s^2\tau\tau_d) \qquad (12)$$
$$= M(1 + s324.86 * 10^{-6} + s^2 324.86 * 10^{-6} * 289.13 * 10^{-6})$$

where M is the steady state voltage transfer ratio and M

$M = d/(1 - d)$ where d is the duty cycle. The transfer function of the POLC is of the second order and it gives a steady value after a short period of oscillations.

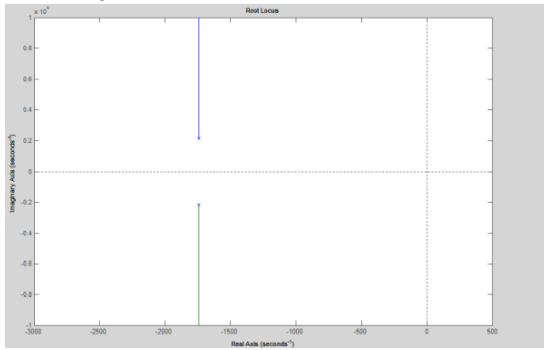## 3.2. Stability of the POLC

Figure 4.a. Stability of POLC by the Root Locus plot
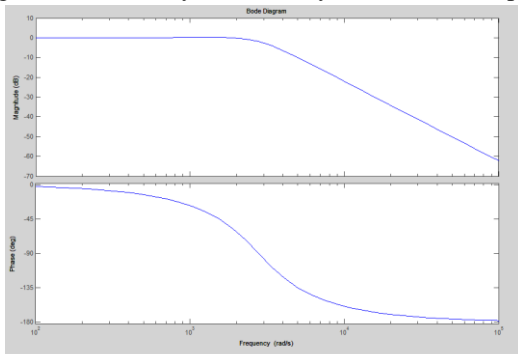

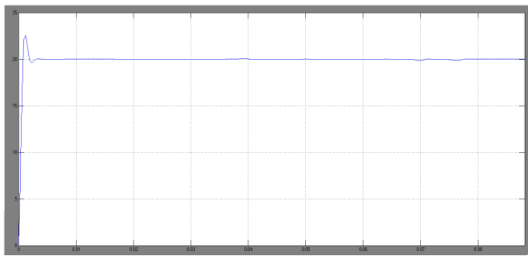Figure 4.b. Stability of POLC by the Bode Plot

Figure 4.c. Stability of POLC by Transfer Function response

4. Maximum Power Point tracking in PV panel

The function of the PV panels used for harvesting the solar power depends upon two environmental conditions and they are the temperature and solar insolation. Increased solar insolation increases the power generated by the PV panel while increase in temperature causes the reduction of electric power generated by the PV. It is the internal resistance of the solar panel that varies with regard to the available solar insolation and the prevailing temperature. In order to ensure that the power which is produced by the solar panel, is delivered to the load, the load resistance must be made equal to the source resistance automatically, by some special mechanism, called as Maximum Power Point Tracking. With the POLC as the power conversion system, the duty cycle of the power conversion switch is the only degree of freedom that is used for MPPT.

With reference to the circuit arrangement of the POLC as shown in Figure 3 the duty cycle of the POLC decides the equivalent resistance of the circuit that is connected across the solar PV panel.

In the conventional MPPT techniques like the Perturb and Observe method or the Incremental Conductance method of MPPT an explicit carrier is used and the duty cycle is decided by a reference signal generated by the MPPT algorithm. But in the case of the Sliding mode control technique there is no explicit carrier generated and the switching frequency and the duty cycle are both decided by the strength of the power available and the time constants of the circuit elements which take part in the active circuit with the switch in the open and closed conditions.

3.2. The Sliding Mode Controller

From the name plate details of the PV panel four important parameters are known and they are the V_{oc}, I_{sc}, V_{pmax} and I_{pmax} for the insolation of $1000 w/m^2$ and temperature 25^oC. The ratio between the voltage at maximum power point V_{pmax} and the Open circuit voltage V_{oc} is a constant of the panel K. If the panel terminal voltage is maintained at that voltage manipulated with the constant K and the particular V_{oc} for the prevailing solar insolation and temperature then MPPT is said to be achieved.

With reference to the circuit arrangement of the POLC as shown in Figure 3, if the switch S is opened then the capacitor C gets charged and eventually the charging current reaches zero thus reaching a condition when the solar panel delvers zero output power and the PV panel is left open circuited exhibiting the open circuit voltage V_{oc} across its terminals.

If the switch S is closed then the solar panel drives an exponentially increasing current through the front end inductor L_1. The rise of current causes the PV panels terminal voltage to fall and if left unchecked and if the internal resistance of the inductor is zero then the PV panel current will eventually reach the short circuit current.

Thus the power control switch can cause the PV panel to swing between the open circuit and short circuit conditions. In either of these two extreme conditions the power delivered by the PV panel will be zero. The maximum power point lies between these two extremes on the surface of the voltage current characteristic of the PV panel.

At the MPPT point, the terminal voltage of the PV panel should be $V_{pmax} = K * V_{oc}$ When the switch is closed, as the PV current rises and as the PV terminal voltage falls eventually this will reach the V_{pmax} value and as the PV voltage just crosses this voltage of V_{pmax} then the power control switch is opened and the

direction of the change in voltage now changes and it rises again above the V_{pmax} level. Once the terminal voltage crosses the V_{pmax} in its direction towards V_{oc} then the switch is immediately closed again. Thus the power control switch is opened and closed again and again, by considering the open circuit voltage V_{oc} and the terminal voltage with the switch closed.

The algorithm for the SMC method of MPPT can be simplified as follows [13].

$$If \ V_{pv} > V_{pmax} \ then \ S = 1;$$
$$If \ V_{pv} < V_{pmax} \ then \ S = 0;$$

The typical rate of fall of terminal voltage when the switch is closed can be observed by a simple MATLAB SIMULINK simulation as shown in the Figure 5.
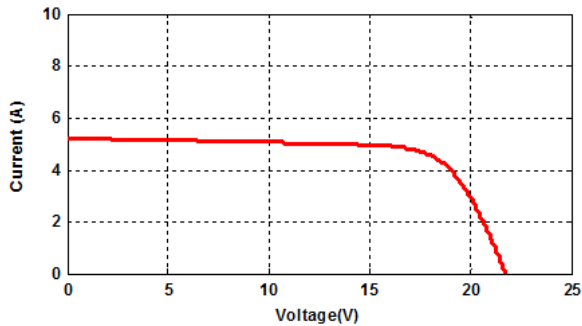
Figure 5. With the power control switch in the On state the rate of fall of voltage and rise of current through the panel with the POLC connected to the PV panel.
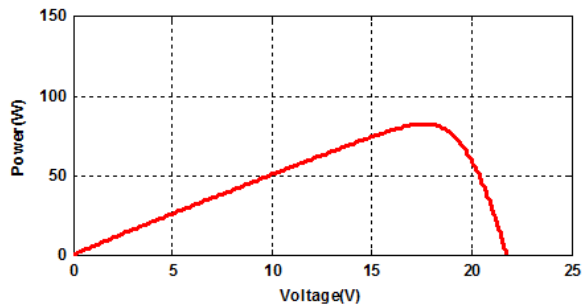

Figure 6. With the power control switch in the On state the rate of rise of Power output reaching a maximum and then falling down with the power control switch continuing in the On state with the POLC connected to the PV panel.

3.3. The sliding surface and System stability with the SMC

In the sliding mode type of MPPT the main power control switch S is initially in the off state. With the POLC the power control switch S being in series with the PV panel the PV panel is now in the open circuit mode and the terminal voltage of the PV panel is now maximum with PV current in zero state offering zero output power.
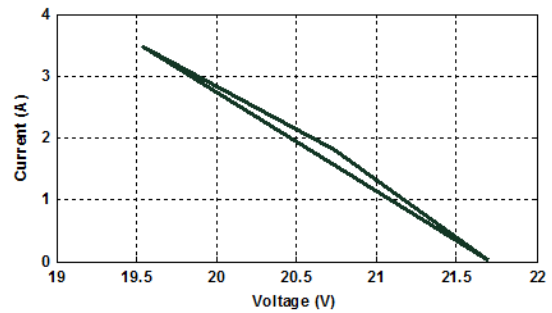

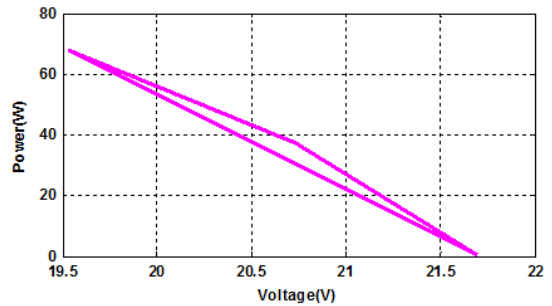Figure 7. The sliding surface in the current vs. voltage curve of the PV panel with insolation 600 w/m^2

Figure 8. The sliding surface in the Power vs. voltage curve of the PV panel with insolation 600 w/m^2
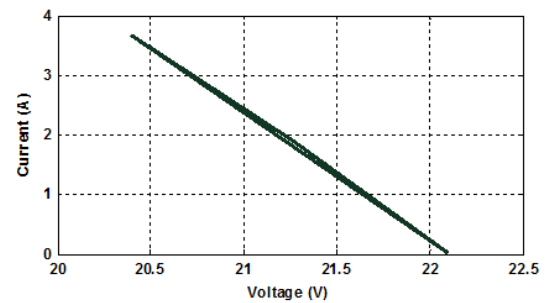

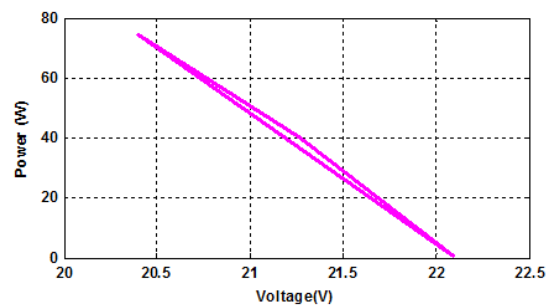Figure 9. The sliding surface in the current vs. voltage curve of the PV panel with insolation 900 w/m^2

Figure 10. The sliding surface in the Power vs. voltage curve of the PV panel with insolation 900 w/m^2

With the switch S turned on the current rises slowly and the terminal voltage across the PV panel falls. As the falling PV panel voltage just crosses the critical maximum power voltage the switch S is turned Off. The current suddenly becomes zero.

Thus transient of rise and fall of the panel current do not follow the same path and thus traces a closed curve forming a surface on the Voltage Vs Current plane of the PV panel.

This is the surface created by the SMC and this surface varies in accordance with the solar insolation as shown in Fig, 7 and 8.

3.4. The P and O Algorithm

The P and O algorithm is the simple and the foremost of all MPPT algorithms [17]. It is a simple technique in which the output power is continuously monitored and the manipulated parameter is repeatedly altered such that the power output is kept at the maximum possible level.

To start with, an arbitrary duty cycle for the converter is used and the output power is measured. Then the duty cycle of the converter switching pulse is incremented by a small constant and the resulting output power is again measured. If the measured output power has now reduced compared to the earlier measurement then the duty cycle is also reduced otherwise it is increased by the same constant and the new output power is measured and the process continues such that the maximum possible power output is tracked.

a. If observed power increases then continue perturbation in the same direction.

b. If the observed power exhibits a decrement then perturb in the opposite direction compared to the previous direction of perturbation.

This method of MPPT requires that the perturbation is a continuous process and is to be carried out even when the system is at the MPPT condition. Perturbation is a perpetual process.

Perturbation even at the MPPT level will cause the system to deviate from the MPPT condition frequently and this leads to a loss of power.

Further developments have been carried out with modifications in the P and O algorithm including variable increment method.

The P and O algorithm may fail when the solar irradiation changes rapidly.

In this work the P and O algorithm and the sliding mode control algorithm both have been tested with the POLC.

5. MATLAB SIMULINK Simulation

The MATLAB SIMULINK is shown in Figure 11. It represents the overall arrangement of the entire system comprising of the POLC and the solar power sub system with SMC based MPPT.
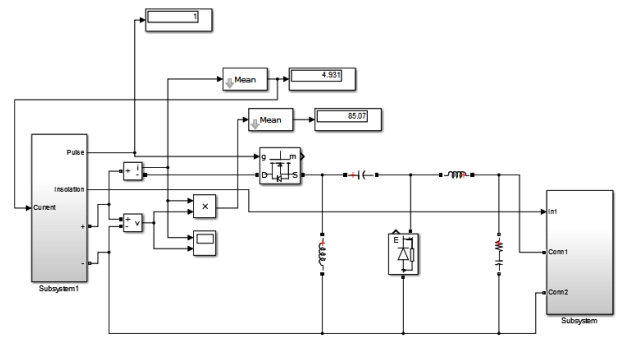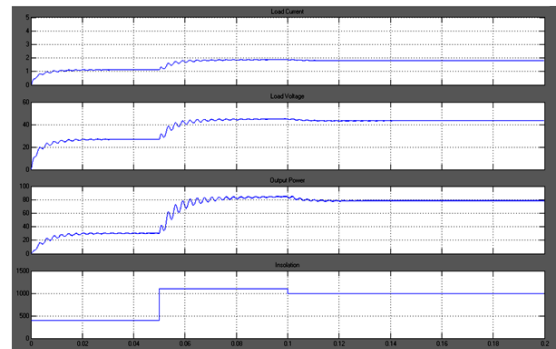

Figure 11. The MATLAB SIMULINK realisation of the POLC

Figure 12 represents the changes in the Load voltage, Load current, Output Power of solar PV for due to change in insolation level.

6. The experimental verification

An experimental verification setup for validating the proposed idea has been constructed and tested. The ratings of the experimental setup are as given in Table 1.

Table 1 Panel Specifications

Solar Panel Rating at 1000w/m2 and T = 25ºC	125W; V_{oc} = 22.32V; V_{pmax} = 18.1V; I_{pmax} = 6.91A; I_{sc} = 7.37A
Power electronic Switch	IRF 840;
L_1	1 mH
L_2	1 mH
C	22 µF
C_o	220 µF
Load	R = 0 to 10 Ohms Variable Rheostat 10A
V_{out}	24 V (Nominal)
Switching Frequency	5 KHz (Implicitly generated) observed.

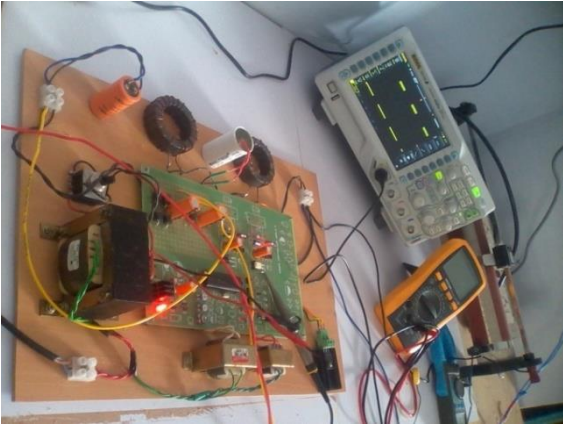A photographic view of the experimental setup is shown in Figure 13.

Figure 13. Photographic view of the experimental setup

The entire control system has been implemented using the PIC micro controller IC 16F877A. The control sub system and the power sub systems are electrically isolated and optically coupled using an opto coupler IC MCT 2E.

The terminal voltage of the PV panel is attenuated and fed to the analogue input terminal of the microcontroller.

Since the power electronic switch comes in series with the source the PV panel is in the open circuit condition, when the switch is open. When the power electronic switch is closed the PV panel is connected to the rest of the POLC and it delivers power into the POLC.

In the open circuit condition the terminal voltage V_{oc} of the panel is read by the micro controller and stored in a variable. This is done by a simple algorithm having the following two steps only.

       1. Turn off the switch.
       3. Delay
       2. Read V_{in}
       3. $Voc = V_{in}$

The delay is required because even after the switching On signal is removed from the gate of the MOSFET it takes a finite Off delay as given in the data sheet of the MOSFET.

After the switch is opened the terminal voltage of the panel rises towards the Voc level. During this transient period the terminal voltage of the PV panel crosses the voltage corresponding to the V_{pmax} value. The moment V_{pmax} is observed the switch is again closed. This procedure is carried out in the following steps.

       1. $If\ V_{pmax} = V_{oc} * 0.81;$
       2. $If\ V_{pv} > V_{pmax}\ then\ S = 1$
       3. $If\ V_{pv} < V_{pmax}\ then\ S = 0;$

After the switch is closed the terminal voltage of the PV panel starts falling down slowly, as the inductor current rises exponentially. Now energy is being transferred to the inductor. Pumping of real power into the inductor causes the terminal voltage of the panel to drop and as the terminal voltage of the PV panel just falls below V_{pmax} the switch is again opened.

This process is repeated again and again. In the SMC based MPPT technique there is no explicit switching pulse generation system like the Pulse Width Modulation (PWM) sub system is required. The switching pulses are generated automatically at a frequency and duty cycle as decided by the properties of the PV panel as well as the circuit components of the power electronic converter that is being used.

6.1 Discussions on Results

An exhaustive experimental verification has been carried out. Table 1 gives the values of each components used for the conduct of the experimental verification. The results of the experimental verification are presented in this chapter. The observations carried out during the experimental verifications have been given through Figure 14 to 24. All the waveforms have been recorded with the RIGOL 4 channel Digital Storage Oscilloscope.

Figure 14 shows the switching pulses applied to the opto coupler which drives the MOSFET.

With reference to Figure 14, the waveform has been zoomed to 1: 10 and the amplitude of the switching pulses swing between 0 and 5 volts with a frequency of 3 KHz and a duty cycle of 40%.
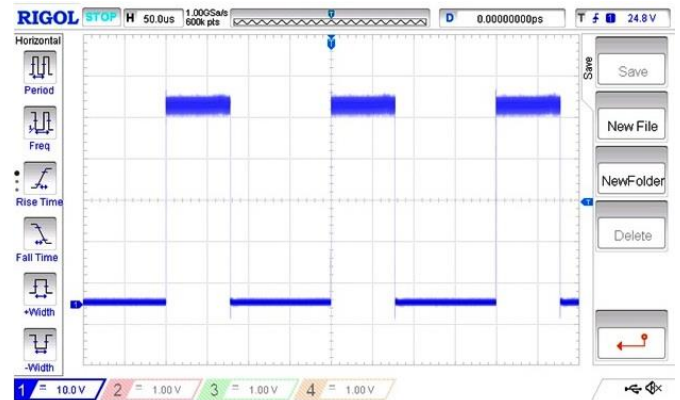

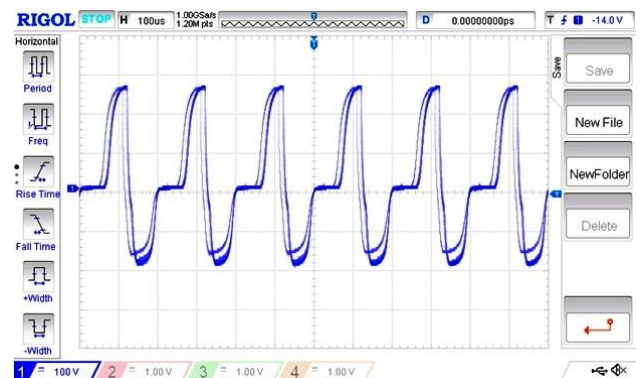Figure 14. The screen shot of the Switching Pulses generated by the SMC.

Figure 15. Voltage across the inductor L_1

With the switching pulses in action the voltage across the front end inductor L_1 is observed to be as shown Figure 15. The rise and fall of the switching pulses applied to the MOSFET causes the reversal of polarity of voltage across the inductor L_1.
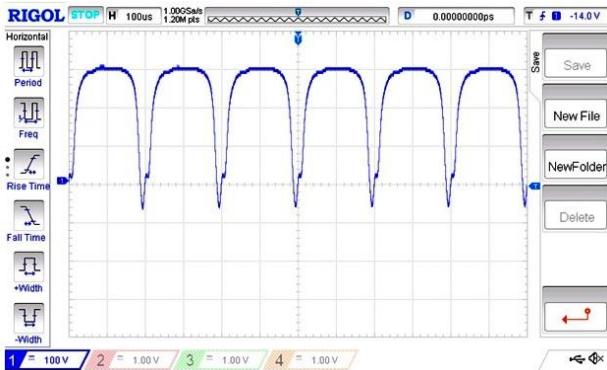

Figure 16. Voltage across the interlink Capacitor C.

The positive output Luo converter is a DC to DC converter. However the power transaction between the input and the output sides flow through the series capacitor. At steady state operation, the DC voltage drop across this capacitor is equal to the supply DC voltage. Because of the switching action the voltage across the capacitor is pulsating with a mean value that is equal to the source DC voltage and the waveform of the voltage across the capacitor is shown in Figure 16.
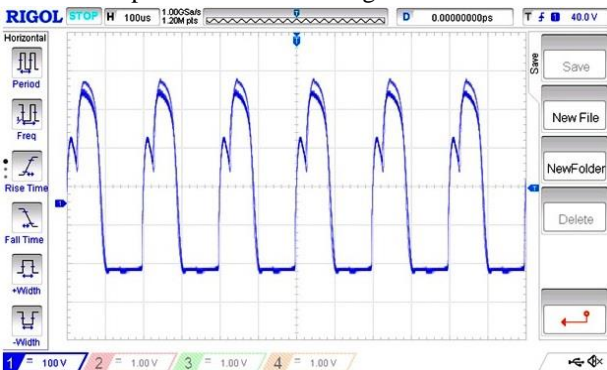

Figure 17. Voltage across the Inductor L_2.

The purpose of the inductor L_2 is to smoothen the output current and give a ripple free current through the load. As such the ripple voltage present in the output voltage will drop across this series inductor L_2. There is no average DC voltage drop across this inductor except for the very low inherent resistance of this inductor which is negligible. The ripple voltage drop across the series inductor L_2 is shown in Figure 17.
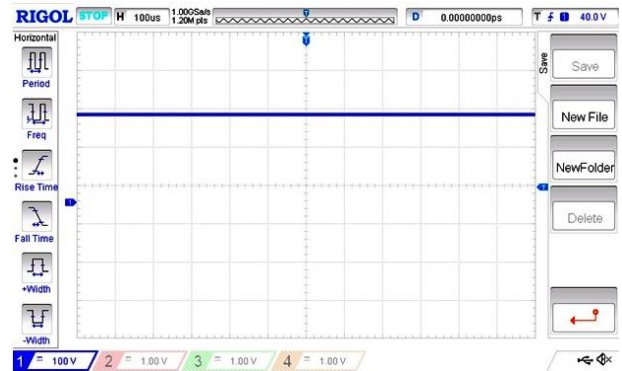

Figure 18. Output DC voltage 24V

Figure 18 shows the output DC voltage across the load with a selected scale of 1:10 the steady state output voltage, for the given duty cycle and the solar insolation, is observed to be 24 V DC.
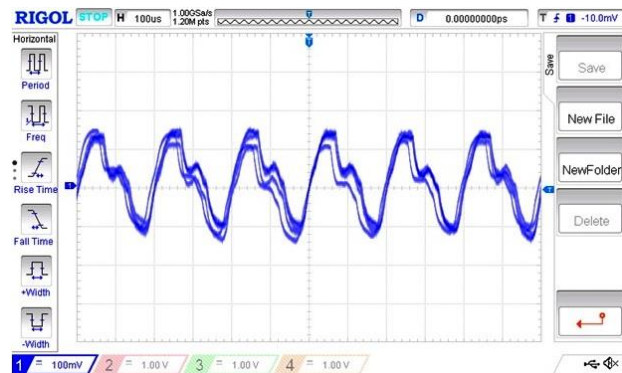

Figure 19. Ripple of load current with SMC

With the sliding mode converter in action the switching pulses are generated implicitly and the switching action is carried out at the frequency as decided by the SMC. This causes a ripple at the load current. After due filtering by the series inductor L_2 and the parallel capacitor C_o a fine ripple current flowing through the load in the order of 10mA has been observed as shown in Figure 19.
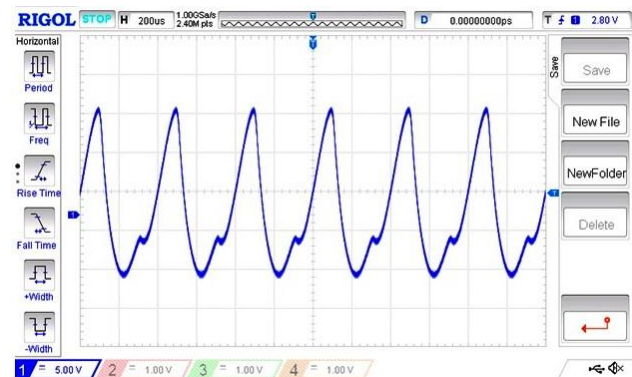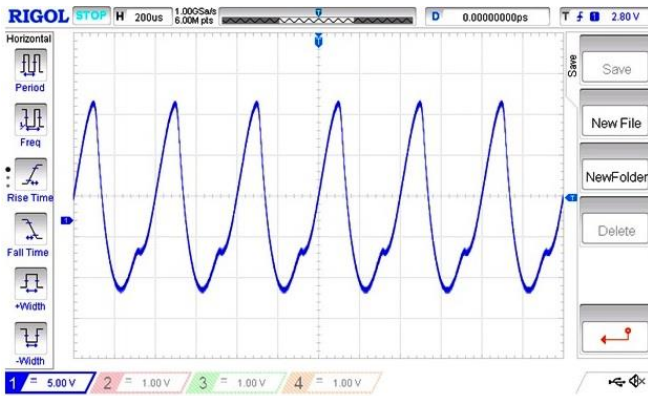

Figure 20. PV Current with insolation 450w/m^2
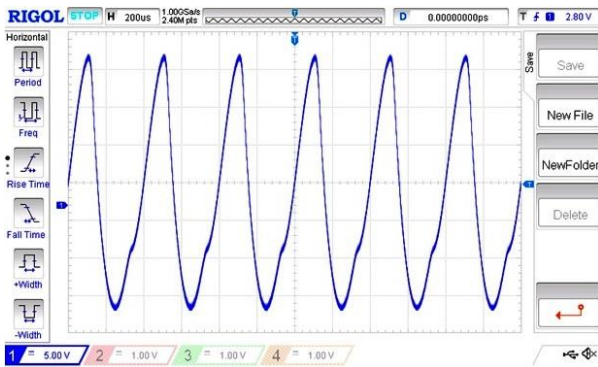
Figure 21. PV Current with insolation 627w/m^2

Figure 22. PV Current with insolation 870w/m^2

Figure 20 to 22 show the PV panel current for an insolation of 450w/m^2, 627w/m^2 and 870w/m^2 respectively. Because of the switching action of the series power control switch the PV current is intermittent.
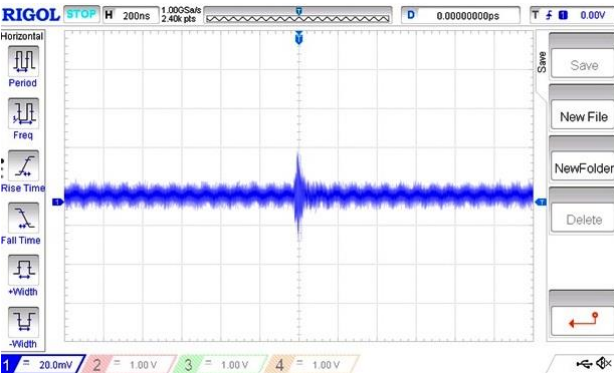

Figure 23. Ripple in Load current with P and O and explicit carrier observed before and after the change in insoaltion.
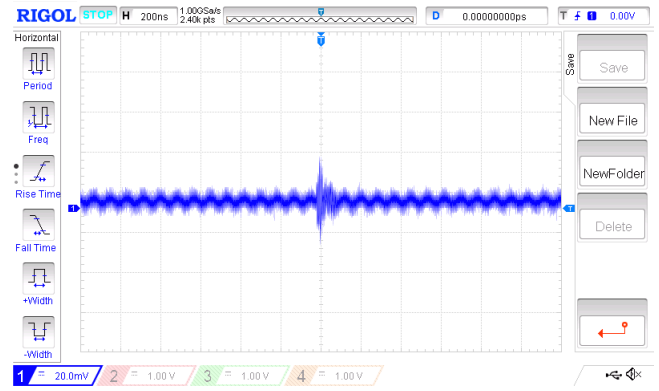

Figure 24. Ripple in Load current with SMC before and after change in insolation.

The change in solar insolation causes changes in the output power as well as changes in the load current ripple. With the P and O algorithm the load side ripple current which is in the order of 20 mA with a change in insolation from 870 w/m^2 to 450 w/m^2 is as shown in Figure 23. With the sliding mode control scheme this ripple is reduced below 18 mA and the results for the same change in solar insolation levels is shown in Figure 24. Table 2 gives a comparison of the key parameters of the P and O and the SMC type of MPPT, as observed in this study.

Table 2. Comparison of the key parameters

Parameters	P and O Algorithm	Sliding Mode Control
Carrier	Explicit	Implicit
Parameters monitored	PV Voltage and Current	PV Voltage
Tracking Speed	Fair 300Ms	Good 180Ms
Efficiency	92% (Simulation)	96% (Simulation)
Ripple	Fixed Frequency	Variable Frequency

7. Conclusion

An SMC based MPPT scheme has been designed and developed for the Positive Output Luo Converter. The stability analysis of the POLC has been carried out after determining the transfer function of the POLC.

A sliding mode controller has been implemented for the harvest of maximum power when the POLC was used with a 125 W Solar panel.

The results of MPPT with SMC have been compared against the results obtained with the P and O algorithm. It has been concluded that the proposed design of the POLC has been stable, the SMC based MPPT for the POLC has proved to be better than the P and O algorithm. The proposed methodology has been validated using both simulation and experimental verification.

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