DESIGN OF CONVERTER FOR NON CHAOTIC OPERATION OF SOLAR PV SYSTEM

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Abstract: *The paper presents a new design approach for the parameters of the dc-dc boost converter to address the non linear dynamics and issue of chaos in the process of maximum power point tracking (MPPT) in solar energy systems. The operational requirements of dc-dc converters employed in MPPT applications differ widely from their conventional voltage regulation applications. The emphasis augurs to minimize the voltage and current ripples and explore a fresh direction to arrive at the appropriate values of the inductor and capacitor. The approach entails standard test conditions and involves perturb and observe algorithm to articulate the theory. The methodology attempts to uphold the system stability with a view to identify the pathways to bifurcations and eventual transition to chaos. The MATLAB based simulation results adequately validated through a prototype strives to keep the operating point of the MPPT system in the stable operating region and improve their performance necessities such as fast tracking of MPP, reduced oscillations around MPP, reduced current rating for the switch, higher conversion efficiency and higher voltage gains. The experimental results forge to validate the formulation and evince a fresh scope for the effective use of solar power in the real world applications.*

Key words: *solar PV, boost converter, MPPT, bifurcations, chaos*

1. Introduction

The solar photovoltaic energy continues to emerge as an inevitable alternative in the existing crisis scenario and offers a remedy for the incessant global warming and greenhouse gas emissions [1]. The grid-connected PV power generation systems appear to be commercialized in many countries because of its potential long-term benefits [2]. The PV stand-alone system on the other hand augurs to hold promise as a substitute for the utility grid connection. The system with adequate storage can cover the energy needs of house electrical loads and find a place in aerospace and naval applications. [3].

The presence of switching and reactive components in dc-dc converters together with its intrinsic characteristic of topology mixing classifies them to be a nonlinear dynamical system that remain sensitive to initial conditions and appear to be easily prone to chaos [4]. The existing design of circuit parameters for the dc-dc converters relates to satisfy the voltage and current ripple requirements.

The principle of maximum power point tracking (MPPT) however owes to transfer the maximum energy available from the panel to the load and does not envisage realizing the voltage and current requirements of the utility. The way of tracking the maximum power leaves way for the converter to follow various bifurcation pathways. This depart from the normal expected mode of operation because of the inherent non-linearity present in them result in deterioration of the performance in these converters [5].

A host of techniques have been used to search the MPP in photovoltaic systems which employ both the P and O algorithm and incremental conductance algorithm [6]. A stream of variations has been reported in [7-11] to orient the tracking of the MPP. The P and O algorithm used by many researchers has been directed to improve the MPPT efficiency (the ratio of maximum power extracted from the panel to the maximum power potential of the panel) [12].

Operating at a high perturbation frequency in [13] has been shown to offer a higher energy utilization efficiency and better system performance, despite the resulting non-periodic waveforms of the system. The corresponding utilization factor has been only a measure of how effectively the algorithm tracks the MPP of the module and remains unanswered to the conversion efficiency of the converter system.

The design technique introduced in [14] has been aimed to maximize the energetic efficiency of the converter by optimal selection of power components. However the selection has been based on the use of a conventional duty cycle equation and not the case of reality in a direct duty cycle controlled P and O algorithm. The design has been solely a search algorithm to select among the preset database of real devices to suit the design operating range that optimize the efficiency and the cost without any consideration to the stability of speed of tracking around MPP.

With the duty cycle being the perturbed parameter in the P and O algorithm, it allows the PWM generator to move the operating voltage of the PV module to the MPP. However the perturbation rate and the perturbation size require to be optimized in the sense lowering the perturbation size reduces the steady state losses caused by oscillations around MPP, but results in slower transient response.

Besides the introduction of chaos by the higher perturbation frequency results in the increase of losses in the dc-dc converter and leads to a decrease in the energy conversion efficiency and reduced power at the output of the converter. Therefore it necessitates evolving measures for enhancing the conversion efficiency through astute design methodologies for the choice of the parameters involved in the system.

2. Problem formulation

The basic focus endeavors to investigate the nonlinear dynamics of the solar MPPT system in order to bring out the adverse effects of chaos in the reliable operation of the system. The investigation fosters the role of a fresh design of boost dc-dc converters customized for MPPT systems and formulate an analytical technique to embrace the system state within the desired operating state. The procedure endeavors to evaluate the performance using MATLAB based simulation and illustrate its suitability through the facilities of hardware for establishing its ability to optimally track the maximum power.

3. Modeling of PV system

The single diode equivalent circuit model in [15] cleaves out to be a good compromise between accuracy and simplicity of panel modeling. The specifications of a 250W maximum power PV panel SRP-250-6PB from Seraphim Solar System, Co Ltd, a leading PV company is chosen to be modeled. The procedure simulates the modelling Equations in [15] using the specifications and the single diode equivalent circuit model.

The philosophy explained in Fig. 1 realizes the desired electrical power from a PV source through the use of a boost converter. It necessitates the role of a MPPT controller along with a PWM generator to ensure the reach of the maximum efficiency.

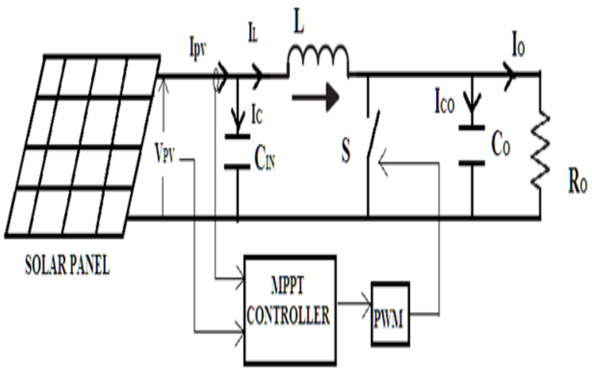

Fig. 1. Boost converter employed for solar PV MPPT

The exercise involves the state space modeling of the boost converter with the PV current as the input variable, input PV voltage, inductor current and output voltage as both state and output variables. The state model in (1) governs the operation of the MPPT system.

$$\begin{bmatrix} \dot{V}_{pv} \\ \dot{I}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{C_{in}} & 0 \\ \frac{1}{L} & 0 & \frac{-(1-D)}{L} \\ 0 & \frac{(1-D)}{C_o} & \frac{-1}{RC_o} \end{bmatrix} \begin{bmatrix} V_{pv} \\ I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{C_{in}} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} I_{pv} \end{bmatrix}$$

$$\begin{bmatrix} V_{pv} \\ I_L \\ V_o \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_{pv} \\ I_L \\ V_o \end{bmatrix}$$

It requires a simulation analysis of MPPT system performance to decide the value of parameters appropriate for the fast tracking of the MPP with reduced oscillations. The solar panel SRP-250-6PB modeled as a current source energizes the boost converter with an input current Ipv. The MPPT converter operate at a switching frequency of 20 kHz and supply a load resistance of 400Ω. The initial system parameters for design include Cin = 200µF; L= 0.1mH; and Co=200µF. The conventional perturb and observe algorithm with direct duty cycle perturbation in [16] is used for the simulation analysis and design of boost converter parameters.

4. Design of Input Capacitor

The input capacitor in the event of not being selected properly can restrain the conversion ratio and efficiency of the boost converter. The Table 1 includes measures that influence the performance of the system over a range of viable parametric value for the input capacitor.

The simulation under STC of temperature and insolation from the Table 1 shows that as larger the capacitor, slower is the system response towards tracking of the MPP. The time constant of the capacitor adds up to the system delay in tracking the maximum power. On the other hand, it becomes possible to reduce the oscillations with sufficiently large value of capacitor. It further reveals the trade-off between tracking time and oscillations around MPP in the choice of input capacitor. It can also be seen that the power ousted from the converter depends on the choice of the input capacitor up to a threshold value of 1000µF beyond which the system goes into saturation.

The switching nature of the MPPT system necessitates maintaining the operation of the system around MPP which causes ripples in the PV current Ipv and PV voltage Vpv. The analysis of ripples in Ipv and Vpv, which accounts for the oscillation around MPP, turns out to be significant in the selection of input the capacitor. The related entries in the Table 1 illustrate the steepness in the ripple reduction of the PV current and voltage, when the input capacitor increases from 200µF up to a value of 1000µF, beyond which the extent becomes extremely small.

Table 1
Performance measures for different choices of input capacitor

Input capacitor (µF)	**Speed of tracking (ms)**	**Oscillation around MPPT (Volts)**	**Boost Output Power (Watts)**	**Peak-Peak ripple in PV current (Amps)**	**Peak-Peak ripple in PV voltage (Volts)**
200	1.34	33	195	2.34	8.5
400	2.1	11	202	1.25	4.5
600	2.67	5	203	0.77	2.88
800	3.38	2.4	204	0.59	2.1
1000	4.07	1.5	205	0.47	1.7
1200	4.7	1.2	205	0.41	1.45
1400	5.38	1	205	0.36	1.27
1600	6.07	0.7	205	0.31	1.11
1800	6.72	0.6	205	0.27	1
2000	7.38	0.4	205	0.25	0.87

The design of MPPT system augurs the analysis of the system using phase portraits of state variables to strive the operation of the converter in a stable region. It requires a detailed analysis for deciding the value of input capacitor using the inductor current and the input PV voltage of the system. The portraits relating to the design of the input capacitor involves the two state variables namely PV voltage and inductor current. It can be seen from the phase portraits in Fig.2 that, beyond the capacitor value of 1000µF, the system undergoes multiple bifurcations and quasi-periodicity which may eventually lead into chaos.

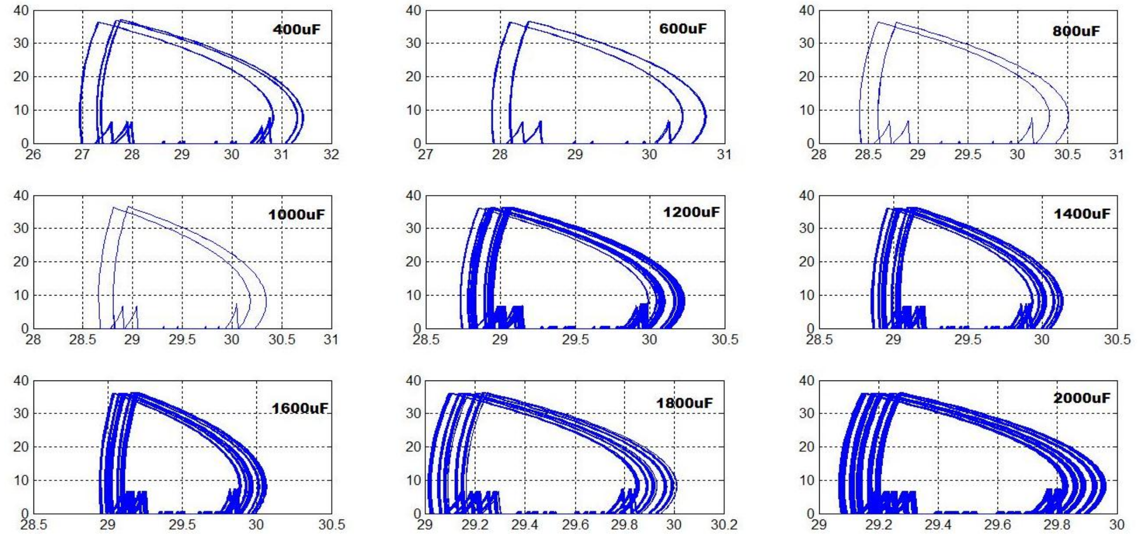

Fig. 2 Phase portraits of PV voltage(x) and inductor current (y) for different values of input capacitor with L= 0.1mH, Co=200µF and Ro=400Ω and Fs=20 kHz

The phase portraits corresponding to 600µF, 800µF and 1000µF for the same number of iterations shows a period-2 operation. However the portrait corresponding to 1000µF produces a translucent loop compared to the portraits for 600µF and 800µF. The translucent nature of the loop points toward the rigidity of the system in the period-2 operation, whereas the denser orbits indicate the floppy temperament of the system to enter into multiple bifurcations. The analysis suggests the choice of input capacitor to be 1000µF which corresponds to a speed of tracking of around 4ms. A proper choice of inductor value can bring the system into stable period-1 operation.

5. Design of Inductor

The choice of the inductor adjoins to the complex design of boost converter for MPPT applications. The conventional design procedure calculates the duty cycle form the known ranges of input and output voltages and assume a change of inductor current for a known time Ton to determine the inductor value. It does not find its place in MPPT since the purpose orients to track the maximum power available from the input rather than to boost the output voltage to a particular value.

The Table 2 displays the effects of the parametric choice of inductor on the various indices that govern the performance of the system under study. It traces the oscillations of power around MPP, the duty cycle at which it tracks the maximum power, which eventually decides the conversion ratio and the efficiency of the converter, over a range of different values of inductor. While the effort suggests a lower value of inductor to lean towards reduced oscillations, it shows the need for a larger inductor to offer a higher efficiency for the converter. Besides, the value of inductor decides the peak value of current that flows through the power converter switch.

The phase portrait analysis of the system becomes imminent to validate the choice of inductor. It uses three dimensional plots to analyze the behaviour of the complete system for different values of inductor as seen in Fig.3. The portraits for values of inductor below 2mH show a variety of nonlinear dynamics which may eventually collapse the stability of the system. It exhibits a period-I operation of the system in the stable region for portraits of inductor values equal to 2mH. The inductor choice above 2mH results in the creation of larger ripples in the output voltage. It implies the choice of inductor to be 2mH for enjoying the benefits of continuous conduction, stable region of operation and reduced rating for switch of the boost converter.

Table 2
Performance measures for different parametric inductor values

Inductor (mH)	Oscillation around MPPT (Volts)	Average duty cycle	Peak Inductor current (Amps)
0.1	1.52	0.52	36.48
0.5	4.5	0.72	22.1
1	8	0.78	19.5
2	18.2	0.82	16.86
3	33	0.84	15.65
5	63	0.88	14

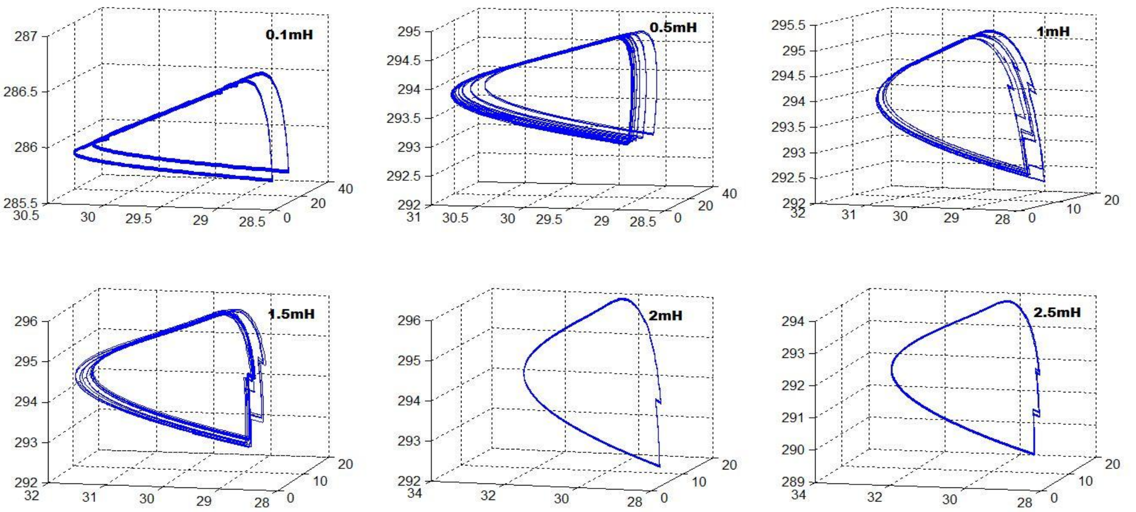

Fig. 3 Phase portraits of PV voltage(x), inductor current(y) and output voltage(z) for different values of inductor with Cin= 1000µF, Co=200µF and Ro=400Ω and Fs=20 kHz

The output capacitor together with the load resistance value decides the amount of ripple in the output voltage and response time of the overall MPPT system. The amount of ripples in the output voltage turns out to be lower and the response time slower for higher values of the capacitor. The tradeoff between the ripple content and response time of output voltage becomes balanced by a practical choice of 200µF output capacitor for a 400Ω load resistor to yield a satisfactory performance.

6. Experimental results

The SRP-250-6PB solar panel of 250W peak at STC made by Seraphim Solar System Co., Ltd seen powers the boost converter. The 3-busbar technology used in the panel helps to increase its power output. The Fig.4 explains the prototype of the boost converter constructed using the parameters obtained from the design methodology.

The dSPIC30F4011 controller with a 16- bit digital signal controller specially devised for power conversion applications includes a 10-bit ADC with nine channels and four sample and hold circuits along with the six PWM output channels for duty cycle generators. The flow diagram shown in Fig. 5 enumerates the process of generating the PWM pulses for the IGBT switch in accordance with the direct duty cycle perturbation to suit the implementation of the perturb and observe algorithm.

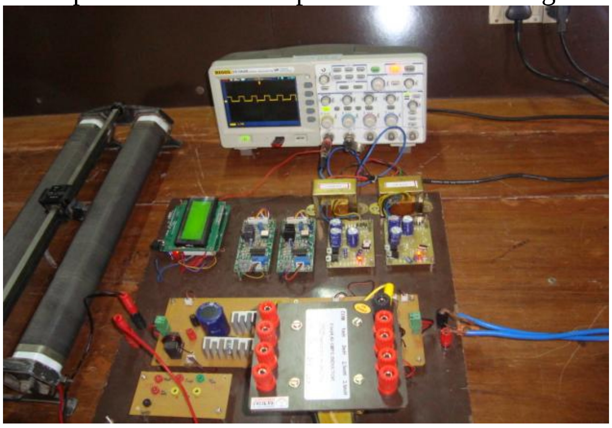

Fig. 4 Experimental setup for the proposed design

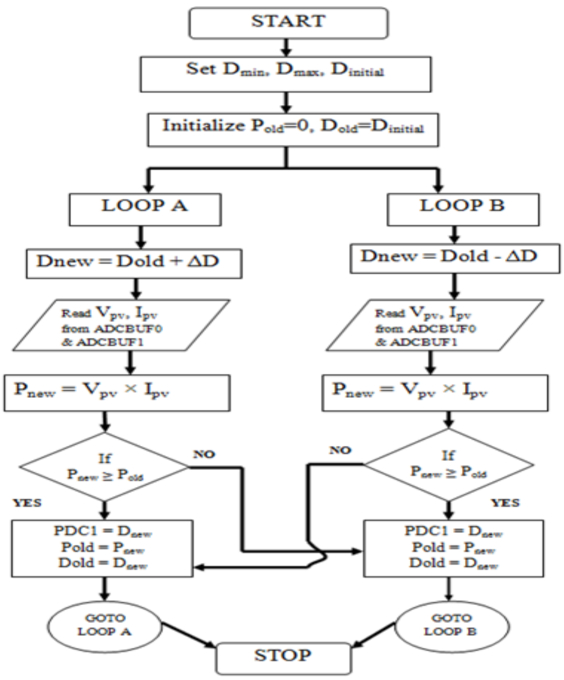

Fig. 5 Control algorithm for proposed system

The experiments relate with the inductor specially customized for the purpose with various tapings suitable to operate at high frequency of up to 1MHz and peak current rating of 45A and the capacitors that are commercially available in the market. The inductor current waveform and phase portraits in Fig. 6 and Fig. 7 respectively, corresponding to input capacitor choice of 680µF and L=0.1mH reveals the period-2 operation of the system as explained in the simulation results. The inductor current waveform and phase portraits in Fig. 8 and Fig. 9 respectively corresponds to system operation with input capacitor of 1000µF and inductor current of 1mH.

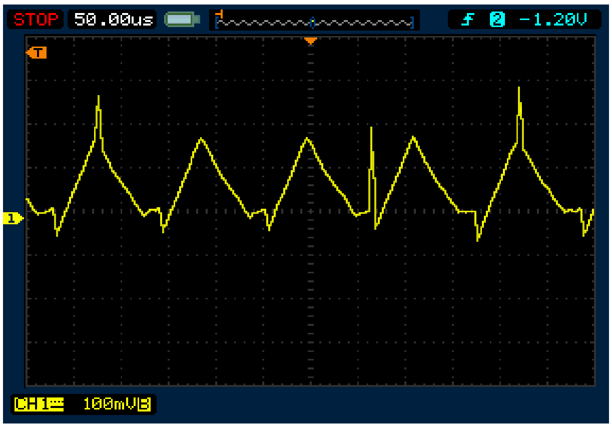

Fig.6 Inductor current waveform Cin= 680µF, L= 0.1mH, Co=200µF and Ro=400Ω and Fs=20 kHz

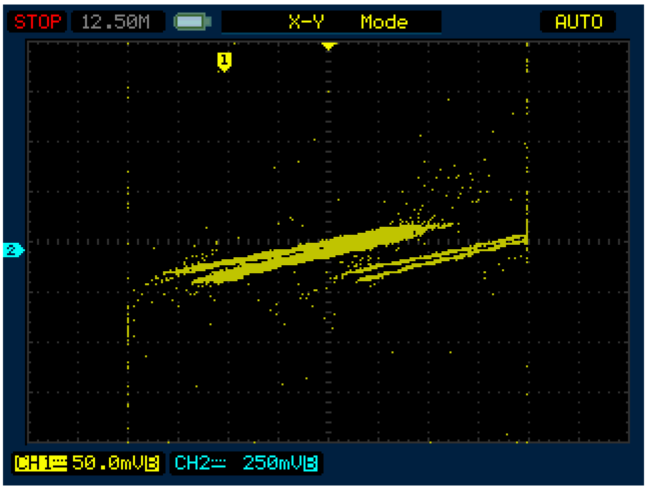

Fig.7 Phase portrait: Cin= 680µF, L= 0.1mH, Co=200µF and Ro=400Ω and Fs=20 kHz

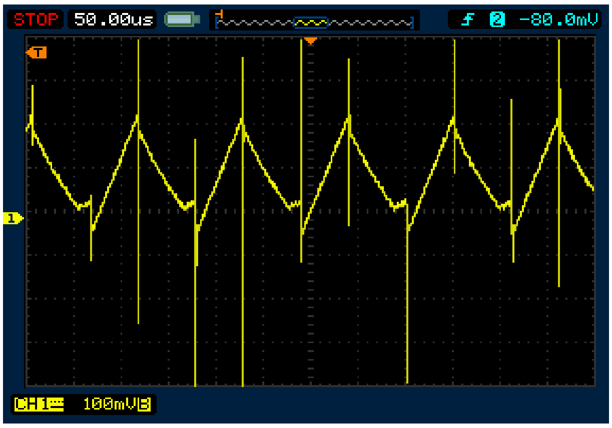

Fig. 8 Inductor current waveform: Cin= 1000µF, L= 1mH, Co=200µF and Ro=400Ω and Fs=20 kHz

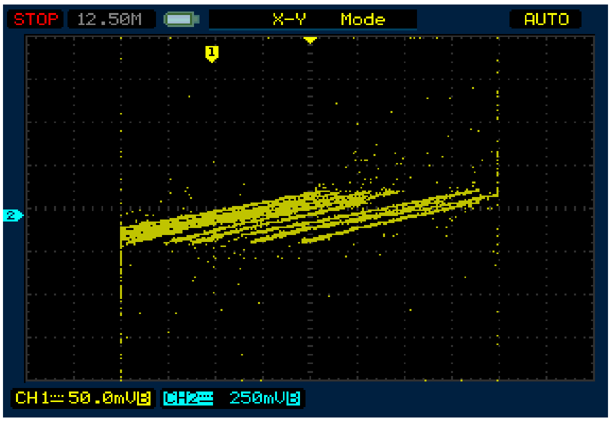

Fig. 9 Phase portrait: Cin= 1000μF, L= 1mH, Co=200μF and Ro=400Ω and Fs=20 kHz

The two dimensional phase portrait with input voltage and inductor current as its vectors bring out the multiple periodicities in the system operation and are in line with the simulation. It discloses the shortcoming of the system inclination towards instability. The inductor current waveform and phase portraits in Fig. 10 and Fig. 11 respectively corresponds to proposed system design with input capacitor of 1000μF and inductor current of 2mH and portray the periodic stable operation of the converter for STC.

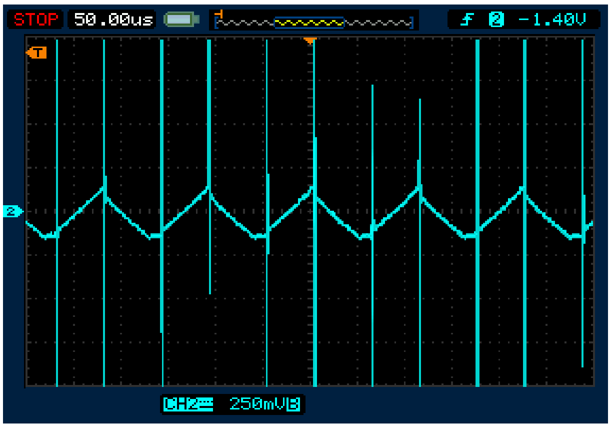

Fig. 10 Inductor current waveform corresponding Cin= 1000μF, L= 2mH, Co=200μF and Ro=400Ω and Fs=20 kHz

The Table 3 displays the simulation and experimental observations of the proposed design and there closeness reveals the viability of the control scheme for use in practice. The potential of the design over a wide operating range in continuous and efficient tracking of MPP in conjunction with sustaining the stability of the converter operation is evident from Table 4 from where the duty ratio, voltage gain and efficiency that can be extracted from the design find a place for a range of operating loads. The small variation in the simulation and experimental interpretation can be reasoned for the changes in real time irradiance and temperature conditions.

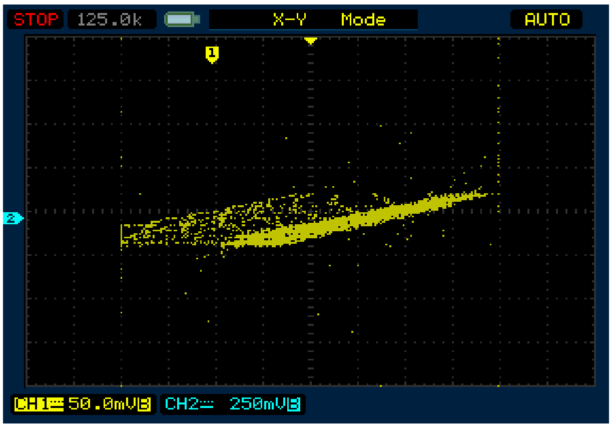

Fig. 11 Phase portrait waveform corresponding Cin= 1000μF, L= 1mH, Co=200μF and Ro=400Ω and Fs=20 kHz

Table 3
Comparison of simulation and experimental observations

Parameters Observed	**Simulation done at STC**	**Experimental Observation around G = 900W/m^2 T=30°C**
Time taken to reach MPP	4 ms	5 ms
Offset in MPP tracked	3 W	7 W
Oscillations around MPP	18.2 W	15 W
Ripple in input voltage	3V	2.8 V
Ripple in input current	1.3A	1.2 A
Nature of inductor current	CCM, Periodic	CCM, Periodic
Average duty cycle	0.85	0.8
Response time of converter	0.2	0.18
Ripple in output voltage	4V	3 V
Voltage gain	9.6	9.6
Efficiency	91%	89 %

Table 4
Experimental load test of the boost converter

S. No	Load Current (Amps)	Whether MPP Tracked	System Stability	Duty Ratio		Voltage Gain		Efficiency (%)	
				Sim	Exp	Sim	Exp	Sim	Exp
1	0.17	YES	STABLE PERIODIC	0.92	0.9	23	22	53	50
2	0.22	YES	STABLE PERIODIC	0.92	0.9	21.5	22	62	60
3	0.3	YES	STABLE PERIODIC	0.9	0.9	19.2	20	74	70
4	0.35	YES	STABLE PERIODIC	0.9	0.9	17.3	17	80	78
5	0.45	YES	STABLE PERIODIC	0.88	0.8	14.7	15	86	85
6	0.55	YES	STABLE PERIODIC	0.87	0.8	12.5	12	89	90
7	0.74	YES	STABLE PERIODIC	0.85	0.8	9.6	10	91	90
8	1.05	YES	STABLE PERIODIC	0.82	0.8	6.9	7	94	92

7. Conclusion

The dc-dc boost converter interface has been modelled in state space and its parameters designed with MPPT perspectives in the solar PV system to offer effective speed of tracking, lower oscillations around maximum power, lower ripples in the PV voltage and current, minimum peak inductor current and maximum power conversion at the output of the converter. The design of PV system parameters using analytical procedures has been validated at STC with the help of phase portraits and performance measures.

The simulation has been carried out with the conventional P and O with direct duty cycle perturbation. The experimental circuitry has been set with the parameters obtained from the proposed design procedure and the results validate the simulated performance. The PV system performance has been evaluated for various load conditions to exhibit that it provides high voltage gain, maximum power conversion and its ability to sustain the prolonged period-I operation brings out the effectiveness of the mechanism.

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