Simulation of a Nonlinear Controller for Solar Photovoltaic Applications

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Abstract. The paper attempts to analyze the nonlinear dynamics of the solar PV system with a view to propose a control technique for maximum power point tracking (MPPT) in accordance with the requirements of the chosen utility. It involves the nonlinear control design attributes of a MPPT system using a boost dc-dc converter and forge to incorporate a comprehensive regulating mechanism. Investigations on multi periodicity, bifurcation, sub-harmonic oscillations and chaotic operations of the converter invite emphasis. The philosophy owes to analyze the nonlinear dynamics of the MPPT system in order to reap an enhanced performance for the system over a range of the variable environmental conditions. The MATLAB based simulation results compare the system performance with conventional MPPT methods to showcase the pathway of non-periodicity in the system as a function of the PV irradiation. It includes the chaotic dynamics of the system in an effort to establish the effectiveness of the controller for eliminating the chaotic phenomena and to espouse its role in critical applications.

Keywords: Bifurcation, chaos, multi-periodicity, boost converter, MPPT, sliding mode control

1 Introduction

The choice of energy resource, the pattern of energy utilization and the technologies behind them foster a new dimension in planning a robust energy sector to comply the energy demands of the nation as well as being judiciable towards the global commitments in reducing the carbon footprints[5, 24, 31, 34].

Approaches towards standardizing the energy consumption norms for energy intensive industries through robust energy management controls, low energy instrumentation, energy saving of equipment and appliances can reduce the demand and prevent the irreversible damage to our earth’s ecosystem[4, 6, 16, 23]. Well-designed energy strategies and well-engineered energy efficiency programs along with a blend of different renewable technologies and innovative utilization approaches serve as keys to offer a substantial contribution for minimizing the environmental damage together with enhancing economic growth[3, 8, 21, 25, 33, 35].

The source of renewable energy appears to be attractive due to the prevailing economic stimulation, enhancement of energy security and diversification of the energy supply[22] and [14]. The solar PV can especially be harnessed in a variety of ways and range of scales in tropical countries due to its endless availability, cleanliness, and sustainability. The initial investment of solar PV continues to decrease to levels that make solar PV commercially competitive with fossil energy[26].

The solar PV stands as a viable solution for decentralizing the control of power flow through micro grids[30]. Utilizing the PV solar farm temporarily[36] for providing rapid reactive power support to stabilize the voltage[29] and for the control of real and reactive power in an effort to maintain the voltage profile presents a novel strategy for confronting the intermittency of the PV systems.

The extraction of the maximum power from the solar Panel turns out to be a vital consideration in the design of an effective solar PV supported system. The nonlinear V-I characteristics of the solar panels with

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distinct and environmental dependent maximum power point calls for a maximum power point tracking control to balance the impedance between the load and the PV panel[9, 15, 18].

The role of an MPP tracker orients to assuage the operation of a dc-dc converter which forms the main constituent of the solar PV system. Though most switching-mode power supplies adapt to function with high efficiency still the issues relating to the availability of a continuous source of power augur the use of a solar source. However, the approach of tracking maximum power from a solar energy relies on the capability of the current source and possibly leaves way for the dc-dc converter to deviate from its expected mode of operation. It creates various bifurcation pathways and allows the system to experience a nonlinear dynamics across its operating range.

2 Literature survey

The dc-dc switching circuits have been known to present complex dynamical scenarios and uncommon routes to chaos[13]. The nonlinear behaviour of DC-DC converters in regulatory applications has been studied over the last three decades and several insights drawn. The inherent inhomogeneity and switching nature of the buck, boost and buck-boost converters have been seen to depart from normal expected operation mode and exhibit various type of nonlinear behaviour such as bifurcation, sub-harmonics and chaos[20, 28, 39].

The inherently arising non-idealities that include delays, the time lag in the propagation of the control signal, have been found to lead to the drastic changes in the overall dynamics of the system. The effects of the magnitude of the overall delay on the dynamics of boost converter under current-mode control have been studied[27].

The complex bifurcation phenomena of a voltage-controlled Buck-inverter cascade system have been explored in [37] and a state-flow chart introduced to illustrate the complex relations among the linear operating modes. The coexistence of attractors has been analysed by the cell mapping method. Bifurcation diagrams with the reference voltage and the input voltage as bifurcation parameters investigated.

The chaotic behaviour in high gain interleaved dc-dc converters with current mode control has been examined in [1]. The bifurcation diagram plotted and stability discussed with different parameter variations such as load resistance and reference current. The interleaved high gain dc-dc converter has been shown to exhibit chaotic behaviour through period-doubling and border collision routes. The stability region of interleaved boost converter has been found narrower than that of the conventional boost converter.

A bifurcation analysis has been performed to study the nonlinear stability of a reduced model of a dc-dc bidirectional converter system[7]. The appearance of different bifurcations for changes in load and control gain parameter has been studied. The nonlinear stability analysis has been used to determine the safe parameter region for the robust system operation under load and power changes.

A multi-phase interleaved dc-dc boost converter with an arbitrary number of legs has been evaluated with state feedback control[11] and shown that interleaving can give rise to more severe bifurcation phenomena, as the number of phases is increased, leading to multiple equilibria. A bifurcation analysis procedure has been illustrated to predict the generation of multiple equilibria and integrate the analysis into the design so that multiple equilibria can be completely avoided or ruled out of the operating region of interest.

A new mathematical technique allows for exact diagnosis of instability for discontinuous conduction mode analysis of dc-dc switching converters has been designed in order to predict bifurcation and chaos[12], perform exact calculation, without truncating any state matrix and analyse the waveforms. It has been laid to exactly predict the parameter values that determine the operation at the border between DCM and CCM and provide the exact prediction of the border collision.

A method to control chaotic behaviour by pulse-frequency modulation for synchronous buck-converters has been presented in [17], seen to suppresses chaotic responses by slightly perturbing the pulse frequency alone and facilitate to stabilize unstable periodic orbits without influence on the voltage regulation scheme.

The nonlinear characteristic analysis of Z-source dc-dc converter has been examined in the continuous conduction mode with peak current control in [38]. The analysis has been used to estimate parameter range in which Z-source bifurcation and chaos occur when reference current, input voltage and load impedance changes.
The optimisation of the control parameters of a buck converter using a Zero Average Dynamics (ZAD) controller and Fixed-Point Induction Control (FPIC) has been achieved by studying the bifurcation diagram \[10\]. The control has been engaged by adjusting the reference voltage and the control parameters \(K_s\) of ZAD and \(N\) of FPIC. The ability of the system to regulate the voltage has been found to decrease with low values of \(K_s\) and enable the system to pass through the regions of chaotic bands. The critical value for parameter \(N\) for which the regulated variable tends to reach a fixed point, rendering the system stable has been identified.

The fast scale bifurcation analysis of continuous input output power buck-boost converters has been presented in \[19\]. The buck-boost converters under average current mode control used to achieve voltage regulation and unity power factor has been subjected to chaos through period doubling by varying parameters like load resistance and input voltage. The nonlinear carrier control has been shown to operate the converter in the fundamental operating region in spite of the parametric variation.

The elude of chaos in solar fed DC-DC boost converter has been achieved using optimal circuit parameters obtained through bacterial foraging optimization algorithm in \[32\]. The bifurcation analysis of the system with optimized and un-optimized parameters has been outlined. The boost converter with optimised parameters has been shown to exhibit increased range of the input voltage for stable operating region.

The literature has been surveyed to present the chaotic behaviours of various dc-dc converters under current mode or voltage mode control used in regulatory applications \[1, 7, 10–13, 17, 20, 27, 28, 37, 39\] and a host of chaos control methods reviewed \[19\] and \[32\]. The behaviour of the boost converter applied to solar PV MPPT has been portrayed in \[2\] which use predefined reference current values from MPP current of i-v characteristics of the solar panel for a particular irradiation. The nonlinear dynamics of dc-dc converters applied to real time MPP tracking applications with the exact simulation model of the PV module have not been analysed as far.

### 3 Novelty of the proposed work

The dc-dc converters being inherently nonlinear due to its topological switching phenomena and the nonlinear circuit elements when applied to a solar PV which exist predominantly as a nonlinear current source may exhibit a different pattern of bifurcation and chaos. The domain of the system space for the nonlinear analysis remains different since the MPPT control techniques aims at controlling the input parameters of the converter with maximum energy transfer objectives rather than the output parameters with regulatory objectives.

The methodology of tracking the maximum power leaves way for the converter to trail various bifurcation pathways and eventually enter a chaotic region which may deteriorate the performance of the converter in tracking of MPP. The need extends to decide the performance of the system as MPP tracker and use the analysis of nonlinear dynamics for designing appropriate physical parameter and control factors with practical relevance to MPPT.

### 4 Problem formulation

Analysis of nonlinear dynamics of DC-DC converters employed for MPPT seems to be challenging and essential due to their potential to develop instabilities. Owing to the fact that the abnormal operations affect the transfer efficiency and switching stress of the converter, a thorough simulation of the system under all possible operating conditions helps provide useful guidelines for appropriate design of the converter and its control with a perspective to keep the bifurcations far enough from the operating conditions in parameter space. The scope includes the formulation of control methods to sustain the system within the stable operating range and aid to efficiently track and transfer the maximum power from the solar energy.

### 5 System configuration

A 250W solar panel of type SRP-250-6PB with MPP current of 8.35A and MPP voltage of 29.9V is considered. Its short circuit current and open circuit voltage are specified as 8.92A and 37.1V at standard test conditions.
conditions. A boost converter bestows the function of a MPPT for extracting the maximum electrical power from a PV source. It necessitates the role of a MPPT controller along with a PWM generator to ensure the reach of the maximum efficiency. The parameters of the boost converter to be chosen as \( L = 2 \text{mH}, C_{IN} = 1000 \mu F, C_o = 200 \mu F, R_o = 400 \Omega \) and \( F_s = 20 \text{kHz} \).

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 input capacitor enables the boost converter MPPT system to fall in the third order category. The state space model of the system takes the form as in Eq. (1)

\[
\begin{bmatrix}
\dot{V}_{pv} \\
\dot{i}_L \\
\dot{V}_o
\end{bmatrix} =
\begin{bmatrix}
0 & -1/C_{IN} & 0 \\
1/L & 0 & -(1-D)/L \\
0 & (1-D)/C_o & 0
\end{bmatrix}
\begin{bmatrix}
V_{pv} \\
i_L \\
V_o
\end{bmatrix} +
\begin{bmatrix}
1/C_{IN} \\
0 \\
0
\end{bmatrix}
I_{pv}
\]

(1)

6 Design of proposed control methodology

The rationale of the MPPT system design echoes the tracking of maximum power, reduced oscillations around maximum operating point, reduced switching stress for the converter which aids in efficient conversion of energy and high voltage gain at the output. The intermittent nature of the solar energy together with the demand for a MPPT system requires providing precise and efficient tracking over wide range of irradiation and sustained tracking even for sudden environmental changes.

The proposed design of the control methodology owes to dissuade the chaotic effects and extract the maximum possible energy from sun and convert the energy efficiently to the load satisfying the necessities of a MPPT system. It also avails the two variations of perturb and observe methods one being the direct duty cycle perturbation and the other the reference PV voltage perturbation with a PI controller to showcase the deviation of the system from expected performance as they enter chaotic operation and to highlight the robustness of the proposed controller over a wide range of environmental changes.

The proposed formulation enables the reference voltage generated by the conventional perturb and observe algorithm and convert it into corresponding reference current. It derives the theory of a variable structure controller (VSC) to maintain the average value of inductor current within the reference current through PWM generation to the boost converter switch which can track the maximum power in addition to control the nonlinear dynamics of the converter.

The VSC design starts with the formulation of sliding surface or sliding line given in Eq. (2)

\[
\sigma = g(I_{ref} - i_L).
\]

(2)

Where \( \dot{\sigma} \) the sliding surface, \( g \) is the gain and \( I_{ref} \) is the reference current calculated from perturb and observe algorithm. The sliding manner exists if all the state trajectories are directed towards the sliding surface. The mathematical form of such a condition is given in Eq. (3) and \( \dot{\sigma} \) is the first order derivative of the sliding surface given in Eq. (4)

\[
\sigma \dot{\sigma} < 0,
\]

(3)

\[
\dot{\sigma} = -g \left( \frac{V_{pv}}{L} - \frac{V_o(1-u)}{L} \right),
\]

(4)
where \( u \) is the discrete form of the continuous variable \( D \). It generates the PWM signal from the artifacts of VSC through a hysteresis formed by Eq. (5).

\[

case \begin{align*}
  u &= 1; \quad \text{if } \sigma < -h/2, \\
  u &= 0; \quad \text{if } \sigma > h/2,
\end{align*}
\]

(5)

where \( h \) refers to the peak to peak value of inductor current whose average value expects to be regulated to the reference current value. The design of the hysteresis value \( h \) corresponds to be \( 2I_{ref} \) for operating the boost converter in the border between discontinuous and continuous mode of operation. Applying the first condition of Eq. (5) to Eq. (3), the gain value is found to be as in Eq. (6)

\[
g < \frac{L I_{pv}}{V_{pv}}
\]

(6)

7 Simulation studies

The exercise evaluates the solar PV MPPT system with proposed controller for steady state variations of insolation and compares the performance with the conventional perturb and observe algorithm using direct duty cycle and reference voltage control. The Fig. 1 depicts the functional block diagram of the proposed control algorithm.

![Functional block diagram of proposed control algorithm for solar MPPT.](image)

The design of the boost converter orients to generate PWM pulses from the analytical procedure and the VSC based P&O. The control strategies involved in the simulations are denoted with the following conventions in the simulation results: ‘dy’ denoting P&O with direct duty cycle control, ‘pi’ meaning P&O with PI control and ‘sm’ representing P&O driven VSC with hysteresis.

The system STC simulation at 1000W/m\(^2\) tracks a maximum power of about 247.7W of the PV panel SRP-250-6PB and observes from Fig. 2 the oscillation around the maximum power is lower for the VSC compared to the conventional P&O control. The inductor current shown in Figs. 3-5 and the phase portraits shown in Fig. 6 showcases the steady state period-1 operation of the MPPT system in all the three control designs. The phase portrait of sliding mode control in Fig. 6 may appear to be aperiodic, but it reveals to be the actual evolution of the system to steady state.

The solar PV system operates from dawn to dusk where the continuously changing solar irradiation poses challenges to the converter designed at STC. The PV system operates at low irradiation conditions at morning and evening in a normal day, which necessitates the study to be made at low irradiation condition and accomplishes the tracking of maximum power of around 50W at 200W/m\(^2\) in Fig. 7. The variations of system parameters over a wide range can result in bifurcations which can eventually lead to chaos. The controller design plays a vital role in extending the stable operating range of a system.

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![Functional block diagram of proposed control algorithm for solar MPPT.](image1)

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![Tracking of maximum PV power at 1000W/m^2.](image2)

![Inductor current waveform in P&O with direct duty ratio control at 1000W/m^2.](image3)

![Inductor current waveform in P&O with PI control at 1000W/m^2.](image4)

The inductor current waveforms of P&O with direct duty ratio control and P&O with PI control in Figs. 8, 9 shows that the system is prone to instability and exhibits chaos. The phase portraits of conventional P&O in Fig. 11 portray a variety of nonlinear dynamics in the system operation. The controller design plays a vital role in extending the stable operating range of a system in the sense the proposed P&O with sliding mode control strives to stabilize the system in its period 1 operation as seen in Fig. 10. The phase portrait of sliding mode shown in Fig. 11 evidences the performance of the control algorithm.
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Fig. 5: Inductor current waveform in P&O with sliding mode control at 1000W/m$^2$

Fig. 6: Phase portraits of system state variables at 1000W/m$^2$

Fig. 7: Tracking of maximum PV power at 200W/m$^2$

8 Conclusion

A solar PV system with a boost converter has been modeled as a MPP tracker from the equivalent model of a real time PV panel. The theory of VSC strategy has been formulated to articulate the nuances of a closed loop regulating methodology through changes in the hysteresis strategy. The performance has been examined using MATLAB based simulation with the control techniques that include the proposed VSC strategy, the convention-
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Fig. 7: Tracking of maximum PV power at 200W/m²

Fig. 8: Inductor current waveform in P&O with direct duty ratio control at 200W/m²

Fig. 9: Inductor current waveform in P&O with PI control at 200W/m²

Fig. 10: Inductor current waveform in P&O with sliding mode control at 200W/m²

al P&O with direct duty cycle perturbation and the conventional P&O with voltage reference perturbation. The PV system performance has been tested for steady state variations of irradiation to bring out the supremacy of the proposed technique and to illustrate that it provides precise tracking, maximum power conversion and prolonged sustainability of period-I operation. The results have been ordained to elicit far reaching consequences on the use of Solar PV system and draw a road map for its use in real world applications.
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