Stability Analysis of Non-linear controlled PV boost Converter

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Abstract

The development of power electronic converters has brought tremendous change in photovoltaic (PV) system. The input voltage of converter is flexible compared to input current but it is more influenced by the nonlinearity in the PV characteristics under different climatic conditions. In this paper the flexible input voltage is controlled by employing cascade control technique in the PV Stand-alone system. First, the input voltage across the capacitor and the current through inductor of the converter are controlled by retaining linear cascade controller, which is liberalized by the PV Characteristics obtained by maximum power point (MPP) by the state space modeling. Finally, the PV System has instability, when the converter is operating at constant current region (CCR) and this problem poses a challenge to control the design. So as to resolve this issue, a non-linear control with Feedback Linearization Control (FBLC) technique is applied to the converter system. The control laws are derived and implemented to the boost converter. The result reflects better performance in the proposed FBLC technique, which is not influenced by PV operating conditions.

Keywords: *Cascade Control, Feedback Linearization Control, Maximum Power Point, Photovoltaic System*

1. Introduction

Renewable sources play a prominent role in the present scenario. The most commonly used energy sources are like Solar, Wind, tidal etc. One of the main renewable energy sources is commonly used in power generation is solar energy. It collects energy from nature and is also abundantly available. The solar energy has a lot of benefits specially to reduce the global warming. The photovoltaic systems are growing rapidly due to advantageous of different ambient conditions. In recent years [1]–[2] the power electronic condition equipment is playing a significant role in PV system and they have been introduced modifications in system configurations. Classifications of PV system have become important in understanding the latest development in improving system performance in energy harvesting.

Choosing an equivalent practical model [3] is become more convenient than ideal model due to the number of unknown parameters. In [4], these parameters always depend on weather conditions like Irradiance and Temperature. In the literature [5], the P-V and I-V characteristics of PV system are very important and need to be determined more accurate. A large range of current can produce in the PV module due to the voltage changes [6]–[7], it is depending on climatic fluctuations. Due to the change in climatic conditions the voltage changes logarithmically and whereas the current changes linearly, so in order to track the change in environmental conditions the voltage should remain constant that can be done through MPP. To overcome these situations, a converter is connected between the load and PV panel in order to obtain the MPP. In this context many strategies [8]–[9] of monitoring the MPP of a PV module was developed. The well-known conventional MPPT techniques are Incremental Conductance approach [10]–[11], Perturb & Observe [12]–[13],

Fractional method and etc. Furthermore, the P&O method is comprehensively used because it is very simplest MPPT technique.

DC-DC converters are commonly used in electronic circuits and various applications such as power system, automotive, aircraft, medical equipment, renewable energy systems, electric vehicle, etc. In recent papers [14]-[16], a major aspect to the modelling of the converter is the controller design. The commonly used control methods are to control the duty cycles and the DC link voltage. They are frequently used to attain a stabilized voltage from buck–boost converters [17]-[18]. To regulate the DC link voltage by choosing of conventional control methods [19]. However, this method cannot be suitable for large load variations. Therefore, nonlinear control technique is coming into the picture. Furthermost used method to control switching power supplies is Pulse-width Modulation (PWM). The conventional modulation was controlled power electronics circuits. Its model based on averaging and controlled specific condition operates in [20]-[22]. The conventional controllers do not offer a good large-signal operating transient. Generally used classical control-based designs of conventional controllers require precise linear mathematical models. The conventional controllers failed to perform satisfactorily [23]-[24] uncertainty in parameters, non-linearity, load disturbance, etc. It can be controlled by means of sliding-mode (SM) control, by using variable structure control system (VSCS). However, there are still a few issues in the converters, which have led to the drift to advanced control strategies like input output linearization [25]-[26], feedback linearization [27]-[28], which are non-linear and does not provide themselves to the application of linear control theory.

In this work, a practical equivalent model of solar cell with series resistance and shunt resistance is considered. Because of the P-V curve characteristics are non-linear; the MPP of a PV can be obtained by using P&O MPPT method [13]. Moreover, it adjusts the converter dc link voltage. In the literature, [25]-[26] the main focus on the cascade controller design of the converter. Here the non-linear system is converted to linearized using the small-signal model. It was having inner and outer loop controller. The inner loop controller response is faster than outer loop, moreover it has a drawback in behavior of converter inner loop controller. So, this problem can be overcome by choosing a new proposed technique for non-linear converter system which is using FBLC. Simulations are carried out for Constant Voltage Region (CVR), CCR and MPP region of the converter system. From the results it is found that, in the proposed method the converter system stability is improved for all the three cases. Furthermore, the proposed control technique is also performing well at different ambient conditions of the PV system.

2. Photovoltaic-Converter Configuration:

2.1 Photovoltaic Modelling:

The practical PV model can be represented by its equivalent circuit [4] as shown in Fig. 1, then the PV current (I_{pv}) is given by:

Fig 1. Equivalent model of PV Panel.

$$I_{pv} = I_{ph} - I_{rs} \left(e^{\left(\frac{V_{pv} + I_{pv} R_s}{A} \right)} - 1 \right) - \left(\frac{V_{pv} + I_{pv} R_s}{R_p} \right) \quad (1)$$

Where I_{ph} the light current is directly proportional to the irradiance, I_{rs} the diode reverse saturation current, $A = N_s * a * V_t$, N_s the number of series connected PV cells of the module, $V_t = k * T$

$T/q, V_t$ the Thermal voltage, T is the temperature of the P-N junction in Kelvin's, a is the diode ideality factor and q is the electron charge. R_s and R_p the series and shunt resistance respectively. The characteristics of PV module at Standard Test Conditions (STC) as shown in Fig. 2.

Fig 2. PV Characteristics STC.

The output voltage of DC-DC converter is maintained as constant for second stage conversion. The tracking can be done by using MPPT algorithm block diagram as shown in Fig.3, by monitoring the power at the terminals of the PV panel and regulated the voltage/current of the converter, compelling the PV array to operate at maximum power.

For this purpose P&O MPPT algorithm have used due to simplicity of execution in the flowchart [13]. From Eqn. (1), I-V characteristics exhibits non-linear relationship between voltage (V_{pv}) and current (I_{pv}) of panel. In order to obtain the linearized behaviour between V_{pv} & I_{pv} . Thevenin's voltage and its equivalent resistances are calculated and may be represented in the equivalent circuit of Fig. 4, where the thevenin's equivalent circuit as followed by Eqn. (2).

Fig 3. Block Diagram for MPPT of DC-DC Converter. Fig 4. Linearized Circuit of a PV Panel.

$$V_{EQ} = V_{pv} - \frac{1}{g} \text{ and } r_{EQ} = -\frac{1}{g} \quad (2)$$

Dynamic and static resistance curves are shown in Fig. 5, where $r_{pv} = r_{EQ}$, is the dynamic resistance and $R_{pv} = \frac{V}{I} = \frac{1}{g}$, is the static resistance which further categorizes the behavior of PV source. It was based on the operating point location in the I-V curve divided into 3 regions. It is Seen from Fig. 2 and Fig. 5, in the CCR, where $r_{pv} > R_{pv}$ at the MPP, $r_{pv} = R_{pv}$ lastly in the CVR, $r_{pv} < R_{pv}$. The PV panel specifications are presented in Table. I.

Fig 5. Dynamic and Static resistance curve.

Table. I: Specifications of KC200GT PV Panel @STC

Parameter	Value
Maximum Power (P_{max})	200W
Maximum Power Voltage (V_{mpp})	26.3V
Maximum Power Current (I_{mpp})	7.61A
Open Circuit Voltage (V_{oc})	32.9V
Short Circuit Current (I_{sc})	8.21A
Number per cells Module	54

2.2 Boost Converter Modeling:

The boost converter with input as I_{pv} , parasitic resistances of the inductor and capacitor as shown in Fig. 6. The control input i_{pv} maintains the output of the converter V_o as constant by switching the MOSFET with the help of duty ratio obtained from the P&O MPPT.

Fig 6. Modelling of Boost Converter.

The operation of converter can be illustrated by its switching conditions as shown in Fig. 7(a) & Fig. 7(b), in order to obtain the linear model for state space representation in Eqn. (3). A linear average model of equations are considered for each switching operation as

$$\dot{x} = Ax(t) + Bu(t)$$

$$y = Cx(t) + Du(t)$$

$$\text{Here } A = A_1d + A_2(1 - d); B = B_1d + B_2(1 - d) \quad (3)$$

Fig 7. Equivalent circuit during state (a) ON, (b) OFF.

During ON-state,

$$\begin{aligned} \frac{dV_{cin}}{dt} &= -i_L \left(\frac{r_{cin}}{C_{in}r_{cin}} \right) + i_{pv} \left(\frac{r_{cin}}{C_{in}r_{cin}} \right) \\ \frac{di_L}{dt} &= \frac{V_{cin}}{L} - i_L \left(\frac{r_{cin} + r_L}{L} \right) + \frac{i_{pv}r_{cin}}{L} \end{aligned} \quad (4)$$

During OFF-state,

$$\begin{aligned}\frac{dV_{cin}}{dt} &= -i_L \left(\frac{r_{cin}}{C_{in}r_{cin}} \right) + i_{PV} \left(\frac{r_{cin}}{C_{in}r_{cin}} \right) \\ \frac{di_L}{dt} &= \frac{V_{cin}}{L} - i_L \left(\frac{r_{cin} + r_L}{L} \right) + \frac{i_{PV}r_{cin}}{L}\end{aligned}\quad (5)$$

Then overall switching cycle average state model is from Eqn. (4) & Eqn. (5), as

$$\begin{bmatrix} \dot{V}_{cin} \\ \dot{i}_L \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{C_{in}} \\ \frac{1}{L} & \frac{-(r_{cin} + r_L)}{L} \end{bmatrix} \begin{bmatrix} V_{cin} \\ i_L \end{bmatrix} + \begin{bmatrix} \frac{1}{C_{in}} & 0 \\ \frac{r_{cin}}{L} & \frac{-(1-d)}{L} \end{bmatrix} \begin{bmatrix} i_{PV} \\ V_0 \end{bmatrix}\quad (6)$$

3. Control Strategy

3.1 Linear Cascade Control

The overall average switching model of the converter system in Eqn. (6), controls the converter according to large signal stability which consists of both steady part and small-signal stability. In this control, the non-linear system can be linearized by performing perturbation and linearization at operating point, then linear small-signal state equation can be represented in the state space model $\dot{\hat{x}} = A\hat{x} + B\hat{u}$.

$$\begin{bmatrix} \dot{\hat{V}}_{cin} \\ \dot{\hat{i}}_L \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{C_{in}} \\ \frac{1}{L} & \frac{-(r_{cin} + r_L)}{L} \end{bmatrix} \begin{bmatrix} \hat{V}_{cin} \\ \hat{i}_L \end{bmatrix} + \begin{bmatrix} \frac{1}{C_{in}} & 0 & 0 \\ \frac{r_{cin}}{L} & \frac{-(1-D)V_0}{L} & \frac{V_0}{L} \end{bmatrix} \begin{bmatrix} \hat{i}_{PV} \\ \hat{V}_0 \\ \hat{d} \end{bmatrix}\quad (7)$$

In Eqn. (7), the values of A and B analogous to operating point, where $\hat{x} = [\hat{V}_{cin} \hat{i}_L]^T$ and $\hat{u} = [\hat{i}_{PV} \hat{V}_0 \hat{d}]^T$ are the state variables and inputs of the small signal model and $\hat{y} = [\hat{V}_{cin} \hat{i}_L]^T$ is the small signal output. The transfer function of the small signal model can be obtained by $\hat{y}(s) = [(SI - A)^{-1}B]\hat{u}(s)$ which gives

$$\begin{bmatrix} \hat{V}_{cin}(s) \\ \hat{i}_L(s) \end{bmatrix} = \begin{bmatrix} G_{V_{cin}i_{PV}} & G_{V_{cin}V_0} & G_{V_{cin}d} \\ G_{i_Li_{PV}} & G_{i_LV_0} & G_{i_Ld} \end{bmatrix} \begin{bmatrix} \hat{i}_{PV} \\ \hat{V}_0 \\ \hat{d} \end{bmatrix}\quad (8)$$

From Eqn. (8), the inner loop plant transfer function and outer loop plant transfer function, used in the design of linear cascade control are shown in Fig. 8, followed by Eqn. (9) & Eqn. (10).

$$G_{i_Ld} = \frac{\hat{i}_L}{\hat{d}} = \frac{\left(\frac{V_0}{L}\right)S}{S^2 + \left(\frac{r_{cin} + r_L}{L} + \frac{1}{LC_{in}}\right)}\quad (9)$$

$$G_{V_{cin}i_L} = \frac{\hat{V}_{cin}}{\hat{i}_L} = \frac{-1}{C_{in}S}\quad (10)$$

Fig 8. Linear Cascade Control.

3.2 Feedback Linearization Control

Prior to analyzing the FBLC method in contrast to linear cascade controller, the FBLC laws are obtained from Eqn. (6). The non-linearity's appeared in Eqn. (6) is the cause of connection between the control inputs and the state variables in converter and by the non-linear term I_{pv} , which changes based on Eqn. (1). FBLC is a non-linear cascade controller developed with the help of input/output feedback linearization.

3.2.1. Feedback Linearization Control:

The inductor current dynamic equation from Eqn. (6) is,

$$\frac{di_L}{dt} = \frac{V_{cin}}{L} - i_L \left(\frac{r_{cin} + r_L}{L} \right) + \frac{i_{pv}r_{cin}}{L} - \frac{V_0(1-d)}{L} \quad (11)$$

where the state variable can be treated as an i_L and V_L is a new control input of the inner loop, then the current through inductor can be written in the linearized model as

$$\frac{di_L}{dt} = \frac{V_L}{L} \quad (12)$$

We get linearized current controller $G_{ci}(s)$, with its output v_L is applied to the new linear plant of transfer function $\frac{1}{LS}$. Consider a proportional integral (PI) controller, then Eqn. (12) can be modified as

$$\frac{di_L}{dt} = \frac{1}{L} (K_{pi}(i_L^* - i_L) + K_{ii}\alpha_i) \quad (13)$$

$$\frac{d\alpha_i}{dt} = (i_L^* - i_L) \quad (14)$$

Where α_i is the integrator output, but the actual control input 'd' of the converter can be obtained by substitute Eqn. (13) into Eqn. (11), we get,

$$d = \frac{-V_{cin} + i_L(r_{cin} + r_L) - i_{pv}r_{cin} + V_0 + (K_{pi}(i_L^* - i_L) + K_{ii}\alpha_i)}{V_0} \quad (15)$$

is the inner loop current control law.

Generally, the bandwidth of inner loop is compares bandwidth of outer loop is very high, because of this reason compared to outer voltage loop, inner current loop reaches the actual value in quick manner, so $i_L^* \cong i_L$. Then the dynamics of the inductor current does not affect the outer voltage loop. Actually, when $i_L^* \cong i_L$, Eqn (15) gives $V_0(1-d) = V_{cin} - i_L(r_{cin} + r_L) + i_{pv}r_{cin}$, is placed in Eqn. (11) returns $i_L \cong 0$.

The capacitor voltage dynamic equation from Eqn. (6) is,

$$\frac{dV_{cin}}{dt} \cong \frac{-i_L^*}{C_{in}} + \frac{i_{pv}}{C_{in}} \quad (16)$$

Where i_L^* is the control input of the outer voltage loop and V_{cin} is the state variable. The linearized average value of the capacitor voltage can be obtained by taking new control input i_{cin} (rather than i_L^*), is

$$\frac{dV_{cin}}{dt} = \frac{i_{cin}}{C_{in}} \quad (17)$$

We get linear current controller $G_{cin}(S)$, whose output is i_{cin} applied to the new linear plant of transfer function $\frac{1}{C_{in}S}$. Consider a proportional integral (PI) controller, then Eqn. (17) can be modified as

$$\frac{dV_{cin}}{dt} = \frac{1}{C_{in}} (K_{pv}(V_{cin}^* - V_{cin}) + K_{iv}\alpha_v) \quad (18)$$

$$\frac{d\alpha_v}{dt} = (V_{cin}^* - V_{cin}) \quad (19)$$

Where α_v is the integrator output, but the actual control input i_L^* of the converter can be obtained by substitute Eqn. (18) into Eqn. (16).

If substitute the Eqn. (20) in Eqn. (16), which cancels the non-linearity produced by the term i_{pv} .

$$i_L^* = i_{pv} - (K_{pv}(V_{cin}^* - V_{cin}) + K_{iv}\alpha_v) \quad (20)$$

Fig 9. Controller design of Feedback Linearization

4. Result Analysis

In this section, the results of simulation are delivered to validate the successful of the proposed controller on boost converter. A 200W boost converter is designed with the help of parameters mentioned in Table. I and Table. II. First, the behaviour of the converter system is analysed for uncertainties in gain parameters and stability of converter system by applying cascade control technique. Later, the proposed controller is also analysed for uncertainties in control parameters, different irradiance and different temperature conditions. The FBLC technique is used to test the output of the converter under this condition using MATLAB/Simulink software.

4.1 Cascade Control

A linear cascade controller was developed with the Eqn. (9) & Eqn. (10). From the block diagram as shown in Fig. 8, The conventional controllers have with outer loop and inner loop, which are used to control the input capacitor voltage and average inductor current respectively. The controller is evaluated by changing the proportional gain of the outer loop controller. During simulation, a constant voltage is maintained to the converter at the STC.

Table. II: Converter Parameters.

Parameter	Value
Inductor	48.15μH
Capacitor	40 μF
Input Resistance	3mΩ
Output Resistance	3mΩ
Load Resistance	8.9mΩ

4.1.1. Uncontrolled/Controlled Study of Cascade Controller:

The output of the converter system for uncontrolled case can be seen in Fig. 10. The input capacitor voltage value reached a peak value of 31.7V and settled at 0.3msec without any oscillatory behavior and the average inductor current was not reached to steady value in uncontrolled case indicates the blue line. In order to considering controlled case as shown in Fig. 10 represents the response of the input capacitor voltage of 32.7 V is settled at 2msec and the Inductor current still not reached steady value to the specified values of the gain controller in Table. III.

Table. III: Converter Parameters.

Gain	Outer Loop	Inner Loop
Proportional	0.4	45
Integral	0.1	0.01

Fig 10. Uncontrolled and Controlled cases (a) Inductor Current (b) Capacitor Voltage.

4.1.2. Considering Uncertainties in Control Parameters:

The output of the converter control system has considering uncertainties in the control parameters as like 25%, 50% and 75% in Fig. 11. While V_{cin} reaches a value of 32.7V with steady state value at 2msec, 1msec and 0.9m sec. For the different changed gain values of the cascaded control analysis of the inductor current responses not much significant value is represented in Fig. 11(a). The proportional gain of the outer loop controller was set to different uncertainties of its actual value as shown in Fig. 11(b). From these, the maximum value of the input capacitor voltage was obtained by introducing a control parameter compare to uncontrolled system, although this increases the system settling time, resulting in decreased stability. The response to different irradiance (G) and temperature (T) conditions of the Fig. 13. Transfer Function of Inductor Current to Capacitor Voltage and inductor current was also observed, but due to the linearization of the parameters, they had almost no effect.

Fig 11. Uncertainties in control parameter variations (a) Inductor Current. (b) Capacitor Voltage.

4.1.3. Stability Analysis of Converter System Operating Regions:

Fig. 12 shows the ratio of duty cycle to inductor current transfer function for the three operating regions of I-V curve as mentioned in Table. IV. Blue, Red, Green line indicates the response of transfer function operating at CCR, MPP, CVR regions. In the current source region, from Fig. 5, the value of equivalent resistance R_{eqn} is very high which results in poor controllability of the inductor current due to the negative value of DC gain. Fig. 13 indicates the inductor current to input voltage transfer function for the three operating regions of I-V curve. In CVR, from Fig. 5, the value of equivalent resistance R_{eqn} is low. This leads to a low value of DC gain, due to which variations in the inductor current have a small effect in the input voltage of the converter.

Fig 12. Transfer Function (G_{ILD}) Duty to Current through Inductor

Fig 13. Transfer Function of Inductor Current to Capacitor Voltage.

Table. IV: Equivalent Voltage and Resistance of Linearized PV Curve

Region	V_{eqn} (V)	$R_{eqn}(\Omega)$
CCR	3412	415.37
MPR	51.635	3.329
CVR	32.9	0.2195

4.2 Feedback linearization Control

The proposed controller has been developed with the help of Eqn. (13) - Eqn. (15) and Eqn.(18) - Eqn.(20). From the diagram shown in Fig. 9, where the inner loop controls the average value of the inductor current with control parameters while the outer loop controls the voltage of the input capacitor, with voltage control parameters. The controller is assessed by varying the outer loop voltage controller proportional gain in Table. V. A constant voltage load, set to 28V and PV at STC along with different irradiances and ambient temperature is applied to the converter during the test cycle.

Table. V: Controller Parameters.

Gain	Outer Loop	Inner Loop
Proportional	1.2	530
Integral	0.9	0.87

4.2.1. Uncontrolled/Controlled Study of Feedback Linearization:

In Fig. 14 depicts the response of a converter system with and without controller. Here the voltage of the input capacitor and average inductor current reaches to the steady state value 32.9V, 8.21A at 0.7msec and 0.6m sec respectively in uncontrolled case indicates the red line. The responses of input capacitor voltage and inductor current with the specified values of the controller gains are depicted in Fig. 14. Where V_{cin} reaches to a value of 32.9V at 0.7msec, i_L value is reached to steady state value 8.21A with a settling time of 0.6msec without any oscillator behavior.

Fig 14. Uncontrolled and Controlled Case study of FBLC (a) Inductor Current. (b) Capacitor Voltage.

4.2.2. Considering Uncertainties in Control Parameters:

The proportional gain parameter of the outer loop considered in 25%, 50% and 75% uncertainties in the actual value respectively in Fig. 15(a) & Fig. 15(b), then V_{cin} , i_L hits 32.9V with a settling time of 0.7msec, 0.4msec and 0.3msec respectively and 8.21 A at 0.6msec, 0.4msec and 0.3msec to reaches a steady state value.

Fig 15. Uncertainties in control parameter variations in FBLC (a) Inductor Current. (b) Capacitor Voltage.

4.2.3. Comparison of Cascade and Feedback Linearization:

The comparison of cascade and feedback linearization response is represented in Fig. 16. Here, the performance of both inductor current as well as capacitor voltage gives better response in settling time is less, inductor current reaches the steady state value and voltage is almost constant as mentioned in Table. VI.

Fig 16. Simulation results for Comparison of Cascade and Feedback Linearization (a) Inductor Current. (b) Capacitor Voltage.

Table. VI. Comparison of Cascade and Feedback Linearization

Control	Magnitudes		Settling Time	
	i_L (A)	V_c (V)	i_L	V_c
Cascade	0	32.7	1m sec	2m sec
FBLC	8.21	32.9	0.6m sec	0.7msec

4.2.4. Different irradiation and temperatures conditions:

The inductor current response can be analyzed by applying different irradiance and temperature conditions. Here, inductor current is varied in significant manner for changing in irradiance in Fig. 17 (a). In climatic conditions, the magnitude of inductor current in Fig. 17 (b). In both cases capacitor voltage was unchanged.

Fig 17. Simulation Results of Different irradiance and temperature conditions (a) Inductor Current. (b) Capacitor Voltage.

5. Conclusion

A non-inverting converter with control input voltage for PV applications was designed and tested by applying the FBLC technique. The weaknesses of linear cascade control scheme were discussed as earlier. The equivalent resistance R_{eqn} of CCR region was very high, due to this high value of resistance it leads to negative value of dc gain and the inductor current response was also very poor. So, that the FBLC technique overcome these issues and also improve the stability of the converter which are highly affected on control gain parameters. Moreover, the proposed technique inductor current and capacitor voltage responses reach steady state in quick manner and also settling time was reduced. The input voltage is selected to be the control variable because it presents small variations with changes in irradiance and temperatures also observed. So, we conclude the stability of the converter system behavior was improved and also the proposed control law cancels the system non-linearity.

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