2016 IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics Engineering (UPCON)
Indian Institute of Technology (Banaras Hindu University) Varanasi, India, Dec 9-11, 2016

Feedback control and simulation of DC-DC Cuk converter for solar photovoltaic array

Piyush Choudhary, Research Scholar
Department of Electrical Engineering
Indian Institute of Technology (BHU)
Varanasi, India
piyush.rs.eee@iitbhu.ac.in

Som Nath Mahendra, Professor
Department of Electrical Engineering
Indian Institute of Technology (BHU)
Varanasi, India
snmahendra.eee@iitbhu.ac.in

Abstract— **The DC-DC Cuk converter is a combination of a cascade connection of the boost converter and the buck converter having a coupling capacitor to transfer the energy. The non-isolated Cuk DC-DC converter are having fourth-order and non-linear dynamic characteristics and it`s advantages mainly include the use of fewer number of switches, smooth input as well as output current and magnetic component integrability. Solar Photovoltaic array has variable power production based on irradiance and temperature of solar cell. To control the output, the Cuk converter is analyzed using state space equations and tested for its stability analysis. The simulation has compared the system with a compensation scheme to minimize output voltage deviation in response to change in the input voltage of the system. Using this configuration, it requires only voltage sensor and non-requirement of the current sensor. Various issues concerning the controller design like the detailed stability and feasibility analysis are also discussed to get some insight into the controlled system. Using state space equation method, the transfer function is derived and simulated in Matlab and judged the stability of whole system.**

Keywords—cuk converter; solar photovoltaic array; stability analysis; feedback controller; matlab.

I. INTRODUCTION

The research and developments in the area of Solar Photo Voltaic technology is at par with growing commercial applications. At present, the solar PV market is growing rapidly with worldwide around 55 GW in 2015 and which makes photovoltaic as one of the fastest industry [1]. The improvement of overall efficiency of SPV system depends upon various factors including materials of solar cells, Maximum Power Tracking, DC power conditioning, factor affecting the performance of PV module.

The electrical power produced by SPV array is transferred to load side using maximum power transfer aspects by using fast MPPT algorithm and power electronics plays an important role. MPPT uses the DC-DC converter for regulating the input voltage at the PV module's MPP and providing load matching for the maximum power transfer. Under fluctuation of climatic conditions, MPP changes and MPPT adjust the converter duty cycle to track the new MPP [2] [3]. A comparison on various DC-DC converter topologies by way of their dynamic models, frequency characteristics, and component cost is studied exhaustively. A theoretical study of four basic non-isolated converters (buck, boost, buck-boost, and Cuk) DC-DC converters are studied and compared under different atmospheric conditions in order to determine the best DC-DC converter for the PV system. Out of this comparison, a conclusion has evolved that the stability of Cuk converter is better for varying atmospheric conditions and gives effective voltage and power output[4][5]. Based on the characteristics of the system, proper designing of any controller is required and for this purpose, the state space block diagram, open-loop and closed loop model are examined. The idea of controllability refers to the ability of the input control to affect the system dynamics, if the closed-loop system poles may be arbitrarily placed in the complex plane [6]. As such some nonlinear means of controlling are usually required to achieve the tight regulation of these converters over a wide range of operating conditions. Sliding-mode control is a one of the widely used non-linear control methodology for dc-dc converters. Further, the voltage-mode control and the current-mode control are two widely used methodologies for regulating the output voltage in dc-dc converters [7].

The output feedback control strategy is found to be useful for the regulation of the output voltage of higher order converters. However, it should be noted that the control law derived for the non-inverting converters like the fifth order dc-dc boost converter and the two-stage cascade boost converter cannot be readily applied to the inverting Cuk converter. The main advantage of the feedback controller is that it requires only one state variable i.e. output voltage for feedback purposes [6]. The paper is organized as follows. The PV modeling and specifications used are given in Section II. The theory of power conditioning, principle of Cuk converter with linkage with solar PV array is explained in Section III. Section IV explains the power losses in converter and how efficiency is derived for a range of output power. Section V explains about the control concepts, state space equations, stability analysis and transfer function analysis, followed by the simulation results in Section VI. Section VII presents the conclusion.

II. MATHEMATICAL PV MODELING

A. PV system Modeling

The mathematical model of PV module consists of a diode which represents the PN junction, two resistors (series and shunt) which represent the losses of the system. The direct conversion of solar energy to electrical energy is function of the incident solar irradiance and solar panel temperature.

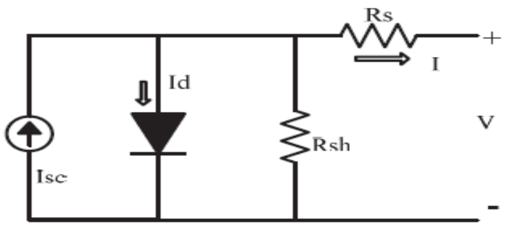

Fig. 1 Equivalent Circuit of a solar cell [8]

The equation of the mathematical model is

$$I = I_{ph} - I_{sat}\left\{\exp\left[\frac{(V+IR_s)}{\eta V_T}\right]-1\right\} - I_{sat,2}\left\{\exp\left[\frac{(V+IR_s)}{\eta_2 V_t}\right]-1\right\} - \frac{(V+IR_s)}{R_p} \quad \text{----(1)}$$

Where, the second saturation current shows the nonlinear dependence on temperature:

$$I_{sat,2} = C_2 * T^{\frac{5}{2}} * e^{\left(\frac{E_{gap}}{2kT}\right)} \quad \text{-------------------(2)}$$

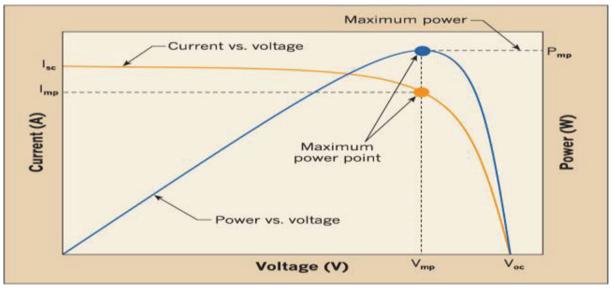

Fig. 2: *A typical Current vs voltage curve for PV module*

The output power of the solar panel depends on the parameters, solar irradiance and temperature. The relation between the voltage and power of the PV panel is shown as the PV- characteristics in Fig. 2. From this characteristic, it is clear that a MPPT algorithm is required to track the maximum power and to generate the appropriate duty cycle for firing the converter [8][24].

B. Specifications used

Table 1: Specification used from Jindal Solar Module

Parameter	Specifications
Power	100-500 watts
Open circuit voltage(V_{OC})	43 V DC
Short Circuit current(I_{SC})	8.6 A
Voltage at Maximum Power(V_{MP})	36.0 V
Current at Maximum Power(I_{MP})	6.94 A
Load resistance	15 Ohms

III. POWER CONDITIONING STAGE

The power conditioning unit or voltage regulator is capable of more than simple constant voltage regulation. It often based on some significant factors line isolation, noise attenuation, lower harmonics, lower cost, higher efficiency, ripple free and reliable operation. This paper focuses on loop gain for a Cuk converter utilizing the state space equations and analyses, how to design a compensation scheme to minimize output voltage deviation with respect to input voltage disturbances.

A. Design Objective and Requirements

The solar PV array considered for simulation has following parameter and condition:

Table 2: Objective, Solar Module with Cuk Converter

Input voltage V_g	43-76 V DC
Output voltage V_O	200 V DC
Output Power P_O	100W- 500 W
Switching frequency f_s	250kHz
Efficiency	>90%for all input voltage and output power conditions
Peak-peak value of output voltage ripple	< 10 V
Peak-peak value of current ripple on input inductor	L1 < 20%, on L2 < 50%

B. Operating Principle of non-Isolated Ćuk Converter

In DC-DC voltage regulators, it is important to supply a constant output voltage, regardless of disturbances on the input voltage. The Cuk converter is operated in both step-up and step-down principle [9]. The output voltage can be increased or decreased than that of the input voltage and the output has reversed polarity. This converter consists of two inductors, two capacitors, a diode and a switch as shown in Fig.3.

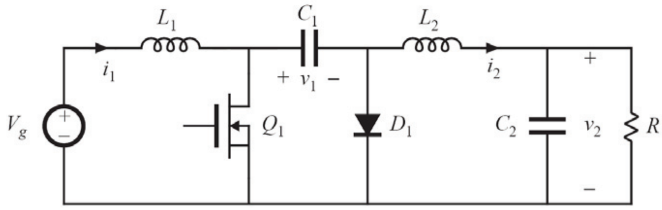

Fig 3: Topology of Non-isolated Ćuk Converter

When the switch Q_1 turns on, inductor L_1 will be charged and capacitor C_1 discharges energy through Q_1. On the secondary side, the current i_2 will be negative and the capacitor C_2 and inductor L_2 will discharge their energy to the load together. For the design, it is also assumed that the converter operating in Continuous Conduction Mode (CCM) and maximum acceptable output ripple for the system will be 5%. The solar PV array has V_{OC}= 86 V with two modules are in series. For Cuk Converter duty ratio D, the design parameters could be derived from formulae in Table 4:

Table 4: Cuk Converter design parameters formulae [10]

Duty Cycle	$\frac{V_{out}}{V_{in}} = \frac{D}{1-D}$	Minimum value of L_1	$L_{1\min} = \frac{(1-D)R}{2Df}$
Minimum value of L_2	$L_{2\min} = \frac{(1-D)R}{2f}$	Coupling capacitor	$C_{1\min} = \frac{DV_{out}}{V_{ref}Rf}$

Filter Capacitor	$C_{min} = \frac{(1-D)V_{out}}{V_{ref}\, 8 L_{2\,min}\, f^2}$

Table 5: Calculation for storage elements

Sl No	Vin	Vout	Duty ratio	L1 (min)	L2 (min)	C1 (min)	C2 (min)
1	75	100	0.571	112 µH	64.3 µH	15.22µF	6.56µF
2	77	100	0.564	116 µH	65.4 µH	15.04 µF	6.67 µF
3	80	100	0.555	120 µH	66.75µH	14.8 µF	6.97µF
4	86	100	0.537	129.3µH	69.5 µH	14.32 µF	7.6 µF

$L1_{min}$= 130 µH, $L2_{min}$= 70 µH, $C1_{min}$= 20 µF, $C2_{min}$= 10 µF

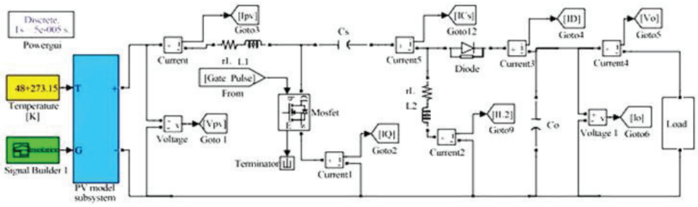

Fig 4: Simulink model of PV model with Cuk Converter[11]

IV. EFFICIENCY OF CONVERTER

The efficiency of the power conditioner unit depends upon the conduction losses of passive components and switching losses of actual devices.

A. *Power loss calculation:*

The conduction losses can be effectively reduced by reducing the usage of components and their operating ranges. The switching losses can be reduced by soft switching techniques. Better the efficiency, the control of converter is easy [9][10]. In addition, the power losses in diode and switch also have impact on the efficiency. These losses could be minimized using suitable diodes and efficient switching transistors devices. Total Power Losses:

$$P_{Loss} = P_L + P_{Cond} + P_{C_O} + P_{Diode}$$

Table 6: Power loss calculation formulae

Power Loss in the Inductor L1:	$P_L = \frac{r_{L1} D^2 P_O}{R(1-D)^2}$
Power Loss in the Mosfet Switch	$P_{Cond} = \frac{r_{Ds} D^2 P_O}{R(1-D)^2}$, $\quad P_{sw} = \frac{f C_o R P_O}{D^2}$
Power loss in the coupling capacitor C_O	$P_{C_o} = \frac{r_{C_o} D P_O}{R(1-D)}$

Total Power Losses:

$$P_{Loss} = P_L + P_{Cond} + P_{C_O} + P_{Diode}$$

B. *Power efficiency calculation:*

$$\eta = \frac{1}{1 + \frac{P_{Loss}}{P_O}}$$

The efficiency curves for a set of input voltages are derived with respect to different power (P_O) rate. Using Matlab codes, the efficiency is calculated and plotted for an input voltage range produced by Solar PV array.

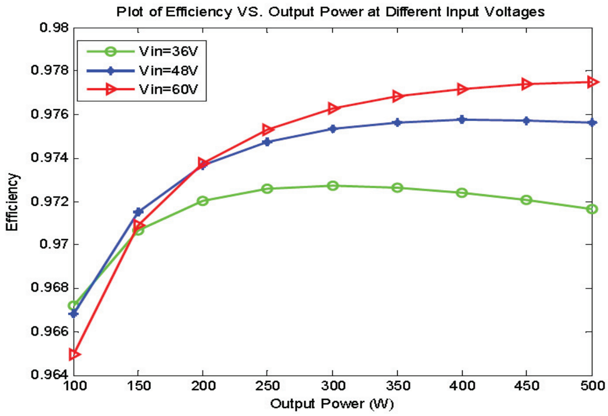

Fig 5: Plot of Efficiency

V. CONTROL OF CUK CONVERTER

Switching DC-to-DC voltage converters comprise of two elements: A controller and a power stage. The power stage incorporates the switching elements and converts the input voltage to the desired output. The controller supervises the switching operation to regulate the output voltage. The two are linked by a feedback loop that compares the actual output voltage with the desired output to derive the error voltage. The controller is the key to the stability and precision of the power supply, and virtually every design uses a pulse-width modulation (PWM) technique for regulation[12][13]. Two main methods of generating the PWM signal: Voltage-mode control and current-mode control.

In this section, an output feedback controller suitable for the regulation of the inverting Cuk converter is examined. The control law uses only the output voltage state variable feedback and as such eliminates the use of the current sensor[14]. The feedback compensation technique for the Cuk converter limits the voltage deviation in response to a voltage step on the input.

A. *Theory of Control*

The proposed output feedback control law can be expressed as below:

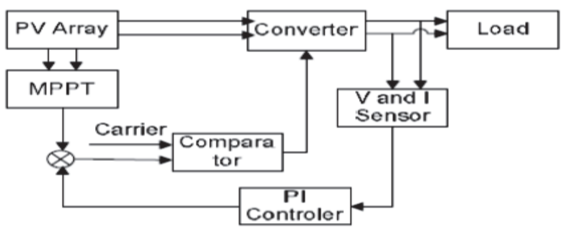

Fig 6: Block diagram of the whole system

Feedback control design based on voltage mode control detail design of a voltage close loop, which can meet specifications when load changes from 500W to 100W.

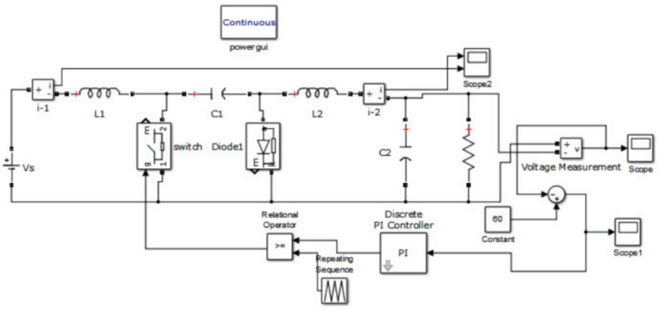

Fig 7: Simulink Model of Cuk Converter with feedback controller.

B. State Space equations

The small signal averaged state-space method is a generalized analysis tool which is readily applicable to either simple circuits or complex structures and it provides an excellent understanding of the frequency domain behavior and a tool to design and analyze the feedback control loops for them[15]. The fundamental equations for state space analysis incorporate the state variables of the system and the all input variables. The number of states is defined by the number of storage elements in the system. For the Cuk converter, there are four states. The output voltage of the converter is the voltage across the capacitor C_2.

When switch Q in ON

$$L_1 \frac{di_1}{dt} = V_g \qquad L_2 \frac{di_2}{dt} = -V_1 - V_0$$

$$C_1 \frac{dV_1}{dt} = i_2 \qquad C_2 \frac{dV_0}{dt} = i_2 - \frac{V_0}{R}$$

When switch Q in OFF

$$L_1 \frac{di_1}{dt} = V_g - V_1 \qquad L_2 \frac{di_2}{dt} = -V_0$$

$$C_1 \frac{dV_1}{dt} = i_1 \qquad C_2 \frac{dV_0}{dt} = i_2 - \frac{V_0}{R}$$

For a full interval: Circuit averaging concept is used as under

$$\begin{bmatrix} \overset{*}{i_1} \\ i_2 \\ V_1 \\ V_0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -(1-d)/L_1 & 0 \\ 0 & 0 & d/L_2 & -1/L_2 \\ (1-d)/C_1 & -d/C_1 & 0 & 0 \\ 0 & 1/C_0 & 0 & -1/RC_0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ V_1 \\ V_0 \end{bmatrix} + \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_g]$$

Small Signal Analysis by adding small perturbation in all state(s) as under:

$$i_1 = I_1 + \hat{i}_1 \quad i_2 = I_2 + \hat{i}_2 \quad v_1 = V_1 + \hat{v}_1 \quad v_o = Vo + \hat{v}_o \quad d = D + \hat{d}$$

The state space equations would transformed as shown below:

$$\frac{d}{dt}\begin{bmatrix} I_1 + \hat{i}_1 \\ I_2 + \hat{i}_2 \\ V_1 + \hat{v}_1 \\ V_o + \hat{v}_0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1/L1 & 0 \\ 0 & 0 & 0 & -1/L2 \\ 1/C1 & 0 & 0 & 0 \\ 0 & 1/C2 & 0 & -1/RC2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ V_1 \\ V_2 \end{bmatrix} +$$

$$\begin{bmatrix} 0 & 0 & -1/L1 & 0 \\ 0 & 0 & 0 & -1/L2 \\ 1/C1 & 0 & 0 & 0 \\ 0 & 1/C2 & 0 & -1/RC2 \end{bmatrix} \begin{bmatrix} \hat{i}_1 \\ \hat{i}_2 \\ \hat{v}_1 \\ \hat{v}_2 \end{bmatrix} + \begin{bmatrix} \frac{(D+\hat{d}) + L2(V_1+\hat{v}_1)}{L1L2} \\ \frac{(D+\hat{d})(-L2)(V_1+\hat{v}_1)}{L1L2} \\ \frac{(D+\hat{d})(-(I_1+i_1)+(I_2+i_2))}{C1} \\ 0 \end{bmatrix} + \begin{bmatrix} 1/L1 \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_g] +$$

$$\begin{bmatrix} 1/L1 \\ 0 \\ 0 \\ 0 \end{bmatrix} [\hat{v}_g]$$

$$\frac{d}{dt}\begin{bmatrix} \hat{i}_1 \\ \hat{i}_2 \\ \hat{v}_1 \\ \hat{v}_0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -(1-D)/L1 & 0 \\ 0 & 0 & -d/L2 & -1/L2 \\ (1-d)/C1 & d/C1 & 0 & 0 \\ 0 & 1/C2 & 0 & -1/RC2 \end{bmatrix} \begin{bmatrix} \hat{i}_1 \\ \hat{i}_2 \\ \hat{v}_1 \\ \hat{v}_2 \end{bmatrix} +$$

$$+ \begin{bmatrix} V_1/L1 \\ -V_1/L1 \\ (I_2 - I_1)/C1 \\ 0 \end{bmatrix} [\hat{d}] + \begin{bmatrix} 1/L1 \\ 0 \\ 0 \\ 0 \end{bmatrix} [\hat{v}_g] + STEADYSTAT \quad E$$

From above equations it is derived that

$$[A] = \begin{bmatrix} 0 & 0 & -(1-D)/L1 & 0 \\ 0 & 0 & -d/L2 & -1/L2 \\ (1-d)/C1 & d/C1 & 0 & 0 \\ 0 & 1/C2 & 0 & -1/RC2 \end{bmatrix} \qquad [B] = \begin{bmatrix} V_1/L1 \\ -V_1/L1 \\ (I_2 - I_1)/C1 \\ 0 \end{bmatrix}$$

$$[X] = \begin{bmatrix} 1/L1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The small signal equations are further be translated into transfer functions:

$$TransferFu \quad nction = [C][sI - A]^{-1}[B]$$

Control to output transfer function: $V_g = 0$

$$\frac{\hat{i}_1}{\hat{d}} = [1 \quad 0 \quad 0 \quad 0][sI - A]^{-1}[B]$$

$$\frac{\hat{i}_2}{\hat{d}} = [0 \quad 1 \quad 0 \quad 0][sI - A]^{-1}[B]$$

$$\frac{\hat{v}_0}{\hat{d}} = [0 \quad 0 \quad 0 \quad 1][sI - A]^{-1}[B]$$

Line to output transfer function (Audio Susceptibility): $\hat{d} = 0$

$$\frac{\hat{v}_0}{\hat{v}_g} = [0 \quad 0 \quad 0 \quad 1][sI - A]^{-1}[B]$$

C. *Transfer Function of Ćuk Converter*

The functional block control diagram of voltage mode feedback system is shown Figure 8:

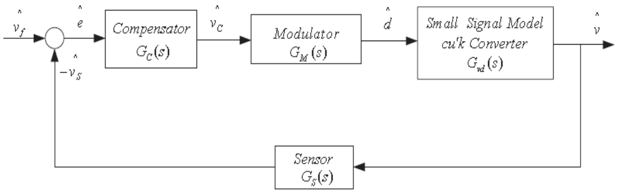

Fig 8: Control block diagram on Voltage Mode Control

Transfer Function from Duty Ratio (Control) to Output voltage G_{vd} (s) of Cuk Converter[20]:

$$G_{vd}(s) = \frac{C_1 L_1 R V_g s^2 / D' + L_1 V_g D^2 (D' - D) / D'^2 s + R V_g}{L_1 C_1 R C_2 s^4 + L_1 C_1 L_2 s^3 + (D'^2 L_2 R C_2 + L_1 C_1 R + L_1 D^2 R C_2) s^2 + (D'^2 L_2 + L_1 D^2) s + D'^2 R}$$

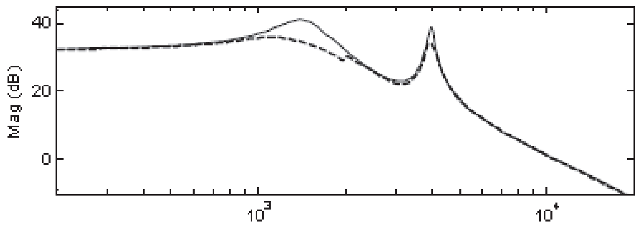

Fig 9: Loop gain of Cuk converter feedback controlled

Transfer function of control to output is derived as above equations using small signal averaged state space model. The Bode plots are depicted in Fig. 10. The Cuk converter has four left half-plane poles and two right half-plane zeros[17].

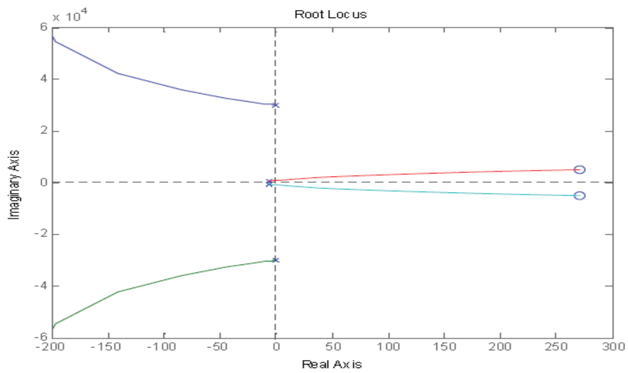

Fig 10: Root Locus of the controller.

If the duty cycle quickly changes in response to a perturbation, the inductor naturally limits the current slew rate and the output voltage drops. The presence of right half-plane zeros means a serious limit on the available loop bandwidth.

D. *Stability analysis*

Cuk Converter has two RHP zeros and the phase response decrease sharply from 0 to -180 degree. So the crossover frequency will be near the first pair of complex conjugate poles after compensation (PID can only give 90 degree or less additional phase margin to the compensated system). So the speed for response to the input is naturally low, if a conventional Voltage Mode PID type controller is used [21].

VI. Simulation and Results

The frequency response of a simple PD feedback controller is simulated in Matlab and from figure 10, it is evident that the magnitude of the compensator continuously grows with the increase in frequency.

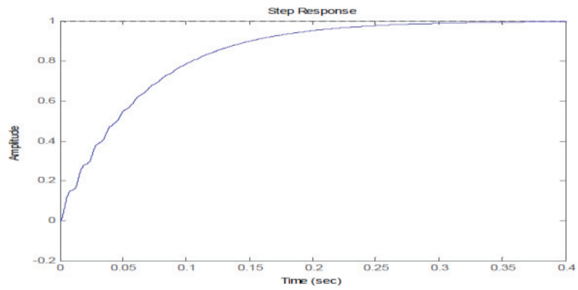

Fig 11: Controller Compensating Step Response

The eigenvalues of transfer function helps for the stability analysis. The system will be stable if and only if all eigenvalues lie in the open left-half complex plane. The root locus method could be used to analyze system stability as shown in figure 11. Because Cuk Converter has two Right-hand plane zeros, Nyquist criterion is used to judge the stability of the system or modify the Bode plot.

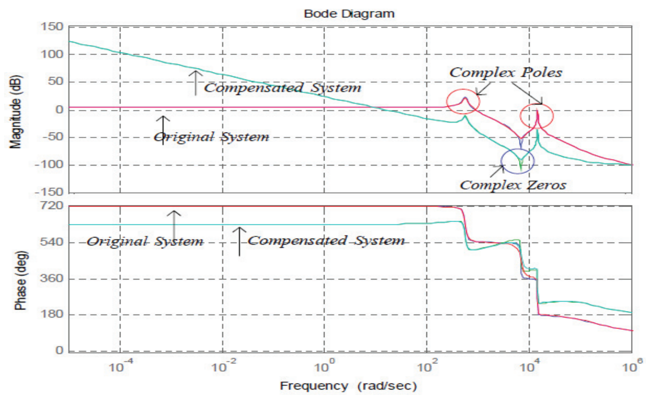

Fig 12. Bode Plot for controller design under Different Conditions

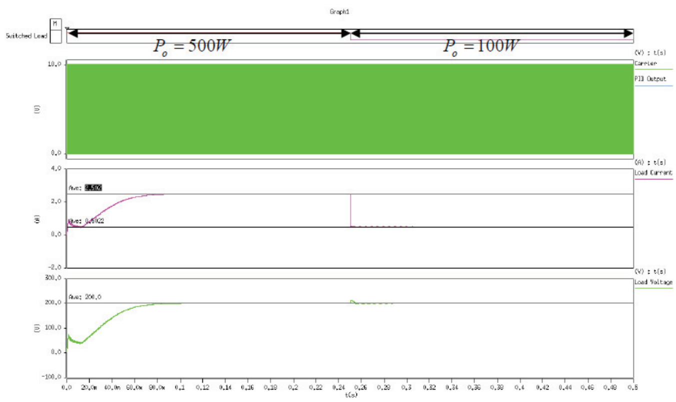

Fig 13. Stability testing using Nyquist Criteria[19]

In summary, through development of a small signal model for the control to output transfer function of the Cuk converter, a method for designing the converter components based on an initial design constraint is formulated. By developing an approximation to the fourth order polynomial in the denominator of $G_{vd}(S)$, optimal placement of the poles and zeros was determined to optimize the stability of the loop gain. By designing a feedback compensator, output deviation in response to an input step changed could be further reduced for the lossless damping case[22].

VII. CONCLUSIONS

With the calculations and analysis of Ćuk Converter, CCM operation mode, actual design parameters are used for the simulation for the design objective that could be derived for solar PV array. The feedback compensation technique for the Cuk converter limits the voltage deviation in response to a voltage step on the input. Transfer function of control to output is derived using small signal averaged state space model. The crossover frequency will be near to the conjugate poles after compensation for additional phase margin to the compensated system which would affect the speed of response. By designing a feedback compensator, output deviation in response to an input step changed could be further reduced for the lossless damping case[23]. The feedback controller can be implemented using only the output voltage feedback and using simple analog components along with the various micro controller chip.

The advantages of Buck, Boost, Buck-Boost, Cuk and Sepic choppers have found a lot of industrial applications [24]. In this paper, the small signal averaged state-space models of these converters are obtained which provide an excellent understanding of the frequency domain behaviour and a tool to design and analyse the feedback control loops for these converters. The theoretical results are validated by simulations in MATLAB software.

REFERENCES

[1] V.V. Tyagi, Nurul A.A. Rahim,N.A. Rahim, Jeyraj A, L. Selvaraj "Progress in solar PV technology: Research and achievement" Renewable and Sustainable Energy Reviews", Volume 20, April 2013, Pages 443–461

[2] K. Kanimozhi, Optimal choice of DC-DC converter for enhancement of power tracking efficiency in photovoltaic system: Optimal choice of DC-DC converter for PV system" 2015 IEEE International Conference on Computational Intelligence and Computing Research (ICCIC), 10-12 Dec. 2015, ISBN: 978-1-4799-7848-9, pages 1 - 7

[3] R.Haroun, R.A.Aroudi, A.Cid-Pastor,G.Garica,"Impedance Matching in Photovoltaic Systems Using Cascaded Boost Converters and Sliding-Mode Control,"IEEE Transactions on Power Electronics,vol.30 , no.6, pp.3185-3199, January 2015.

[4] Chuan Yao, Xinbo Ruan, Xuehua Wang, Chi K. Tse, "Isolated Buck–Boost DC/DC Converters Suitable for Wide Input-Voltage Range" IEEE Transactions on Power Electronics (Volume:26 , Issue: 9) Page(s): 2599 – 2613, ISSN : 0885-8993, Sept. 2011

[5] M. Kasper, D Bortis,J W. Kolar,"Classification and Comparative Evaluation of PV Panel-Integrated DC-DC Converter Concepts, " IEEE Transactions on Power Electronics, vol. 29,no 5, pp. 2511-2526, May 2014.

[6] W. Wonham, "On pole assignment in multi-input controllable linear systems" IEEE Transactions on Automatic Control (Volume:12 ,Issue: 6) Page(s): 660 – 665, ISSN :0018-9286

[7] Y. Panov and M. M. Jovanovic, "Design considerations for 12-V/l.5-V, 50-A voltage regulator modules", IEEE Trans. Power Electron., vol. 16, no. 6, pp. 776-783, 2001

[8] Mohamed A. Eltawil, Zhengming Zhao, MPPT techniques for photovoltaic applications", Renewable and Sustainable Energy Reviews, Volume 25, September 2013, Pages 793–813

[9] R.D.Middlebrook ; Transformerless DC-to-DC converters with large conversion ratios, IEEE Transactions on Power Electronics (Volume:3, Issue: 4) Page(s):484 – 488, ISSN :0885-8993,

[10] Power Electronics: Circuits, Devices, and Applications", Muhammad H. Rashid

[11] Parastoo Khademi Astaneh, Khalil Valipoor, Study of Developed Cuk Converter for Renewable Energy Sources, International Journal of Scientific & Engineering Research Volume 4, Issue3, March-2013 1 ISSN 2229-5518

[12] S. Kavitha, S. Edward Rajan, R. Pon Vengatesh, Performance analysis of interleaved DC-DC boost converter for Photo-Voltaic power generation systems, Green Computing Communication and Electrical Engineering (ICGCCEE), 2014 International Conference on Date of Conference: 6-8 March 2014, Page(s): 1 – 6, INSPEC Accession Number: 14666024, Publisher: IEEE

[13] R. Mastromauro," Control Issues in Single Stage Photovoltaic Systems: MPPT, Current and Voltage Control," IEEE Transactions On Industrial Informatics, vol. 8, no.2, pp.241–254,2012.

[14] B.A Ramdan , Koad and Ahmed Faheem Zobaa ,"A Study of Non-Isolated DC–DC Converters for Photovoltaic Systems,"International Journal on Energy Conversion, vol. 1, no. 4,pp.345-357,2013.

[15] P. Mattavelli, L. Rossetto, and G. Spiazzi, "Small-signal analysis of DC-DC converters with sliding mode control," IEEE Trans. on Power Electron., vol. 12, no. 1, pp. 96-102, 1997.

[16] R. W. Erickson, and D. Maksimovic, Fundamentals of Power Electronics. Boston: Kluwer Academic Publishers, 2004.

[17] Z. S. Chen, et al., "Closed-Loop analysis and cascade control of a nonminimum phase boost converter," IEEE Trans. on Power Electron., vol. 26, no. 4, pp. 1237-1252, April 2011.

[18] T. F. Wu and S. A. Liang, "A systematic approach to developing single-stage soft switching PWM sonverters," IEEE Trans. Power Electron., vol. 16, no. 5, pp. 581-593, Feb. 2001.

[19] Richard Tymerski and Frank Rytkonen, Report on Control System Design

[20] Franklin J. Rytkonen and Dr. Richard Tymerski, Modern Control Regulator Design for DC-DC Converters, Electrical and Computer Engineering Department, Portland State University

[21] Y. C. Sern, "Voltage-based control of a non-isolated Cuk converter," Final Year Project Rep., School Elect. Electron. Eng., Nanyang Tech. Univ., 2015

[22] Satyajit Chincholkar, Chok-You Chan, Design and implementation of an output feedback controller for the Cuk converter" IEEE International Conference -IECON2015-Yokohama, November 9-12, 2015, 978-1-4799-1762-4 pages 86-90

[23] Narendra, K. and Annaswamy, A., Robust adaptive control in the presence of bounded disturbances IEEE Trans. Autom. Control, 31 (4), pp. 306–315, 1986.

[24] S Saravanan, N. Ramesh Babu, Performance Analysis of Boost & Cuk Converter in MPPT Based PV System, 2015, IEEE International Conference on Circuit, Power and Computing Technologies [ICCPCT], 978-1-4799-7075-9