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Controller Design and Analysis for a Buck Converter

[1]Sonali Pandit and [2]V. N. Shet

[1]Assistant Professor, Department of Electrical and Electronics Engineering Goa College of Engineering, Goa, INDIA

[2]Professor, Department of Electrical and Electronics Engineering Goa College of Engineering, Goa, INDIA

E-mail: [1]sonali@gec.ac.in, [2]vns@gec.ac.in

ABSTRACT

A DC-DC converter is one of the simplest and widely used converters in controlled power applications like cell phones, laptops, communication systems and many more devices. The control loop along with the compensator is the important feature in keeping the output voltage constant of the DC-DC converter. This paper discusses four basic compensators for a buck converter. The compensators are designed for a given phase margin and crossover frequency. The designs are validated using the control loop transfer function and analyzed in the frequency domain using Bode plots. The overall system with the converter and the compensator is simulated using Matlab Simulink Model. The output voltage is tested for the variations in the supply voltage and a time domain response of the systems is compared.

Keywords: Control Design, PI Control, Lead Control, PID control, Buck Converter, Matlab, Simulink, Bode Plot, Compensator, Frequency Domain, Time Domain.

1. INTRODUCTION

The demand and usage of devices like cell phone, laptops are increasing. These devices use converters to obtain various voltage levels for their operation. DC-DC converters are devices which convert one voltage level to other voltage level that may be higher in magnitude or lower in magnitude. Accordingly they are classified as boost and buck converters. They are used everywhere because of their high efficiency and single stage conversion. The control of voltage is done by controlling the duty ratio of the switch. Switches used are Mosfets, transistors, GTO's, IGBT's depending upon the circuit or the power transfer capability. The control of output voltage to a constant magnitude is achieved by the help of a feedback. Thus, the compensation provided to control the output voltage plays a very important role [1]-[3].

In the subsequent section, a simple buck converter in open loop configuration is discussed. A closed loop system without any compensation is taken as the basis of the study of effect of compensation. Four compensators viz. PI[4]-[7][10], Lead[4]-[6], PI with Lead[4]-[6][9] and PID[5]-[7][8] are designed for the control of a buck converter. A frequency domain analysis using Bode plots of individual compensators are discussed and then the overall Bode plots of the closed loop system of buck converters are plotted. The design parameters are validated with the Bode plots. Further, a Simulink model in Matlab of the closed loop system with these compensators is designed and simulated. The load is kept constant and the switches are assumed ideal. The change in supply voltage is considered and the time domain responses of the compensators are plotted. The compensator performances are compared with their frequency and time domain characteristics.

2. LITERATURE REVIEW

The buck converter transforms a higher voltage at the input to a lower voltage at the output. The output conversion ratio is given by $V = d * Vg$, where Vg is the input voltage, d is the duty ratio of the switch and V is the output voltage[1]-[3]. The output voltage depends on switching duty cycle and the input voltage. A buck converter in an open loop configuration is shown in Fig. 1

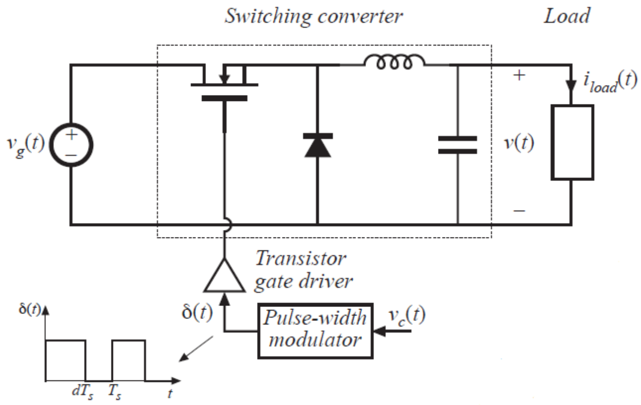

Fig.1 Buck Converter Open loop Configuration [1]

In addition, non-idealities of the relation exist because of the discontinuous conduction mode thus making the output voltage dependent on the load current i_{load} changes in the input voltage v_g and the duty cycle d[1].The functional diagram of the dependence of output voltage on the above parameters is shown in Fig. 2.

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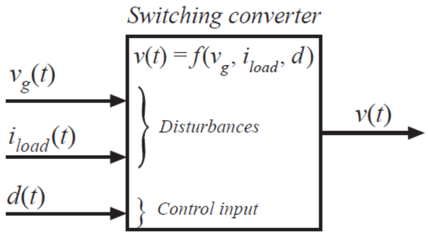

Fig.2 Functional diagram of dependence of output voltage[1]

To maintain a constant output voltage, a negative feedback is essentially required. The duty cycle is adjusted accordingly so as to achieve the desired output voltage with a high accuracy, regardless of variations in input voltage v_g or the load current i_{load} or variations in component values. A block diagram of the buck converter with a feedback loop is shown in Fig. 3.

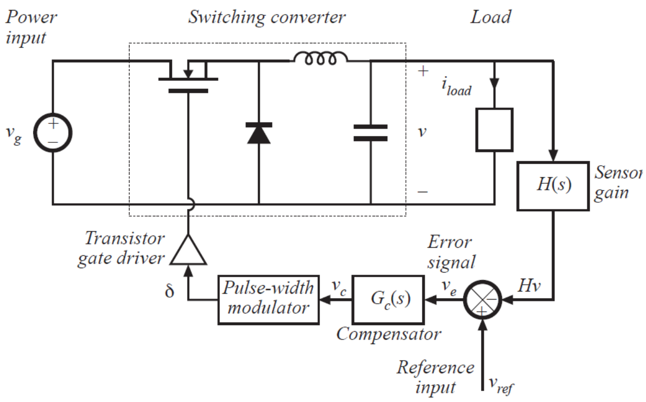

Fig.3 Buck Converter closed loop configuration [1]

The functional block diagram of the negative control loop is shown in Fig. 4. The output voltage v(s) is measured with a sensor having a gain H(s). The sensor circuit usually consists of a voltage divider using precision resistors. The sensor output H(s)v(s) is compared with the reference input voltage $v_{ref}(s)$ The difference between the $v_{ref}(s)$ and H(s)v(s) is the error voltage . The objective is to make this error voltage $v_e(s)$ minimum. The compensator with a gain of $G_c(s)$ is added in the forward loop. The output voltage is the product of error voltage, compensator gain, pulse width modulator gain and the converter power stage gain.

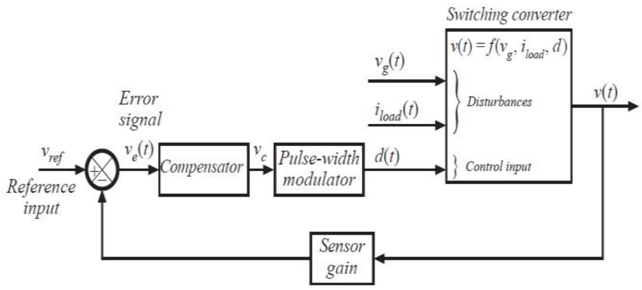

Fig.4 Functional diagram of the control Loop [1]

It is assumed that the converter is working in a continuous conduction mode and duty cycle is taken as the controlled variable. The output voltage is dependent on the changes in the input voltage only and the switch is an ideal switch thereby neglecting the non idealities due to its switching. Control loop is with H(s) as sensor gain, $G_c(s)$ is the transfer function of the compensator and $1/V_m$ is the gain of the Pulse width modulator as shown in Fig. 5.

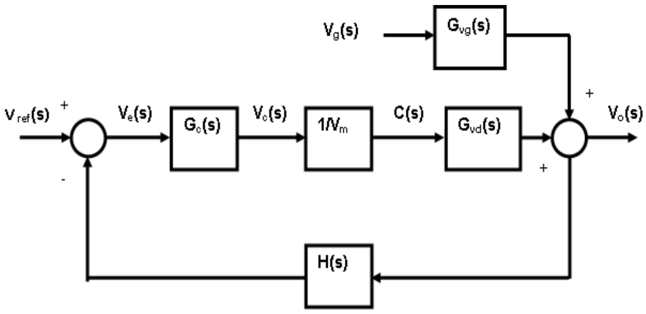

Fig.5 Block Diagram representation of the control loop

Hence the loop gain T(s) is given by

$$T(s) = H(s)G_c(s)G_{vd}(s)/\,V_m \qquad (1)$$

The transfer function from a disturbance to the output is multiplied by the factor 1/ (1+T(s)). If the loop gain T(s) is large in magnitude, the influence of the disturbance on the output voltage is small. Hence the loop gain T(s) is a measure of effectiveness of the feedback loop. Other important parameter of feedback systems is stability. The feedback loop can cause a well behaved circuit to exhibit ringing and overshoot along with oscillations. The phase margin criterion is used to assess the stability. If the Phase margin of the loop gain T(s) is positive then the system is stable. Also increasing the phase margin will lead to a better system transients response with less overshoot [1].

A small signal averaged transfer function model for the converter operation in continuous conduction mode is used [2]. In this model, there are influences of duty cycle and input voltage on the output. To achieve better output, duty cycle is a used as controlled parameter for a given input voltage.

i) Duty Cycle Influence is given by the following equation

$$G_{vd}(s) = \frac{G_{do}}{1 + \frac{s}{Q\omega_o} + \left(\frac{s}{\omega_o}\right)^2} \qquad (2)$$

ii) Input voltage influence is given by the following equation

$$G_{vg}(s) = \frac{G_{go}}{1 + \frac{s}{Q\omega_o} + \left(\frac{s}{\omega_o}\right)^2} \qquad (3)$$

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where G_{go}=d, G_{do}=V/d, $\omega o = {}^{1}/_{\sqrt{LC}}$, $Q = R\sqrt{{}^{C}/_{L}}$

3. DESIGN

3.1. Uncompensated Buck Converter

A Buck converter is designed for 24V /12V, 25Khz frequency, 2A load current. The inductance and capacitance values are calculated to be L=2.4mH and C=450uF [3].The open loop transfer function of the buck converter is given by the following

$$G_{vd}(s) = \frac{V/d}{1 + \frac{s}{Q\omega_o} + \left(\frac{s}{\omega_o}\right)^2} \quad (4)$$

Thus, substituting the values of V, d, Q, ω_o in the equation (4), the open loop transfer function of the buck converter is obtained as follows

$$G_{vd}(s) = \frac{24}{1 + 0.0004s + 1.08X10^{-6}s^2} \quad (5)$$

The loop transfer function is calculated as given in equation (1).The sensor gain H(s) is assumed to be 1/3 and V_m=4. Assuming $G_c(s)$=1 which is the uncompensated system and substituting in the equation (1), the loop gain is obtained as follows

$$T(s) = \frac{1}{12} * \frac{24}{1 + 0.0004s + 1.08X10^{-6}s^2} \quad (6)$$

where,

$$fo = w_o/2\pi = 1/2\pi\sqrt{LC} = 153Hz \;\; = 961.3rad/s$$

$$Q_o = R\sqrt{(C/L)} = 2.598 = 8.29dB$$

Thus,

$$T(s) = \frac{2}{1 + 0.0004s + 1.08X10^{-6}s^2} \quad (7)$$

A Bode plot[6] of the transfer function T(s) is plotted in Matlab and is shown in Fig. 6

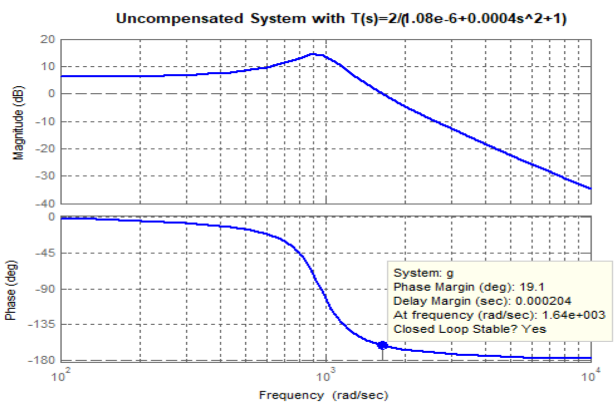

Fig.6 Uncompensated Bode Plot

The Phase margin is 19.1° with infinite Gain Margin. The gain crossover frequency is 1.6X 10^3 rad/s or 260Hz. A Matlab Simulation Model with the basic buck converter is simulated as in Fig. 7 and the output waveform for change in input voltage is shown in Fig. 8.

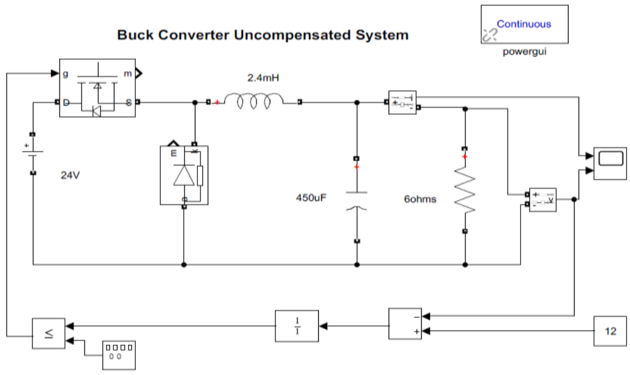

Fig.7 Matlab Simulation of an Uncompensated system

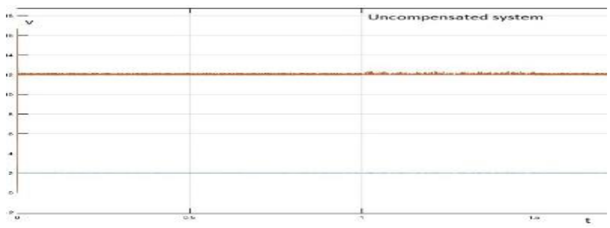

Fig.8 Uncompensated simulink waveform

The output is having oscillations and there is a need for compensation. Analysis of different types of compensators, their individual frequency responses and the effect of changes in input voltage on the output of the buck converter is carried out in the following sections.

3.2. Proportional Integral Compensator

This type of compensator is used to increase the low frequency loop gain so that the output is regulated well for frequencies below the loop crossover frequency. The transfer function of this compensator is given by

$$G_c(s) = G_{co}\frac{\left(1 + \frac{s}{\omega_z}\right)}{s} \quad (8)$$

The PI compensator has a high gain at low frequencies which falls at -20dB per decade and then levels out at zero frequency f_z The phase is initially -90° which increases by a rate of 45°per decade starting at $f_z/10$ to a maximum of 0°at $10f_z$. The high gain at low frequencies eliminates steady state error to step input. The zero is placed at $f_z = f_o/10$ =15.3Hz.$w_z = 2\pi f_z$ = 96.132rad/s .The compensated loop gain T(s)=1. The transfer function of this compensator is given by

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$$T(s) = \frac{T_o\, G_{co}}{2\pi f_z} = 1 \qquad (9)$$

Hence, G_{co} is given as

$$G_{co} = \frac{2\pi X 15.3}{2} = 48 \qquad (10)$$

The transfer function of the compensator after substituting the values is then calculated as follows

$$G_c\,(s) = 48\frac{\left(1+\frac{s}{96.132}\right)}{s} \qquad (11)$$

The Bode plot of the PI compensator is as shown in Fig. 9

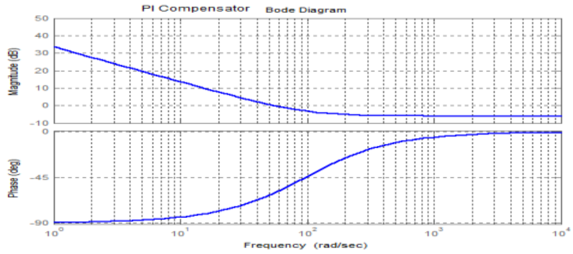

Fig.9 PI Compensator Bode plot

The loop gain of the buck converter with PI compensator can be expressed as

$$T(s) = T_o G_{co} \frac{\left(1+\frac{s}{\omega_z}\right)}{s\left(1+\frac{s}{Q\omega_o}+\left(\frac{s}{\omega_o}\right)^2\right)} \qquad (12)$$

By substituting the values in equation (12), the loop transfer function is obtained as follows

$$T(s) = \frac{48X2\left(1+\frac{s}{96.132}\right)}{s(1+0.0004s+1.08X10^{-6}s^2)} \qquad (13)$$

The Bode plot of loop gain with PI compensator is plotted using Matlab and is shown in Fig. 10

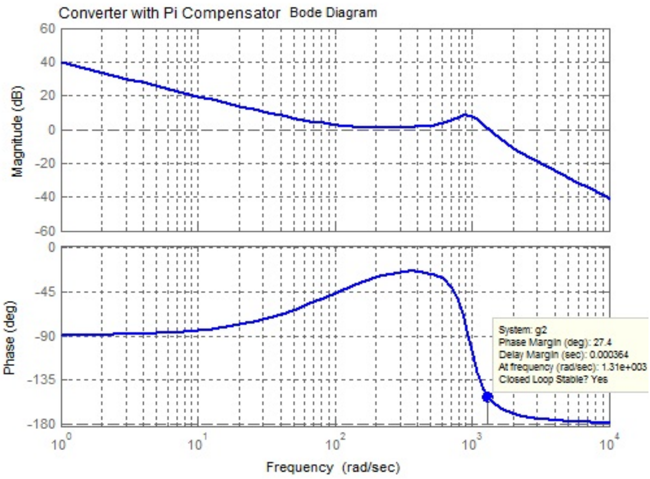

Fig.10 PI Converter with PI compensation Bode plot

From the plot, the Phase Margin= 27.4° and ω_{gc} = 1.31krad/s. A Matlab Simulink Model is simulated using the PI controller. The controller block is simulated with the transfer function of the PI Controller. The model is as shown in Fig. 11.

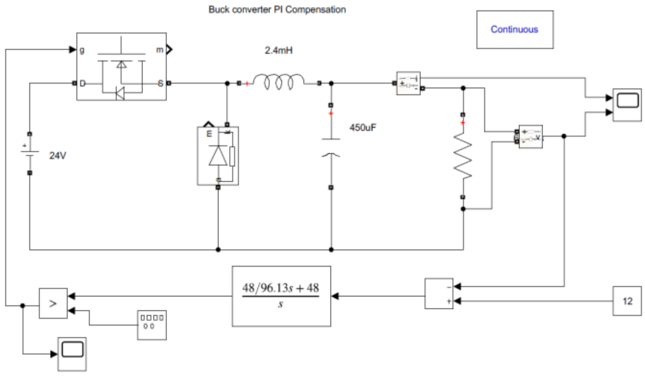

Fig.11 Buck Converter model with PI compensation

The model is simulated with changes in the input voltage and the output is plotted. The time required for the output to settle to 12V is observed as shown in Fig. 12. The transient response is calculated and then compared with other compensators.

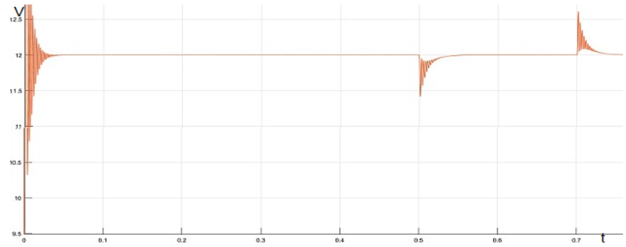

Fig.12 Buck Converter output for PI compensation

3.3. Lead Compensator

The performance of the Buck converter is improved by using a Lead Compensator. The transfer function of this compensator is given by

$$G_c\,(s) = G_{co}\frac{\left(1+\frac{s}{\omega_z}\right)}{\left(1+\frac{s}{\omega_p}\right)} \qquad (14)$$

where $w_z < w_p$. The zero is placed at lower frequency than the pole frequency. It provides a phase boost which is adjustable based on the pole and zero frequencies and a gain boost at higher frequencies giving a higher crossover frequency. Thus the phase margin of the converter can be improved. The design is carried out for a gain margin of ϕ_m=52 ° and a crossover frequency of f_c =5KHz.

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$$f_z = 5X10^3 \sqrt{\frac{1 - sin52}{1 + sin52}} = 1.72Khz$$

$$f_p = 5X10^3 \sqrt{\frac{1 + sin52}{1 - sin52}} = 14.5Khz$$

$$G_{co} = \left(\frac{5000}{153}\right)^2 \sqrt{(1.72/14.5)(0.5)} = 184$$

The transfer function of the lead compensator can be written as follows by substituting the values in equation (14).

$$G_c(s) = 184 \frac{\left(1 + \frac{s}{2\pi X1.72X\,10^3}\right)}{\left(1 + \frac{s}{2\pi X14.5X\,10^3}\right)} \qquad (15)$$

The Bode plot of the Lead compensator is as shown in Fig. 13

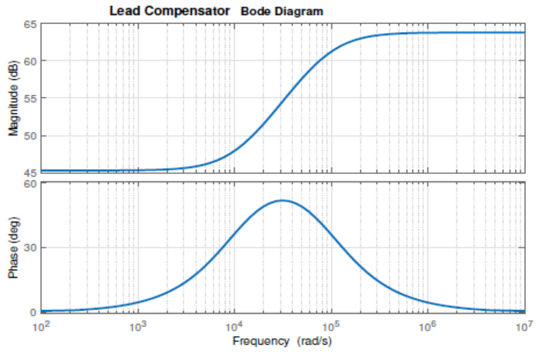

Fig.13 Lead Compensator Bode plot

The loop gain of the buck converter with lead compensator can be expressed as

$$T(s) = T_o G_{co} \frac{\left(1 + \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{\omega_p}\right)\left(1 + \frac{s}{Q\omega_o} + \left(\frac{s}{\omega_o}\right)^2\right)} \qquad (16)$$

Substituting the values in equation (16), loop gain is obtained as follows

$$T(s) = \frac{184X2\left(1+\frac{s}{10807.1}\right)}{\left(1+\frac{s}{91106.2}\right)(1+0.0004s+1.08X10^{-6}s^2)} \qquad (17)$$

The Bode plot of the loop gain with Lead compensator is plotted and shown in Fig. 14. From the Bode plot, the design parameters are validated and phase margin= 52.7°and ω_{gc}> 5krad/s.

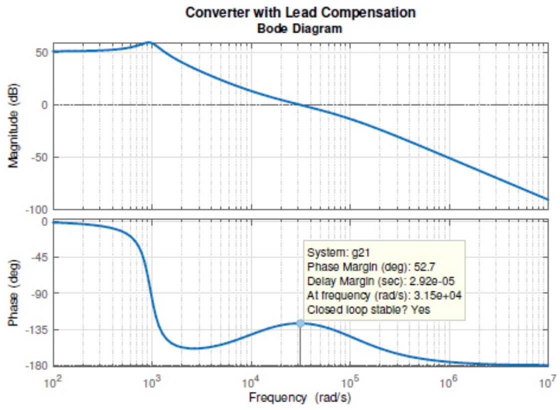

Fig.14 Converter with Lead compensation Bode plot

The Matlab Simulink Model is designed with the Lead compensator transfer function as shown in Fig. 15.

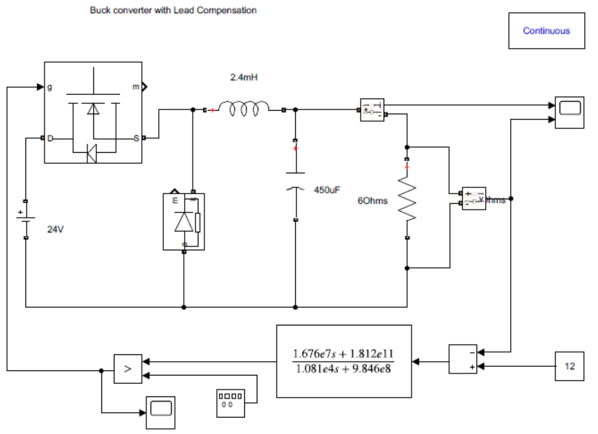

Fig.15 Buck Converter with Lead compensation model

The model is simulated with changes in the input voltage and the output is plotted. The time required for the output to settle to 12V is observed as shown in Fig. 16. The transient response of the lead converter is good but its steady state response is poor.

Fig.16 Buck Converter Output with Lead compensation model

3.4. Combined PI and Lead Compensator

This compensator combines the properties of both PI and Lead Compensators. PI had good steady state response but not very good transient characteristics whereas lead had a very good transient response but bad steady state

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characteristics. Thus PI with lead compensator combines the responses to gives a better transient and steady state response. The transfer function of this compensator is given by equation (18)

$$G_c\,(s) = \quad G_{co}\frac{\left(1+\frac{s}{\omega_{z1}}\right)\left(1+\frac{s}{\omega_{z2}}\right)}{s\left(1+\frac{s}{\omega_p}\right)} \qquad (18)$$

To design this compensator, it is needed to know the placement of the two zeros and the pole. Here, ω_{z2} is the zero introduced by the lead compensator and hence $\omega_{z2} < \omega_p$. It is assumed that the two compensator portions do not interact. To distinguish the effects of lead and PI compensation, it is assumed that $\omega_{z1} < \omega_{z2}$. To design the PI compensator at low frequencies and lead compensator at high frequencies, the zeros and poles are chosen as follows: f_{z1}= 50Hz, f_{z2}= 132Hz, f_p=105KHz .

The compensator is designed for a gain margin of ϕ_m=52 ° and a crossover frequency of f_c =5KHz. Since a large gain at low frequencies is better, design the combined compensator to have a gain factor $G_{co}T_o$ to be 1000. Hence G_{co}=500. Substituting the values in equation (18), a Bode plot in Matlab is plotted for the compensator as shown in Fig. 17.

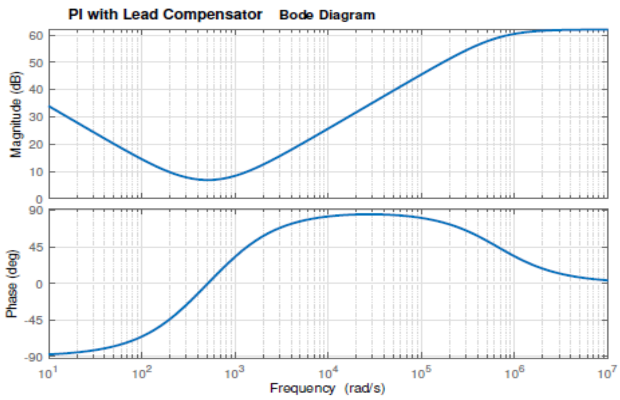

Fig.17 PI with Lead Compensator Bode plot

The loop gain of the buck converter with Lead compensator can be expressed as

$$T(s) = \quad T_oG_{co}\frac{\left(1+\frac{s}{\omega_{z1}}\right)\left(1+\frac{s}{\omega_{z2}}\right)}{s\left(1+\frac{s}{\omega_p}\right)\left(1+\frac{s}{Q\omega_o}+\left(\frac{s}{\omega_o}\right)^2\right)} \qquad (19)$$

Substituting the values of the compensator transfer function in the loop transfer function a combined transfer function is obtained in equation (20).

$$T(s) = \quad \frac{1000\left(1+\frac{s}{314}\right)\left(1+\frac{s}{31415.9}\right)}{s\left(1+\frac{s}{314159.27}\right)(1+0.0004s+1.08X10^{-6}s^2)} \qquad (20)$$

The Bode plot of loop gain of the above compensator is plotted and shown in Fig. 18. From the Bode plot it is observed that the Phase Margin=78.8° and ω_{gc}=620Hz=3.9krad/s.

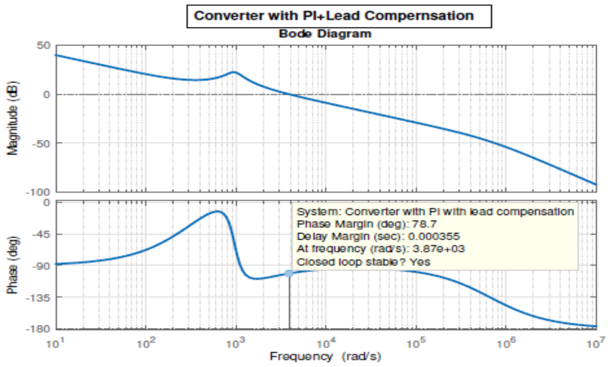

Fig.18 Converter with Pi with Lead compensation Bode plot

The Matlab Simulink model is simulated with the transfer function block of PI with lead compensator as shown in Fig. 19.

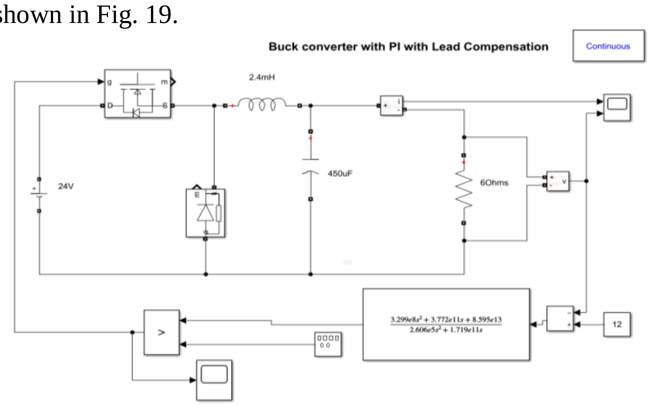

Fig.19 Buck Converter with PI with lead compensation model

The output of the converter with changes in input is shown in Fig. 20. It can be seen that PI with Lead compensator gives a better transient and steady state response as compared with lead compensator alone.

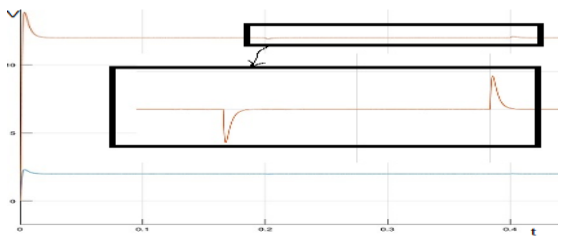

Fig.20 Buck Converter Output with PI with lead compensator

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3.5 PID Compensator

PID compensator combines the advantages of PI and PD compensation. At low frequencies, the compensator integrates the error signal. Thus there is a large low frequency loop gain and hence accurate regulation of the low frequency components of the output voltage. At high frequency, it gives a phase lead into the loop gain. Thus the phase margin can be improved. The transfer function of this compensator is given by equation (21)

$$G_c\,(s) = \; G_{co}\frac{\left(1+\frac{s}{\omega_z}\right)\left(1+\frac{\omega_L}{s}\right)}{\left(1+\frac{s}{\omega_p}\right)} \qquad (21)$$

The inverted zero at f_L functions as a PI compensator while the zero at f_z adds a phase lead in the vicinity of the crossover frequency for a PD compensator. The pole f_p is present to cause gain roll off at high frequencies and to prevent switching ripple in the pulse width modulator.

To derive the PID compensation, an inverted zero is added to the lead compensation transfer function equation (14). The design of cross over frequency f_c is 5khz and the phase margin ϕ_m =52° .The inverted zero f_L is chosen to be one tenth of the crossover frequency so that it does not significantly degrade the phase margin. The value is selected as f_L = 300 Hz to improve the low frequency regulation of the output voltage.

By keeping the other values same as Lead compensator, the transfer function of PID compensator is realized as follows

$$G_c\,(s) = \; 184\frac{\left(1+\frac{s}{2\pi X 1.72 X 10^3}\right)\left(1+\frac{2\pi X 300}{s}\right)}{\left(1+\frac{s}{2\pi X 14.5 X 10^3}\right)} \qquad (22)$$

The Bode plot of the PID compensator is as shown in Fig. 21.

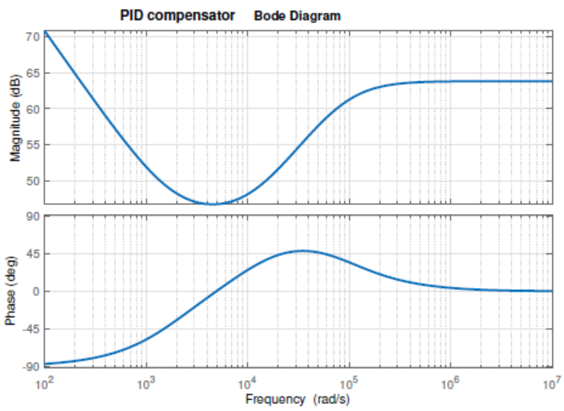

Fig.21 PID Compensator Bode plot

The loop gain of the buck converter with PID compensator can be expressed as

$$T(s) = \; T_o G_{co}\frac{\left(1+\frac{s}{\omega_z}\right)\left(1+\frac{\omega_L}{s}\right)}{\left(1+\frac{s}{\omega_p}\right)\left(1+\frac{s}{Q\omega_o}+\left(\frac{s}{\omega_o}\right)^2\right)} \qquad (23)$$

Substituting the values of the compensator transfer function in the loop transfer function, the combined transfer function is obtained.

$$T(s) = \frac{368\left(1+\frac{s}{10807.1}\right)\left(1+\frac{1884}{s}\right)}{\left(1+\frac{s}{91106.2}\right)\left(1+0.0004s+1.08X10^{-6}s^2\right)} \qquad (24)$$

The Bode plot of loop gain of the above compensator is plotted and shown in Fig. 22. From the Bode plot it is observed that the Phase Margin= 49.2° and ω_{gc} =31.5 krad/s = 5kHz, thus validating the design parameters.

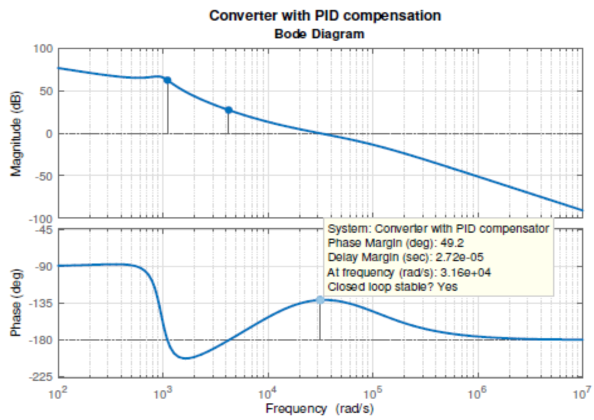

Fig.22 Converter with PID compensation Bode plot

The Matlab Simulink model is simulated with the transfer function block of PID compensator as shown in Fig. 23.

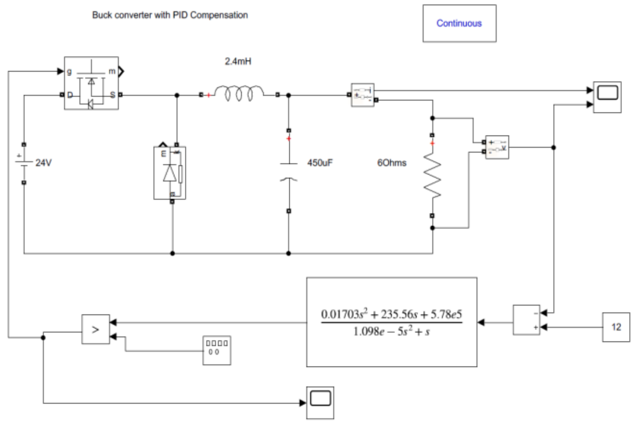

Fig.23 Buck Converter PID compensation model

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The output of the converter with changes in input is shown in Fig. 24. The output shows a faster transient and steady state response as compared to the earlier compensators.

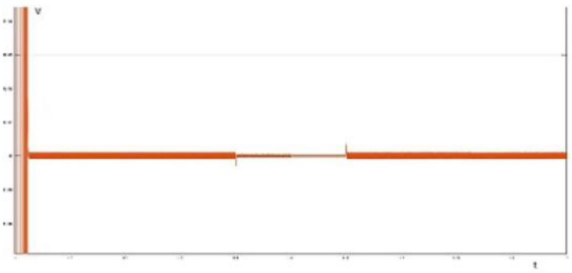

Fig.24 Buck Converter Output with PID compensator

4. RESULTS

A comparative study of the four compensators for a DC-DC Buck converter using PI, Lead, PI with Lead and PID controllers was undertaken for Frequency Domain analysis using Matlab. Bode Plots were plotted for individual compensators and then used with the converter to analyze the loop gain. A combined Bode plot of all four compensators is as shown in Fig. 25.

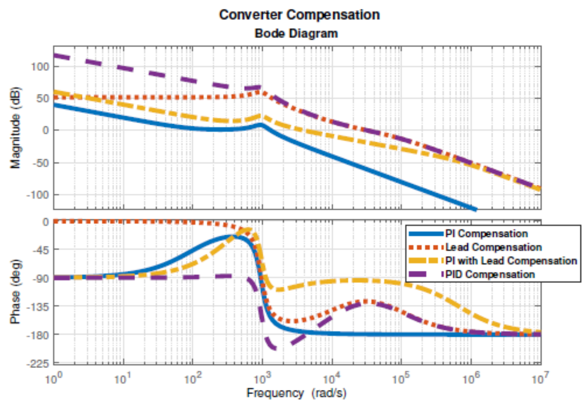

Fig.25 Combined Bode Plot of all Compensators

Results of Frequency Domain analysis of the Phase Margin and the Crossover Frequency is tabulated in Table I.

TABLE I
FREQUENCY DOMAIN ANALYSIS

Type of compensators	Phase Margin in degrees	Gain cross over frequency krad./s
PI	27.4	1.31
Lead	52.7	31.5
PI with Lead	78.7	3.87
PID	49.2	31.6

The time domain responses of the buck converter with various compensators are calculated from the output response of the Matlab Simulink Model. The responses of all four compensators are shown in figure 26.

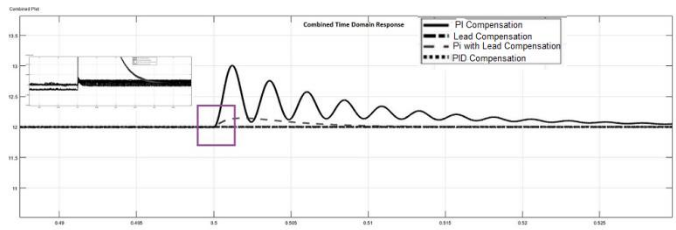

Fig.26 Combined Time domain response of all compensators

A similar analysis of the time domain characteristics is carried out for all compensators. The percentage overshoot and settling time is calculated. The peak voltage variation ΔV_o is also calculated. The comparative results are presented in Table II

TABLE II
TIME DOMAIN ANALYSIS

Type of compensators	Overshoot in %	Settling time in msec	ΔV_o mV
PI	2.11	40	508
Lead	0.013	Large settling time	3
PI with Lead	0.33	15	80
PID	0.03	1.5	7

5. CONCLUSIONS

Analysis for the various compensators in frequency and time domain shows that Lead and PID compensators give a high phase margin along with a high gain cross over frequency. The time domain response shows that lead alone has a poor steady state response and a large settling time. The PID gives a very good steady state and transient response. The design of PID compensator is critical as compared with a PI with lead compensator. Although phase margin is better in PI with lead compensator, the gain cross over frequency is low. Hardware of DC-DC converter is built with digital compensators and evaluated on a FPGA platform.

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AUTHOR PROFILES

Sonali Pandit received B.E degree in Electrical Engineering from College of Engineering, Pune University, in 1994. She received her M.E degree in ETC-Microelectronics from Goa College of Engineering, Goa University, in 2010. Presently, she is an Assistant Professor in Electrical and Electronics Engineering Department in Goa College of Engineering since 2001 and pursuing her research in the same department in Power Electronics. Her research interests include Control Engineering, VLSI Design, Power Electronics, Controller Design on FPGA Platform, DSP.

Vinayak N Shet received his B. E, M. Tech and Ph.D in Electrical Engineering, Power Electronics and Power System and Electrical Engineering from Karnataka University, IIT Bombay, IIT Bombay, India in 1984, 1995 and 2002 respectively. He is currently working as Professor in Electrical and Electronics department at Goa College of Engineering, Farmagudi, Goa. He worked as Lecturer, Assistant Professor, Professor & HOD and then as Principal of Goa College of Engineering during 1986-95, 1995-2003, 2003-14 and 2014-18 respectively. He is the Chief Investigator for Information Security Education and Awareness under the Department of Information technology, Ministry of Electronics and Communication, Government of India. He is actively involved as reviewer for various Journals and Conferences. He has published number of papers in various international Journals and Conferences. He has been awarded with patents based on his research work. His area of Interest is Power Factor Correction, switch mode converter, power quality mitigation, grid connected systems.