EE561: Power Electronics Laboratory

Mini Project: PCB Design of Closed Loop Operation of Buck Converter

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1 Objective:

Realise a closed loop control of buck converter controlled by analogue PI controller. The specifications for the buck converter are given below:

- Input Voltage (V_{in}): 200 V,
- Output Voltage (V_o): 96 V,
- Switching Frequency (f_{sw}): 20 kHz,
- Output Voltage Ripple (ΔV_o): 10%;
- Inductor Current Ripple (Δi_L): 20%;
- Rated Power: 500 W.

2 Circuit Diagram:

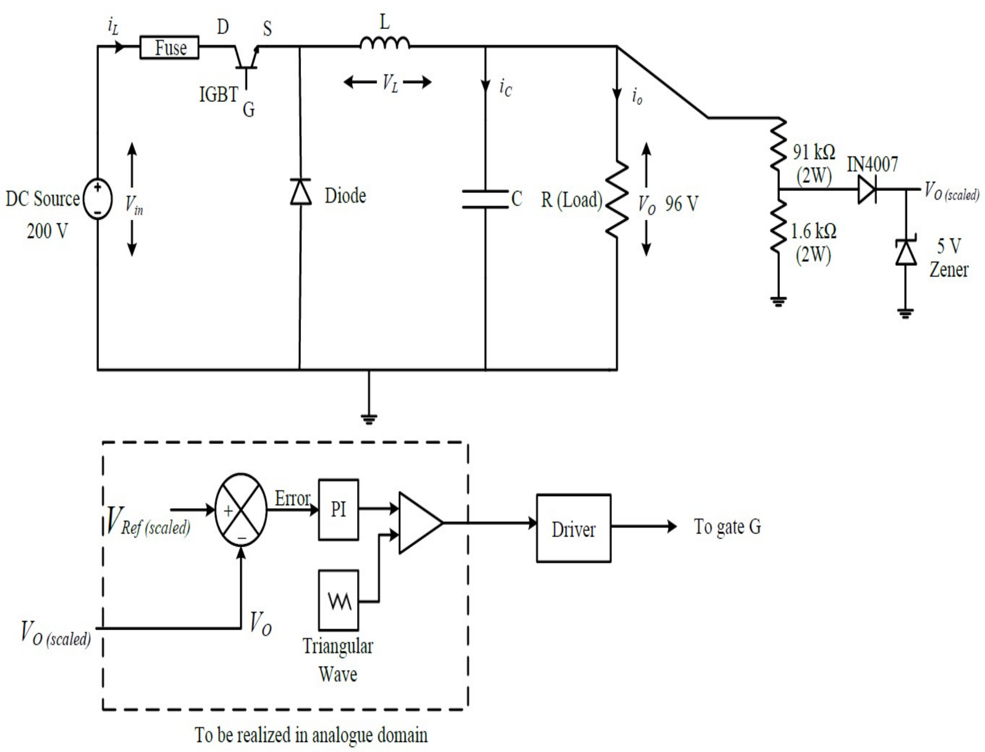

Fig. 1: Overall control diagram of buck converter

3 Buck Converter Design:

3.1 Filter inductor

- The inductor value and its peak current are designated based on the given maximum inductor current ripple.
- During turn ON time (0 < t < DT_s):

$$\begin{aligned} V_{L(ON)} &= V_{in} - V_o, \\ L\frac{\Delta I_L}{DT_s} &= V_{in} - V_o, \\ \Delta I_L &= \frac{D(1-D)V_{in}}{f_s L}. \end{aligned} \tag{1}$$

- Given, inductor current ripple of 20 %. Using Eqn. (1),

$$0.2 * I_L = \frac{D(1-D)V_{in}}{f_s L} \tag{2}$$

- Now taking D as $\frac{V_o}{V_{in}} = \frac{96}{200} = 0.48$, and the given values, inductor value comes out to be:

$$L = 2.39616\ mH \tag{3}$$

- The maximum inductor current ripple can be calculated as:

$$\begin{aligned} I_{L(max)} &= I_L + \frac{\Delta I_L}{2}, \\ I_{L(max)} &= \frac{P_o}{V_o} + \frac{D(1-D)V_{in}}{2 f_s L}, \\ I_{L(max)} &= \frac{500}{96} + \frac{0.48 * 0.52 * 200}{2 * 20000 * 0.00239616}, \\ I_{L(max)} &= 5.2083 + 0.52083 = 5.73A. \end{aligned} \tag{4}$$

- Therefore, the inductor must be chosen such that it can sustain maximum current of 5.73 A without showing saturation.

3.2 Output Capacitor

- The primary objective of output capacitor is to provide stable output voltage. Its value is designated based on the given maximum output voltage ripple.
- The ripple in capacitor voltage is given as:

$$\Delta V_c = \frac{D(1-D)V_{in}}{8 f_s^2 LC} \tag{5}$$

Here, the output voltage ripple is given as 10%. And, based on the calculated value of inductor and other given values, the capacitor value is given as:

$$
\begin{aligned}
0.1 * V_o &= \frac{D(1-D)V_{in}}{8f_s^2LC}, \\
C &= \frac{1-D}{0.8 * f_s^2 * L}, \\
C &= \frac{1-D}{0.8 * f_s^2 * L}, \\
C = \frac{0.52}{0.8 * 20000^2 * 0.00239616} &= 0.6782\ \mu F.
\end{aligned} \tag{6}
$$

3.3 Derivation of Transfer function using small signal analysis:

The derivation will be done later.

$$
G_{vd}(s) = \frac{V_o(s)}{D(s)} = \frac{V_{in}}{1 + \frac{sL}{R} + s^2LC} \tag{7}
$$

$$
G_{vd}(s) = \frac{V_{in}}{1 + \frac{s}{Q\omega_0} + (\frac{s}{\omega_0})^2} \tag{8}
$$

Where,

$$
\begin{aligned}
\omega_0 &= \frac{1}{\sqrt{LC}} \\
Q &= R\sqrt{\frac{C}{L}}
\end{aligned} \tag{9}
$$

3.4 Uncompensated Buck Converter

Substituting the values of V_{in}, f_0, and Q = 0.3101 in the Eqn. (8), the open loop transfer function of the buck converter is obtained as follows:

$$
G_{vd}(s) = \frac{200}{1 + 0.00013s + (1.625076 * 10^{-9})s^2} \tag{10}
$$

Where,

$$
\begin{aligned}
\omega_0 &= 24806.37\ rad/sec \\
f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}} &= 3948.056\ Hz, \\
Q = R\sqrt{\frac{C}{L}} &= 0.3101, \\
Q_{dB} = 20\ log(Q) &= -10.17\ dB.
\end{aligned} \tag{11}
$$

The bode plot of transfer function $G_{vd}(s)$, given in Eqn. (10), is shown in Fig. (2).

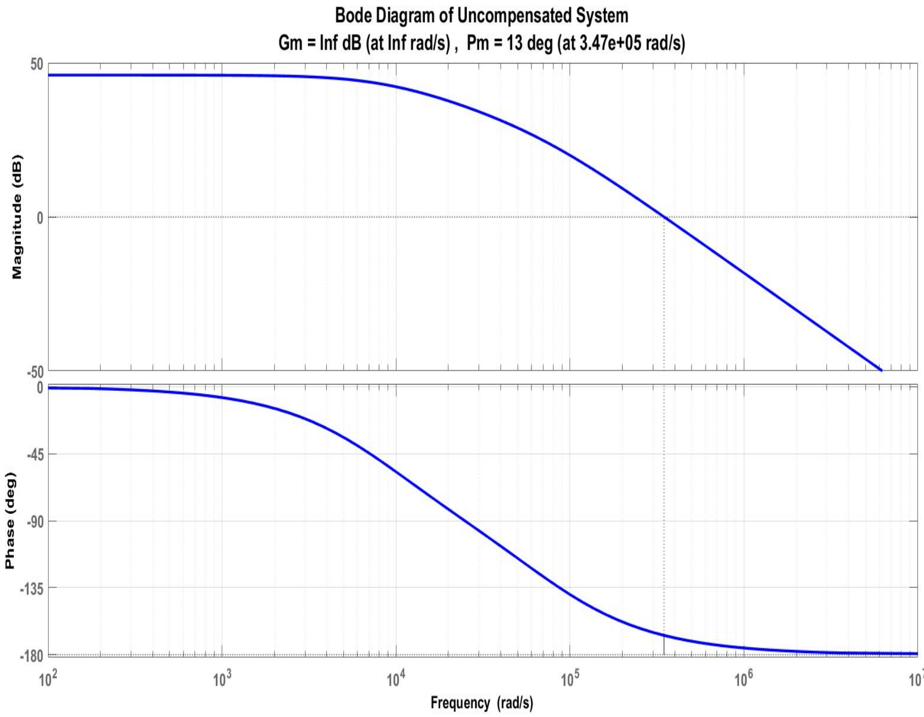

Fig. 2: Bode Plot of Uncompensated Buck Converter

For the uncompensated buck converter, phase margin (PM) is 13.0413°, gain margin (GM) is ∞, and the gain cross-over frequency is 3.4714e+05 rad/sec.

3.5 Proportional Integral (PI) Controller

PI controller 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 controller is given by:

$$G_c(s) = G_{c0}\frac{(1+\frac{s}{\omega_z})}{s} \tag{12}$$

The PI controller has a high gain at low frequencies which falls at -20 dB per decade and then levels out at zero frequency f_z. The phase is initially at -90° which increases by a rate of 45° per decade starting at fz/10 to a maximum of 0° at 10 f_z . The high gain at low frequencies eliminates steady state error to step input.

3.6 Design of PI Controller

- Since the gain cross-over frequency should not be greater than $\frac{f_s}{10}$. Let the gain cross-over frequency of the compensated system is $f_c = \frac{f_s}{20} = 1$ kHz.
- Phase Margin (P.M.) should be atleast 52°, because this choice leads to closed loop having Q-factor, Q = 1. Therefore, a P.M. of 60° has been chosen here.

Now, the transfer function of loop gain can be written as:

$$\begin{aligned} G_c(s)G_{vd}(s) &= \frac{200G_{c0}(1+\frac{s}{\omega_z})}{s(1+0.00013s+(1.625076*10^{-9})s^2)}, \\ G_c(j\omega)G_{vd}(j\omega) &= \frac{200G_{c0}(1+j\frac{\omega}{\omega_z})}{j\omega(1+j0.00013\omega-(1.625076*10^{-9})\omega^2)}. \end{aligned} \tag{13}$$

At $\omega = \omega_c = 2\pi f_c = 6283.185$ rad/sec, the magnitude of loop gain = 1. Therefore,

$$|G_c(j\omega_c)G_{vd}(j\omega_c)| = 1 \tag{14}$$

which results into,

$$G_{c0}\sqrt{1 + (\frac{6283.185}{\omega_z})^2} = 39.776 \tag{15}$$

Now, the P.M. = 60° gives another equation:

$$\begin{aligned} P.M. &= 60°, \\ 180° + \angle G_c(j\omega_c)G_{vd}(j\omega_c) &= 60°, \\ \angle G_c(j\omega_c)G_{vd}(j\omega_c) &= -120°, \\ tan^{-1}(\frac{\omega_c}{\omega_z}) - 90° - tan^{-1}(\frac{0.00013\omega_c}{1-(1.625076*10^{-9})\omega_c^2}) &= -120°, \end{aligned} \tag{16}$$

The value of ω_z is obtained by solving Eqn. (16).

$$\omega_z = 31982.032 rad/sec \tag{17}$$

On putting the value of ω_z from Eqn. (17) into Eqn. (15), the value of G_{c0} is obtained:

$$G_{c0} = 39.03 \tag{18}$$

The transfer function of the controller after substituting the values in Eqn. (12), is obtained as:

$$G_c(s) = 39.03\frac{(1 + \frac{s}{31982.032})}{s} \tag{19}$$

The bode plot of above designed PI controller is shown in Fig. (3).

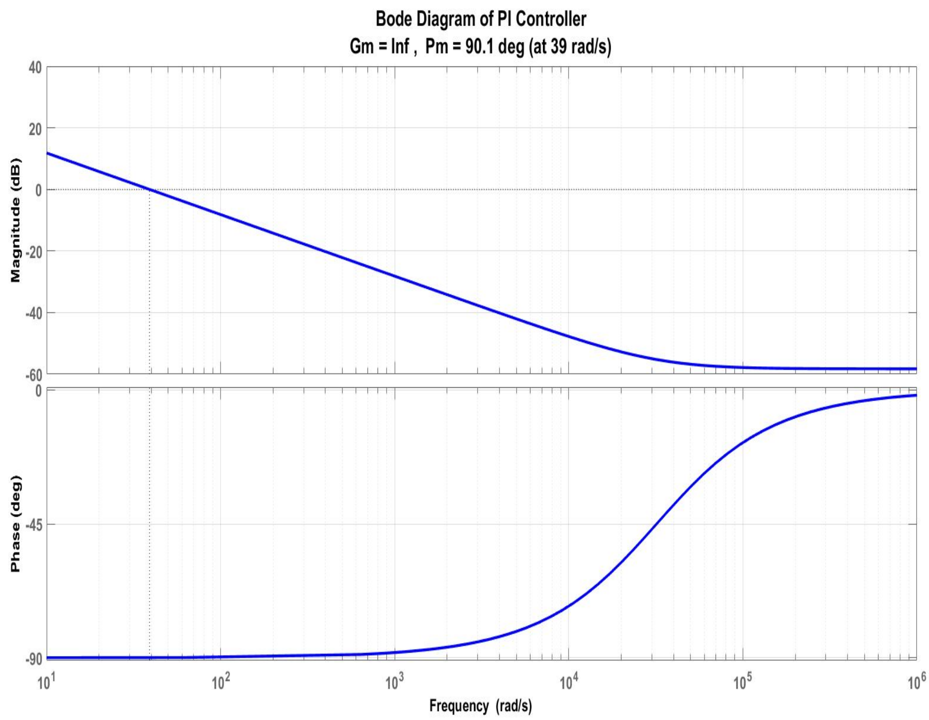

Fig. 3: Bode Plot of PI Controller

3.7 Buck Converter with PI Controller

By substituting the values in equation (13), the loop transfer is obtained as follows:

$$G_c(s)G_{vd}(s) = \frac{7805.9767 + 0.2441s}{s(1 + 0.00013s + (1.625076 * 10^{-9})s^2)} \tag{20}$$

The bode plot of loop gain with PI controller is plotted using MATLAB and is shown in Fig. (4).

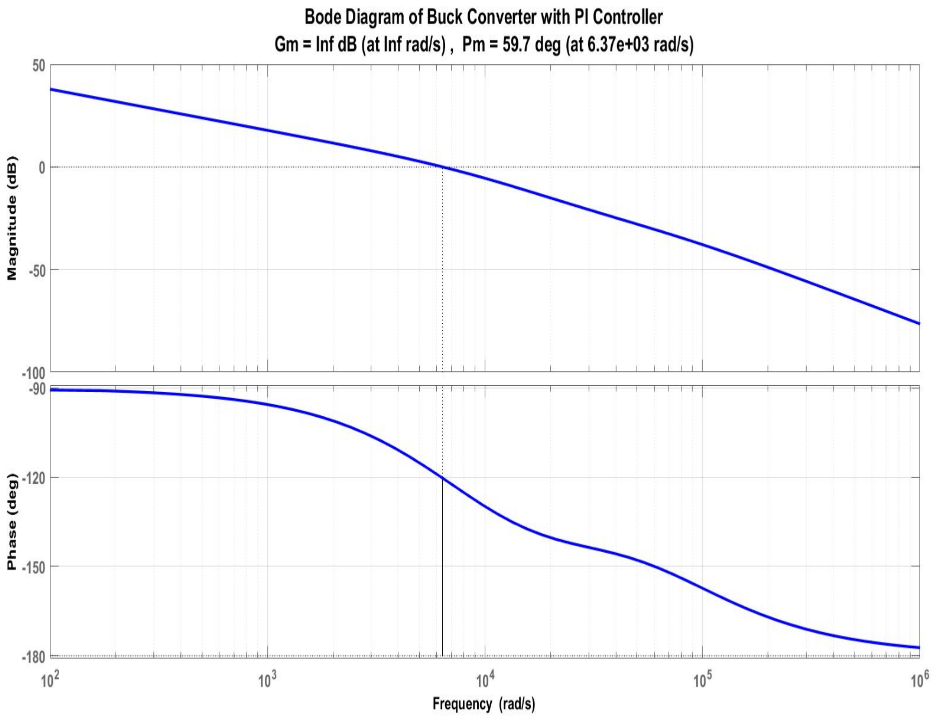

Fig. 4: Bode Plot of Buck Converter with PI Controller

3.8 Components selection of appropriate ratings according to availability in market

3.8.1 MOSFET Rating

- Minimum voltage rating = V_{in} = 200 V.
- Minimum current rating = $I_{L(peak)} = I_o + \frac{\Delta I}{2} = 5.73$ A.

Therefore, the MOSFET specifications will be:

- $V_{ds} \geq 200$ V
- $R_{ds(ON)}$ should be as low as possible.

3.8.2 Diode Rating

- Schootky diode is preferred, since it has higher operating switching frequency and low ON state voltage drop.
- Minimum breakdown voltage (V_{BR}) = V_{in} = 200 V.
- Minimum average forward current = $I_f = I_{L(peak)} = I_o + \frac{\Delta I}{2} = 5.73$ A.

Therefore, the diode specifications will be:

- Schottky diode
- $V_{BR} \geq 200$ V
- $I_f \geq 5.73$ A

3.8.3 Inductor Rating

- Inductance value is calculated according to the given allowable ripple current. Here, the calculated value comes out as 2.396 mH.
- Minimum peak current rating is the minimum current value above which inductor goes into saturation. Here, $I_{L(peak)} = I_o + \frac{\Delta I}{2} = 5.73$ A.
- Series resistance, parallel resistance and parallel capacitance should be as low as possible.

Therefore, the inductor specifications will be:

- The inductance value available in the market nearer to the 2.396 mH is 3.3 mH.

3.8.4 Capacitor Rating

- Capacitance value is calculated according to the given allowable ripple output voltage and also depends on chosen inductance value. Here, the calculated value comes out as 0.6782 μF.
- Minimum voltage rating of capacitor = $V_{c(peak)} = V_o + \frac{\Delta V_o}{2} = 96 + 4.8 = 100.8$ V.
- Equivalent series resistance, series inductance, parallel resistance and parallel capacitance should be as low as possible.

Therefore, the capacitor specifications will be:

- The capacitor value available in the market nearer to the 0.6782 μF is 0.82 μF, having voltage rating of 100 V.

S.No.	Schematic Name	Market Name	Value
1	R1	Resistor	34.8 Ω
2	R2	-	18.432 Ω
3	R3	-	90.9 kΩ
4	R4	-	1.62 kΩ
5	R5	-	4.99 kΩ
6	R6	-	4.99 kΩ
7	R7	-	4.99 kΩ
8	R8	-	4.99 kΩ
9	R9	-	10 kΩ
10	R10	-	12.204 Ω
11	R11	-	100 Ω
12	R12	-	15 kΩ
13	R13	-	120 kΩ
14	R14	-	10 kΩ
15	R15	-	1 kΩ
16	R16	-	8 Ω
17	R17	-	10 kΩ
18	C1	Capacitor	0.001 μF
19	C2	-	0.82 μF
20	C3	-	3.172 nF
21	C4	-	0.001 μF
22	L1	Inductor	3.3 mH
23	Q1	IRF9640 (MOSFET)	V_{DS} = -200V
24	D1	RFN5BM3S (Super Fast Recovery Diode)	V_{BR} = 350 V
25	IC1	LTC6244	Low noise CMOS Op Amp
26	IC2	-	-
27	IC3	-	-
28	IC4	-	-
29	IC5	-	-
30	OK1	PC817A (Photocoupler)	V_{iso}(rms) = 5.0 kV

Tabel 1: Selected Components