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

Input Voltage (V_{in}): 96 V, Output Voltage (V_0): 200 V, Switching Frequency (f_{sw}): 20 kHz, Output Voltage Ripple (ΔV_0): 10%, Inductor Current Ripple (Δi_L): 20%, Rated Power: 500 W.

To do analysis on design of closed loop control of boost converter, the above data is taken as reference. So for clear idea,

Rough calculations for the above example are done.

Power circuit design

- **Calculations:**

Boost Converter →

⇒ $V_{in} = 96\,V$

$V_o = 200\,V$

$f_{sw} = 20\,KHz$

$\Delta V_o = 10\%$ of V_o

$\Delta I_L = 20\%$ of I_L.

$P_o = 500\,W$.

- $P_o = 500\,W$

$V_o I_o = 500$

$I_o = \left[\frac{500}{200}\right]$

$I_o = \frac{5}{2}\,A$

$\frac{V_o}{R} = \frac{5}{2}$

$R = \frac{2}{5} \times 200$

$\boxed{R_b = 80\,\Omega}$ → Routput resistance of boost converter

- for Boost converter,

$\frac{V_o}{V_{in}} = \left[\frac{1}{1-D}\right]$

$(1-D) = \left[\frac{96}{200}\right]$

$(1-D) = 0.48$

$\boxed{D = 0.52}$ → Duty Ratio.

- Given, $\Delta I_L = 20\% \times I_L$

$= \frac{20}{100} \times I_L$

$\Delta I_L = 0.2\,I_L$

where, $I_L = \left(\frac{V_{in}}{R(1-D)^2}\right)$

$= \left[\frac{96}{80(0.48)^2}\right]$

$\boxed{I_L = 5.2\,A}$

$\Delta I_L = 0.2 \times 5.2$

$\boxed{\Delta I_L = 1.041\,A}$

We know that,

$\Delta I_L = \frac{V_{in}}{L}(DT)$

$1.041 = \frac{96}{L} \times \frac{0.52}{20 \times 10}$

$\boxed{L_b = 2.397\,mH}$

Inductor of boost converter

-

• Also given,

$$\Delta V_o = 10\% \times V_o$$

$$= \frac{10}{100} \times 200$$

$$\underline{\Delta V_o = 20V}$$

from, $\Delta V_o = \left[\frac{I_o DT}{C}\right]$

$$20 = \frac{\frac{5}{2} \times 0.52}{C \times 20 \times 10^3}$$

$$C = 0.325 \times 10^{-5}$$

$\boxed{C_b = 3.25\mu F}$ → Capacitance of boost converter

⇒ Snubber circuit —

RC design →

$R = \left[\frac{V_{max}}{I_{max}}\right]$ that appear across circuit

$R = \left[\frac{200}{2.5}\right] = 80\Omega$ → $\boxed{R_s = 80\Omega}$ → Resistance of snubber

$$C = \left[\frac{1}{V^2 \times f}\right] = \frac{1}{(200)^2 \times 20 \times 10^3}$$

$\boxed{C_s = 0.125\mu F}$ → Capacitance of snubber circuit

CONTROLLER DESIGN:

from experiment 7 →

The transfer function of boost converter is →

$$\left(\frac{\Delta V_o}{\Delta D}\right) = \left[\frac{V_o R(1-D)^2 - V_o s L}{sL(1-D) + s^2 LCR(1-D) + (1-D)^3 R}\right]$$

on substituting all values →

$$= \frac{200 \times 80 (1-0.52)^2 - 200 s \times 2.4 \times 10^{-3}}{\left[s \times 2.4 \times 10^{-3}(1-0.52) + s^2 \times 2.4 \times 10^{-3} \times 3.25 \times 10^{-6} \times 80(1-0.52) + (1-0.52)^3 \times 80\right]}$$

$$= \frac{3686.4 - 0.792 s}{\left[1.15 \times 10^{-3} s + 0.299 \times 10^{-6} s^2 + 8.847\right]}$$

$$= \frac{3686.4 \,(1 - 2.14 \times 10^{-4} s)}{0.299 \times 10^{-6} \left[s^2 + 3.846 \times 10^3 s + 29.58 \times 10^6\right]}$$

$$\left(\frac{\Delta V_o}{\Delta D}\right) = \frac{12329.09 \,(1 - 2.14 \times 10^{-4} s)}{\left[s^2 + 3.846 \times 10^3 s + 29.58 \times 10^6\right]}$$

After connecting a PI - controller of $\left(K_p + \frac{K_i}{s}\right)$, the overall transfer function changes to

$$T/F \rightarrow \left(\frac{\Delta V_o}{\Delta D}\right) \times \left[K_p + \frac{K_i}{s}\right] = GH$$

Let $\{s = j\omega\}$

$$T/F = \frac{12329.09 \times 10^3 \,(k_i + j\omega k_p)(1 - j 2.14 \times 10^{-4} \omega)}{j\omega\left[(29.58 \times 10^6 - \omega^2) + j 3.846 \times 10^3 \omega\right]}.$$

At gain-cross-over frequency of 20KHz and PM = 30°

$$180 + \phi\Big|_{\omega=\omega_{gc}} = 30^\circ$$

$$\Rightarrow \quad \phi\Big|_{\omega=\omega_{gc}} = -150^\circ$$

$$\Rightarrow -90^\circ + \tan^{-1}\left(\frac{\omega K_p}{K_i}\right) - \tan^{-1}(2.14\times10^{-4}) - \tan^{-1}\left[\frac{3.846\times10^{3}\omega}{29.58\times10^{6}-\omega^2}\right] = -150^\circ$$

$$\Rightarrow \tan^{-1}\left(\frac{\omega K_p}{K_i}\right) - \tan^{-1}\left(\frac{3.846\times10^{3}\omega}{29.58\times10^{6}-\omega^2}\right) = -150^\circ + 90^\circ + 0.01226 = -59.987^\circ.$$

$$\Rightarrow \tan^{-1}\left[\frac{\frac{\omega K_p}{K_i} - \frac{3.846\times10^{3}\omega}{29.58\times10^{6}-\omega^2}}{1+\left(\frac{\omega K_p}{K_i}\right)\left(\frac{3.846\times10^{3}\omega}{29.58\times10^{6}-\omega^2}\right)}\right] = -59.987^\circ.$$

Take 'tan' on both sides and $\omega = \omega_{gc} = 2\pi\times20K = 40\pi\times10^3\,Hz$

$$\Rightarrow \left\{\frac{\left[\frac{40\pi\times10^3 K_p}{K_i}\right] - \left[\frac{3.846\times10^3\times40\pi\times10^3}{-15761.78\times10^6}\right]}{1+\left(\frac{40\pi\times10^3K_p}{K_i}\right)\left(\frac{3.846\times10^3\times40\pi\times10^3}{-15761.78\times10^6}\right)}\right\} = -\tan 59.987^\circ = -1.7312$$

$$\Rightarrow \left[\frac{125.66\times10^3K_p}{K_i} + \frac{4833\times10^6}{15761.78\times10^6}\right] = -1.732\left[1-\left(\frac{125.6\times10^3K_p}{K_i}\right)\left(\frac{4833\times10^6}{15761.78\times10^6}\right)\right]$$

$$\Rightarrow \frac{125.66\times10^3K_p}{K_i} + 0.03066 = -1.732 + \frac{6.673\times10^3K_p}{K_i}$$

$$\Rightarrow \frac{118.98\times10^3K_p}{K_i} = -1.7013$$

$\therefore$ $\boxed{Ki = -69.933\times10^3 Kp}$ ✓

We also know that,

$$|GH|_{at\ \omega=\omega_{gc}} = 1.$$

$$\left[\frac{12329.09\times10^3}{\omega}\right]\times\sqrt{\frac{(Ki^2+\omega^2Kp^2)(1+(2.14\times10^{-4}\omega)^2)}{(29.58\times10^6-\omega^2)^2+(3.846\times10^3\omega)^2}} = 1$$

squaring on both sides,

$$\frac{[Ki^2+(40\pi)^2\times10^6Kp^2]\times[724.181]}{[2.48\times10^8\times10^{12}+233581.41\times10^{12}]} = \left[\frac{(40\pi\times10^3)^2}{(12329.09\times10^3)^2}\right]$$

$$= 1.0388\times10^{-8}$$

$$[Ki^2+15791.36\times10^6Kp^2] = \left[\frac{2.5786\times10^{12}}{724.181}\right]$$

$$[Ki^2+15791.36\times10^6Kp^2] = [3560.781\times10^6]$$

As $Ki = -69.933\times10^3 Kp$,

$$(4564.35+15791.36)\times\cancel{10^6}\times Kp^2 = 3560.781\times\cancel{10^6}.$$

$$\therefore Kp = \sqrt{\frac{3560.781}{20355.713}}$$

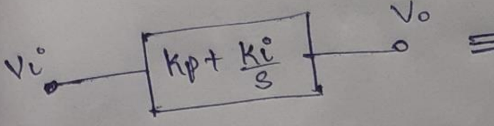
$$\boxed{Kp = 0.4182}$$

Similarly, $Ki = -69.933\times10^3\times Kp$

$$= -69.933\times10^3\times0.4182$$

$$\boxed{Ki = -28256.54}$$

The PI- controller as an op-amp integrator looks like →



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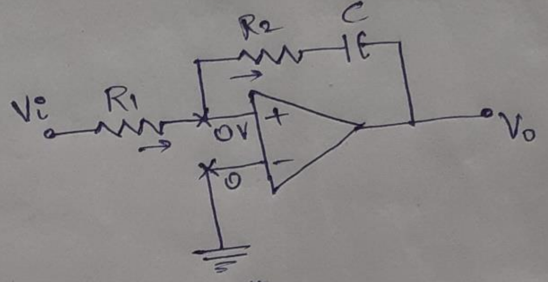

$$\left[\frac{V_o}{V_i}\right]_1 = \left[K_p + \frac{K_i}{s}\right]$$

By Nodal equation,

$$\frac{V_i - 0}{R_1} = \left[\frac{0 - V_o}{R_2 + 1/sC}\right]$$

$$\frac{V_o}{V_i} = -\frac{1}{R_1}\left[R_2 + \frac{1}{sC}\right]$$

$$\left[\frac{V_o}{V_i}\right]_2 = -\left[\frac{R_2}{R_1} + \frac{1}{sCR_1}\right]$$

∴ On comparing both $\left[\frac{V_o}{V_i}\right]_1$ and $\left[\frac{V_o}{V_i}\right]_2$,

we get ;

$$K_p = \left[\frac{R_2}{R_1}\right] \text{ and } K_i = \left[\frac{1}{\cancel{s}CR_1}\right]$$

let $\boxed{R_1 = 10K\Omega}$, then →

$R_2 = K_p \times R_1$

$R_2 = 0.4182 \times 10K$

$R_2 = 4.182 K\Omega$

$\boxed{R_2 \approx 4.3K\Omega}$

$K_i = \left[\frac{1}{CR_1}\right]$

$C = \left[\frac{1}{R_1 \times K_i}\right]$

$= \left[\frac{1}{10 \times 10^3 \times 28256.54}\right]$

$C = 3.54 nF$

$\boxed{C \approx 3.6nF \text{ (or) } 3600pF}$

Devices used in PCB design:

Devices Used:

1. Switch : BSY34
2. Inductor : MS42 : 2.4mH → (2.54mm).
3. Capacitor : C5/3.5 → 0.15µF
   C7.5/3 → 3.25µF
   C2.5/2 → 3.6nF
4. Heat sink : SK129
5. Diodes : IN4446
6. Zener : IN4728
7. Opamps : AD8067
8. Opto Isolator : 4N37
9. Mount pads : 5 in count
10. Battery : 1 with 6V reference
11. Resistors : ~~80Ω~~

		Dimensions.
R-EU_0204	→ 80Ω	(2.5mm)
	200Ω	(5mm)
	1kΩ	(10mm)
	1.6kΩ	(10mm)
	2kΩ	(11mm)
	~~4kΩ~~ 4.3KΩ	(12mm)
	10kΩ	(15mm)
	91kΩ	(22.5mm)

12. Ground