Lecture 8
ECEN 4517/5517

Experiment 4

Lecture 7: Step-up dc-dc converter and PWM chip

Lecture 8: Design of analog feedback loop

Part I—Controller IC:
Demonstrate operating PWM controller IC (UC 3525)

Part II—Power Stage:
Demonstrate operating power converter (cascaded boost converters)

Part III—Closed-Loop Analog Control System:
Demonstrate analog feedback system that regulates the dc output voltage
Measure and document loop gain and compensator design
Due dates

This week: Tuesday at noon (Mar. 8):
   Prelab assignment for Exp. 4 (one from every student)

This week in lab (Mar. 9-10):
   Start Exp. 4

This Friday at 5 pm (Mar. 11):
   Exp. 3 part 2 report due
Discussion: Lab 4 prelab

![Circuit Diagram]

- $V_{batt}$
- $L_1$
- $D_1$
- $L_2$
- $D_2$
- $V_{HVDC}$
- $C_1$
- $C_2$
- $C_3$
- $Q_1$
- $Q_2$
- PWM
- Compensator
- $V_{ref}$
Soft start and shutdown

The shutdown pin (10) turns off the chip outputs. Ground this pin to ensure that the outputs are not shut down.

A capacitor can be connected to the soft start pin (8). The voltage on this pin limits the maximum duty cycle. At turn on, the capacitor will start at 0V, and then will charge from the 50 μA current source. This overrides the feedback loop and starts the converter gently.
Outputs of the UC3525A

Frequency of the outputs is one half the oscillator frequency. Duty cycle cannot be greater than 50%.

Such outputs are needed in some types of switching converters such as “push-pull.”

Outputs A and B can be OR-ed to restore the PWM pulses at the oscillator frequency.
OR-ing the outputs

A cheap way to OR the outputs of the UC3525

The + 5 V can be obtained from the 5 V reference of the UC3525

Bypass the + 5 V so that the switching EMI of this circuit does not disrupt the internal control circuitry of the UC3525, which also uses the + 5 V.

More UC3525 tips:
- You will need to ground the SHUTDOWN pin. Otherwise the UC3525 will shut down.
- $R_T$ must be greater than 2 kΩ; otherwise the UC3525 oscillator will not work
- $R_D$ is usually a few hundred Ohms; $R_D$ must be substantially smaller than $R_T$. 
Exp. 4 Part III
Regulation of output voltage via feedback

- Model and measure control-to-output transfer function $G_{vd}(s)$
- Design and build feedback loop
- Demonstrate closed-loop regulation of $v_{HVDC}$
Negative feedback: a switching regulator system
Transfer functions of some basic CCM converters

Table 8.2. Salient features of the small-signal CCM transfer functions of some basic dc-dc converters

<table>
<thead>
<tr>
<th>Converter</th>
<th>$G_{g0}$</th>
<th>$G_{d0}$</th>
<th>$\omega_0$</th>
<th>$Q$</th>
<th>$\omega_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>buck</td>
<td>$D$</td>
<td>$\frac{V}{D}$</td>
<td>$\frac{1}{\sqrt{LC}}$</td>
<td>$R \sqrt{\frac{C}{L}}$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>boost</td>
<td>$\frac{1}{D'}$</td>
<td>$\frac{V}{D'}$</td>
<td>$\frac{D'}{\sqrt{LC}}$</td>
<td>$D'R \sqrt{\frac{C}{L}}$</td>
<td>$\frac{D'^2R}{L}$</td>
</tr>
<tr>
<td>buck-boost</td>
<td>$-\frac{D}{D'}$</td>
<td>$\frac{V}{DD'^2}$</td>
<td>$\frac{D'}{\sqrt{LC}}$</td>
<td>$D'R \sqrt{\frac{C}{L}}$</td>
<td>$\frac{D'^2R}{DL}$</td>
</tr>
</tbody>
</table>

where the transfer functions are written in the standard forms

$$G_{vd}(s) = G_{d0} \frac{1 - \frac{s}{\omega_z}}{1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

$$G_{vg}(s) = G_{g0} \frac{1}{1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

*Flyback:* push $L$ and $C$ to same side of transformer, then use buck-boost equations. DC gains $G_{g0}$ and $G_{d0}$ have additional factors of $n$ (turns ratio).
Bode plot: control-to-output transfer function
buck-boost or flyback converter example

\[ G_{d0} = 187 \text{ V} \implies 45.5 \text{ dBV} \]
\[ Q = 4 \implies 12 \text{ dB} \]

\[ f_0 = 400 \text{ Hz} \]
\[ 40 \text{ dB/decade} \]

\[ f_z = 2.6 \text{ kHz} \]
\[ \text{RHP} \]

\[ 10^{1/2Q}f_0 = 533 \text{ Hz} \]
\[ 10^{1/2Q}f_0 = 26 \text{ kHz} \]

\[ f_z/10 = 260 \text{ Hz} \]
\[ f_z/10 = 2.6 \text{ kHz} \]

\[ 0^\circ \]
\[ 300 \text{ Hz} \]

\[ \angle G_{vd} \]
\[ 0^\circ \]
\[ 300 \text{ Hz} \]

\[ 20 \text{ dBV} \]
\[ 40 \text{ dBV} \]
\[ 60 \text{ dBV} \]
\[ 80 \text{ dBV} \]

\[ 0^\circ \]
\[ -90^\circ \]
\[ -180^\circ \]
\[ -270^\circ \]

\[ 10 \text{ Hz} \]
\[ 100 \text{ Hz} \]
\[ 1 \text{ kHz} \]
\[ 10 \text{ kHz} \]
\[ 100 \text{ kHz} \]
\[ 1 \text{ MHz} \]
Spice Simulation
Open-loop simulation of control-to-output transfer function

- Replace boost converter switches with averaged switch model
- CCM-DCM1 and other switch models are linked to course web site, inside switch.lib file
- Apply dc voltage (to set steady-state duty cycle) plus ac variation, to terminal 5 of CCM-DCM1 model. Plot output voltage magnitude and phase using ac analysis within Spice.
The loop gain $T(s)$

Loop gain $T(s) = \text{product of gains around the feedback loop}$

More loop gain $||T||$ leads to better regulation of output voltage

$T(s) = G_{vd}(s) \cdot H(s) \cdot G_c(s) / V_M$

$G_{vd}(s) = \text{power stage control-to-output transfer function}$

PWM gain $= 1/V_M$. $V_M = \text{pk-pk amplitude of PWM sawtooth}$
Phase Margin

A test on $T(s)$, to determine stability of the feedback loop

The crossover frequency $f_c$ is defined as the frequency where

$$\| T(j2\pi f_c) \| = 1, \text{ or } 0 \text{ dB}$$

The phase margin $\varphi_m$ is determined from the phase of $T(s)$ at $f_c$, as follows:

$$\varphi_m = 180^\circ + \arg(T(j2\pi f_c))$$

If there is exactly one crossover frequency, and if $T(s)$ contains no RHP poles, then

the quantities $T(s)/(1+T(s))$ and $1/(1+T(s))$ contain no RHP poles whenever the phase margin $\varphi_m$ is positive.
Example: a loop gain leading to a stable closed-loop system

\[
\text{arg}(T(j2\pi f_c)) = -112^\circ
\]

\[\varphi_m = 180^\circ - 112^\circ = +68^\circ\]
Transient response vs. damping factor

\[ \hat{v}(t) \]

\[ \text{vs. } \omega_c t, \text{ radians} \]
$Q$ vs. $\varphi_m$

- $Q = 1 \Rightarrow 0 \text{ dB}$
- $Q = 0.5 \Rightarrow -6 \text{ dB}$
- $\varphi_m = 52^\circ$
- $\varphi_m = 76^\circ$
9.5.2. Lag (PI) compensation

\[ G_c(s) = G_{c\infty} \left(1 + \frac{\omega_L}{s}\right) \]

Improves low-frequency loop gain and regulation
Example: lag compensation

original (uncompensated) loop gain is
\[ T_u(s) = \frac{T_{u0}}{1 + \frac{s}{\omega_0}} \]

compensator:
\[ G_c(s) = G_{c\infty} \left( 1 + \frac{\omega_L}{s} \right) \]

Design strategy: choose
\[ G_{c\infty} \] to obtain desired crossover frequency
\[ \omega_L \] sufficiently low to maintain adequate phase margin
8.4. Measurement of ac transfer functions and impedances

Network Analyzer

**Injection source**
- \( \hat{v}_z \) magnitude
- \( \hat{v}_z \) frequency

**Measured inputs**
- \( \hat{v}_x \) input
- \( \hat{v}_y \) input

**Data**
- \( \frac{\hat{v}_y}{\hat{v}_x} \) magnitude: 17.3 dB
- \( \frac{\hat{v}_y}{\hat{v}_x} \) phase: -134.7°
Swept sinusoidal measurements

- Injection source produces sinusoid $\hat{v}_z$ of controllable amplitude and frequency
- Signal inputs $\hat{v}_x$ and $\hat{v}_y$ perform function of narrowband tracking voltmeter:
  
  Component of input at injection source frequency is measured
  
  Narrowband function is essential: switching harmonics and other noise components are removed
- Network analyzer measures
  
  \[
  \left| \frac{\hat{v}_y}{\hat{v}_x} \right| \quad \text{and} \quad \angle \frac{\hat{v}_y}{\hat{v}_x}
  \]
Measurement of an ac transfer function

- Potentiometer establishes correct quiescent operating point
- Injection sinusoid coupled to device input via dc blocking capacitor
- Actual device input and output voltages are measured as $\hat{v}_x$ and $\hat{v}_y$
- Dynamics of blocking capacitor are irrelevant

\[
\frac{\hat{v}_y(s)}{\hat{v}_x(s)} = G(s)
\]
9.6.1. Voltage injection

- Ac injection source $v_z$ is connected between blocks 1 and 2
- Dc bias is determined by biasing circuits of the system itself
- Injection source does modify loading of block 2 on block 1