Lecture 4
ECEN 4517/5517

Experiment 3

DC-DC converter
Battery charge controller
Peak power tracker

Buck converter

Gate driver with isolation transformer

Pulse-width modulator
Micro controller
Sensors

PV

$V_{pv}$

$C_1$

$L_1$

$C_2$

$v_{batt}$

$i_{batt}$
Upcoming deadlines

Quiz 2 on Exp 2: last 15 minutes today

This week in lab:
  Continue Exp. 3 Part 1.
  Get your converter running open-loop, and take data outside

Next week in lab:
  Finish Exp. 3 Part 1, including simulations
  Exp. 3 Part 1 report will be due Feb 28

Exp. 2 prelab 2 (sensing circuitry + MPPT code) due Feb 24

Exp. 2 on-line modules and quizzes coming up – keep an eye on D2L
Converter modeling and simulation

Conduction modes
  - Continuous conduction mode (CCM)
  - Discontinuous conduction mode (DCM)

Equivalent circuit modeling
  - The dc transformer model: CCM
  - DCM model

Simulation
  - Averaged switch model in CCM
  - Averaged switch model in DCM
  - A combined automatic model for PSPICE (or Simulink, optional)
  - Exp. 3 Part 1: simulation model for your system, including PV panel and converter
Averaged switch modeling
Basic approach (CCM)

Given a switching converter operating in CCM

Buck converter example

Separate the switching elements from the remainder of the converter

Define the terminal voltages and currents of the two-port switch network
Terminal waveforms of the switch network

**Relationship between average terminal waveforms:**

\[
\langle v_1(t) \rangle_{T_s} = \frac{d'(t)}{d(t)} \langle v_2(t) \rangle_{T_s}
\]

\[
\langle i_2(t) \rangle_{T_s} = \frac{d'(t)}{d(t)} \langle i_1(t) \rangle_{T_s}
\]
Averaged model of switch network

\[
\frac{\langle v_1 \rangle}{d'} = \frac{\langle v_2 \rangle}{d} = \langle v_g \rangle
\]

\[
\frac{\langle i_2 \rangle}{d'} = \frac{\langle i_1 \rangle}{d} = \langle i_L \rangle
\]

So

\[
\langle v_1 \rangle = \frac{d'}{d} \langle v_2 \rangle
\]

\[
\langle i_2 \rangle = \frac{d'}{d} \langle i_1 \rangle
\]

Modeling the switch network via averaged dependent sources.
Switch Library File
Spice simulation of averaged waveforms

.subckt CCM1 1 2 3 4 5
Et 1 6 value={\(1-v(5)\)\(v(3,4)/v(5)\)}
Vdum 6 2 0
Gd 4 3 value={\(1-v(5)\)\(i(Vdum)/v(5)\)}
.ends
Basic CCM SEPIC Example
Frequency Response

Ideal SEPIC frequency response
.lib switch.lib
Vg 1 0 dc 120V
L1 1 2x 800uH
RL1 2x 2 1U
C1 2 3 100uF
L2 3 0 100uH
C2 4 0 100uF
RL 4 0 40
Vc 5 0 dc 0.4 ac 1
Rc 5 0 1M
Xswitch 2 0 4 3 5 CCM1
.ac DEC 201 10 100kHz
.PROBE
.end
AC analysis in Spice

Given a nonlinear time-invariant circuit, as on the previous slide, we can get Spice to automatically perturb, linearize, and plot small-signal ac transfer functions:

• Use DC sources to set up the correct quiescent operating conditions
• Include an AC source having amplitude 1
• Perform an AC analysis: Spice will
  • Do a DC analysis to find the quiescent operating point
  • Linearize all nonlinear elements at this point, to construct a linear model
  • Perform an AC (phasor) analysis at specified frequencies to find the magnitudes and phases of all signals
  • Construct Bode plots of selected signals. With an input amplitude of 1, the signal magnitude and phase plot is the transfer function.
AC analysis
SEPIC Example: Control-to-output transfer function

Magnitude

Phase
Discontinuous Conduction Mode

- Again find average values of switch network terminal voltages and currents
- Eliminate variables external to the switch network
- Results on next slides
Input (transistor) port
Averaged equivalent circuit

\[
\langle i_1(t) \rangle_{T_s} = \frac{d_1^2(t) T_s}{2L} \langle v_1(t) \rangle_{T_s}
\]

\[
\langle i_1(t) \rangle_{T_s} = \frac{\langle v_1(t) \rangle_{T_s}}{R_e(d_1)}
\]

\[
R_e(d_1) = \frac{2L}{d_1^2 T_s}
\]
Output (diode) port
Averaged equivalent circuit

\[
\langle i_2(t) \rangle_{T_s} = \frac{d_1^2(t) T_s}{2L} \frac{\langle v_1(t) \rangle_{T_s}^2}{\langle v_2(t) \rangle_{T_s}}
\]

\[
\langle i_2(t) \rangle_{T_s} \langle v_2(t) \rangle_{T_s} = \frac{\langle v_1(t) \rangle_{T_s}^2}{R_e(d_1)} = \langle p(t) \rangle_{T_s}
\]
Averaged modeling of CCM and DCM switch networks

**Switch network**

CCM

\[
\begin{align*}
&i_1(t) & & i_2(t) \\
&v_1(t) & & v_2(t)
\end{align*}
\]

DCM

\[
\begin{align*}
&i_1(t) & & i_2(t) \\
&v_1(t) & & v_2(t)
\end{align*}
\]

**Averaged switch model**

\[
\begin{align*}
&\langle i_1(t) \rangle_{T_s} & & 1 : d(t) & & \langle i_2(t) \rangle_{T_s} \\
&\langle v_1(t) \rangle_{T_s} & & \langle v_2(t) \rangle_{T_s}
\end{align*}
\]

\[
\begin{align*}
&\langle i_1(t) \rangle_{T_s} & & \langle i_2(t) \rangle_{T_s} \\
&\langle v_1(t) \rangle_{T_s} & & \langle v_2(t) \rangle_{T_s}
\end{align*}
\]

\[
\begin{align*}
&\langle i_1(t) \rangle_{T_s} & & \langle p(t) \rangle_{T_s} & & \langle i_2(t) \rangle_{T_s} \\
&\langle v_1(t) \rangle_{T_s} & & R_c(d_1) & & \langle v_2(t) \rangle_{T_s}
\end{align*}
\]
Spice model CCM-DCM1
Combined CCM/DCM switch model

* Model: CCM-DCM1
* Application: two-switch PWM converters, CCM or DCM
* Limitations: ideal switches, no transformer

- This is one of the models inside switch.lib
- It automatically switches between CCM and DCM as necessary

```
* Parameters:
  * L=equivalent inductance for DCM
  * fs=switching frequency

* Nodes:
  * 1: transistor positive (drain of an n-channel MOS)
  * 2: transistor negative (source of an n-channel MOS)
  * 3: diode cathode
  * 4: diode anode
  * 5: duty cycle control input

.subckt CCM-DCM1 1 2 3 4 5
+ params: L=100u fs=1E5
Et 1 2 value={1-v(u)}*v(3,4)/v(u)}
Gd 4 3 value={1-v(u)}*i(Et)/v(u)}
Ga 0 a value={MAX(i(Et),0)}
Va a b
Ra b 0 1k
Eu u 0 table {MAX(v(5), v(5)*v(5)/(v(5)*v(5)+2*L*fs*i(Et)/v(3,4))}) (0 0 (1 1)
.ends
```

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LTspice simulation
Exp. 3 Part 1: open loop

• Use your PV model from Exp. 1
• Replace buck converter switches with averaged switch model
• CCM-DCM1 and other Spice model library elements are linked on the course web page
• Online module and quiz on D2L