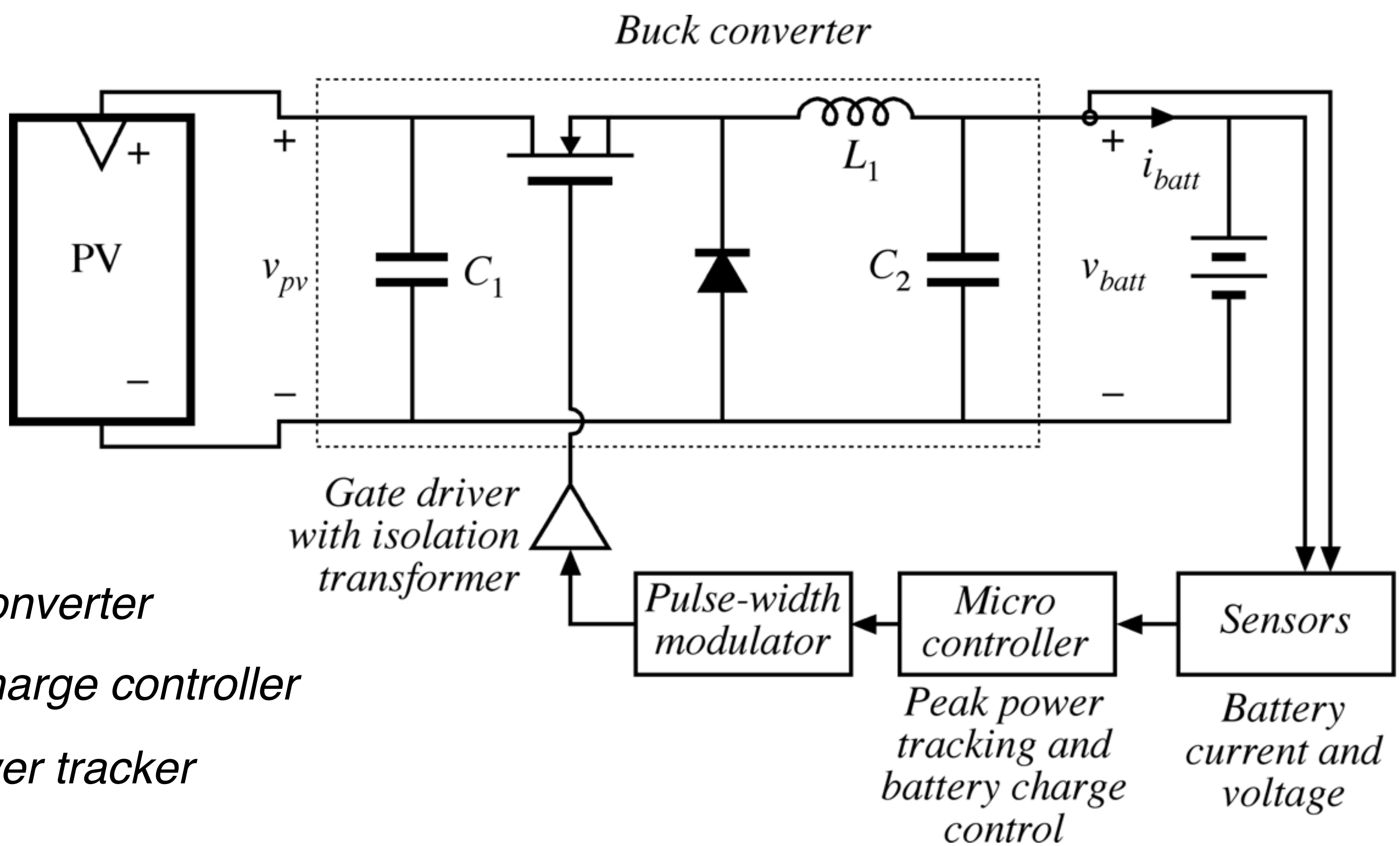
Lecture 4

ECEN 4517 / 5517

Experiment 3



DC-DC converter

Battery charge controller

Peak power tracker

Due dates

This week in lecture (now):

- Quiz 1, on Exp. 1

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 March 1

Next week at beginning of lecture:

- 10 minute quiz on Exp. 2

Converter modeling and simulation

Conduction modes

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

Equivalent circuit modeling

- The dc transformer model: CCM
- DCM model

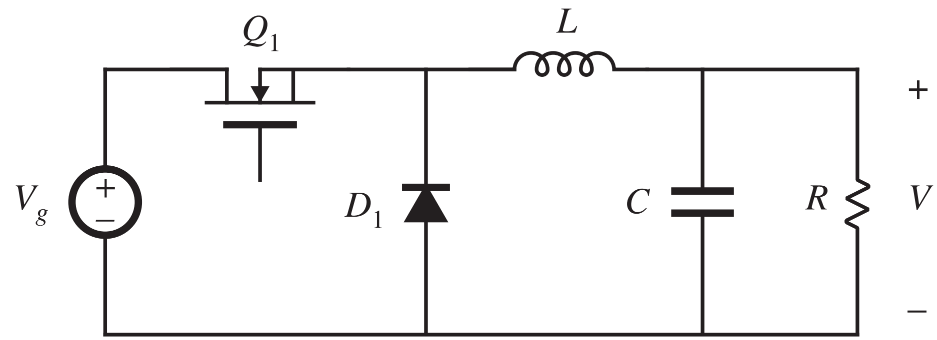
Simulation

- 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



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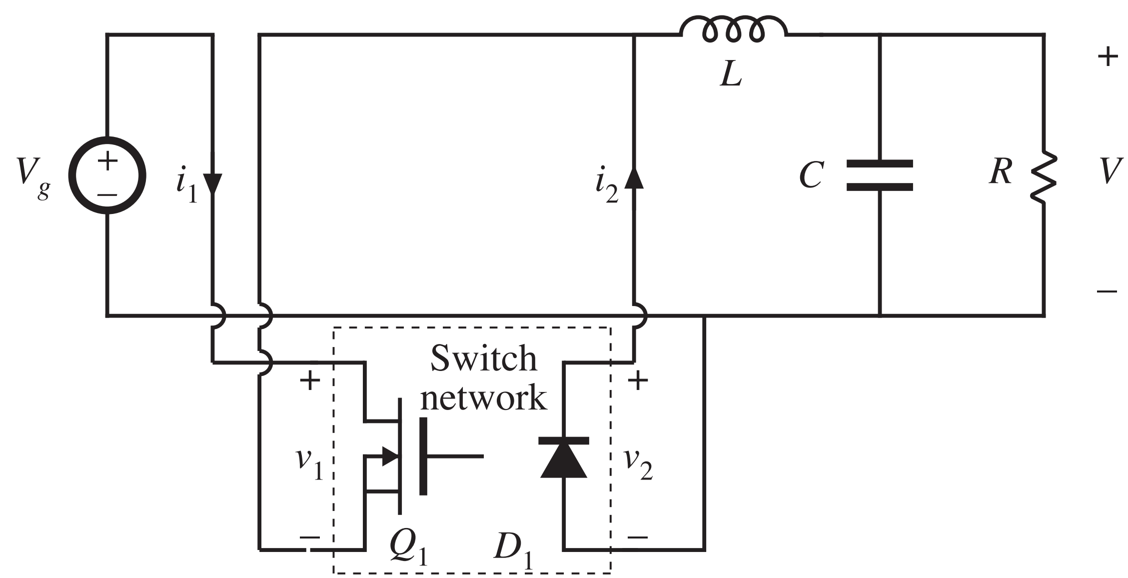
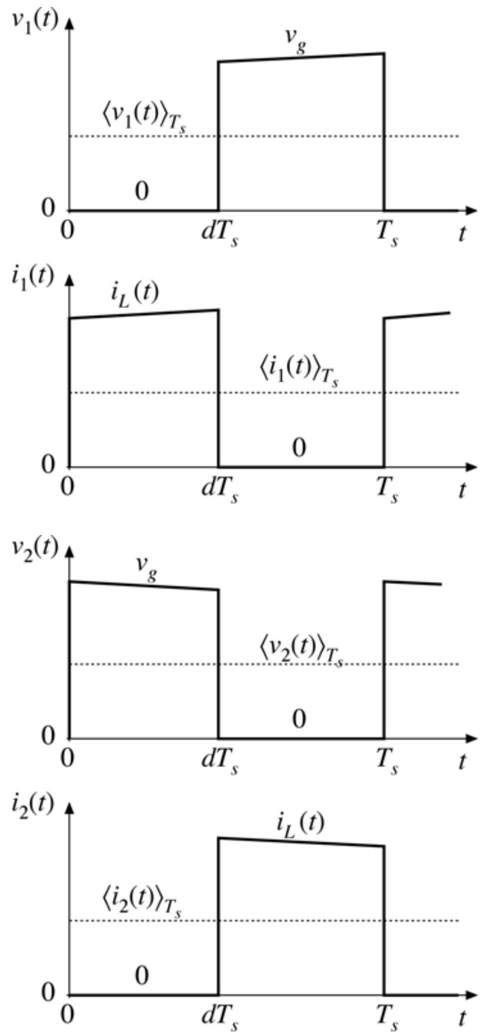
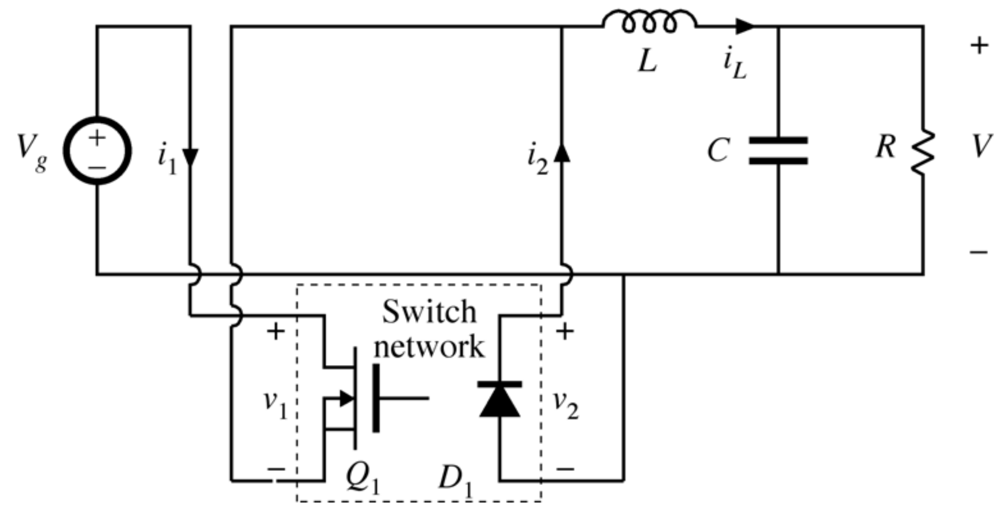
Separate the switching elements from the remainder of the converter

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

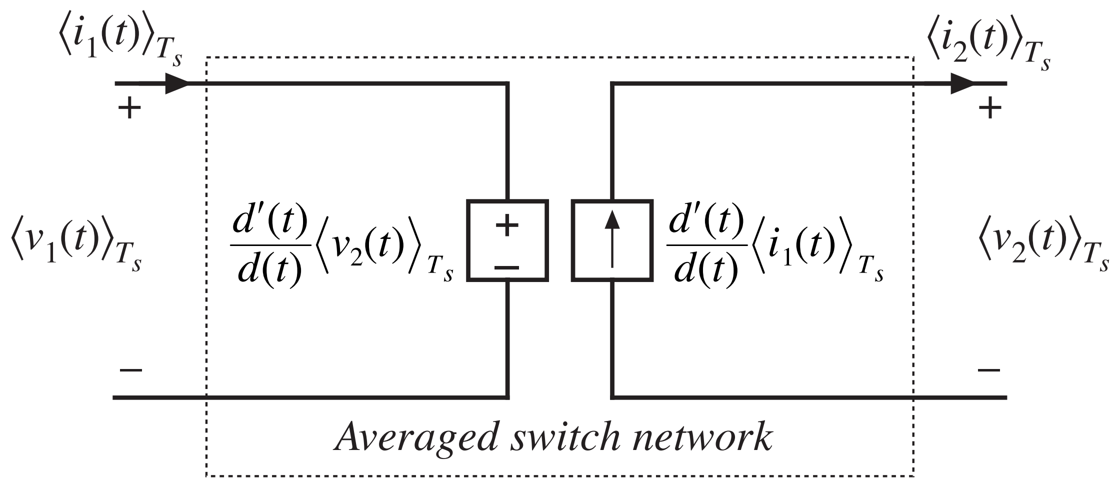
$$\frac{\langle v_1 \rangle}{d'} = \frac{\langle v_2 \rangle}{d} = \langle v_g \rangle$$

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

So

$$\langle v_1 \rangle = \frac{d'}{d} \langle v_2 \rangle$$

$$\langle i_2 \rangle = \frac{d'}{d} \langle i_1 \rangle$$

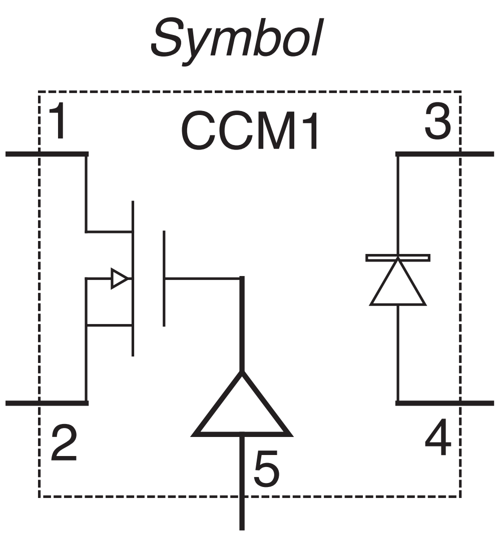


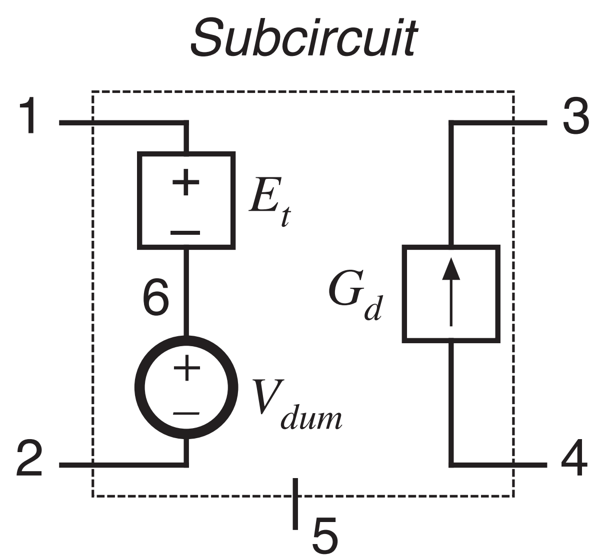
Modeling the switch network via averaged dependent sources

Switch Library File

Spice simulation of averaged waveforms

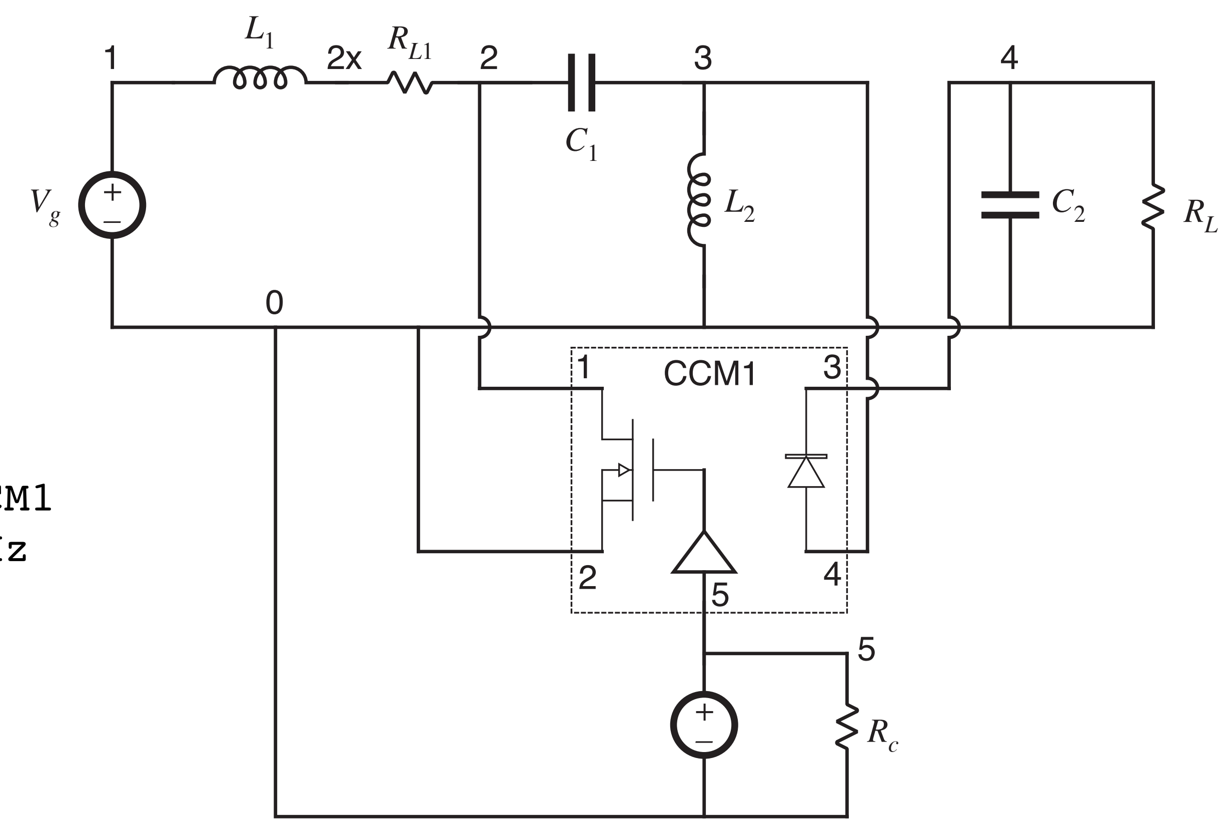
```
.subckt CCM1 1 2 3 4 5
Et 1 6 value={(1-v(5))*v(3,4)/v(5)}
Vdum 6 2 0
Gd 4 3 value={(1-v(5))*i(Vdum)/v(5)}
.ends
```





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

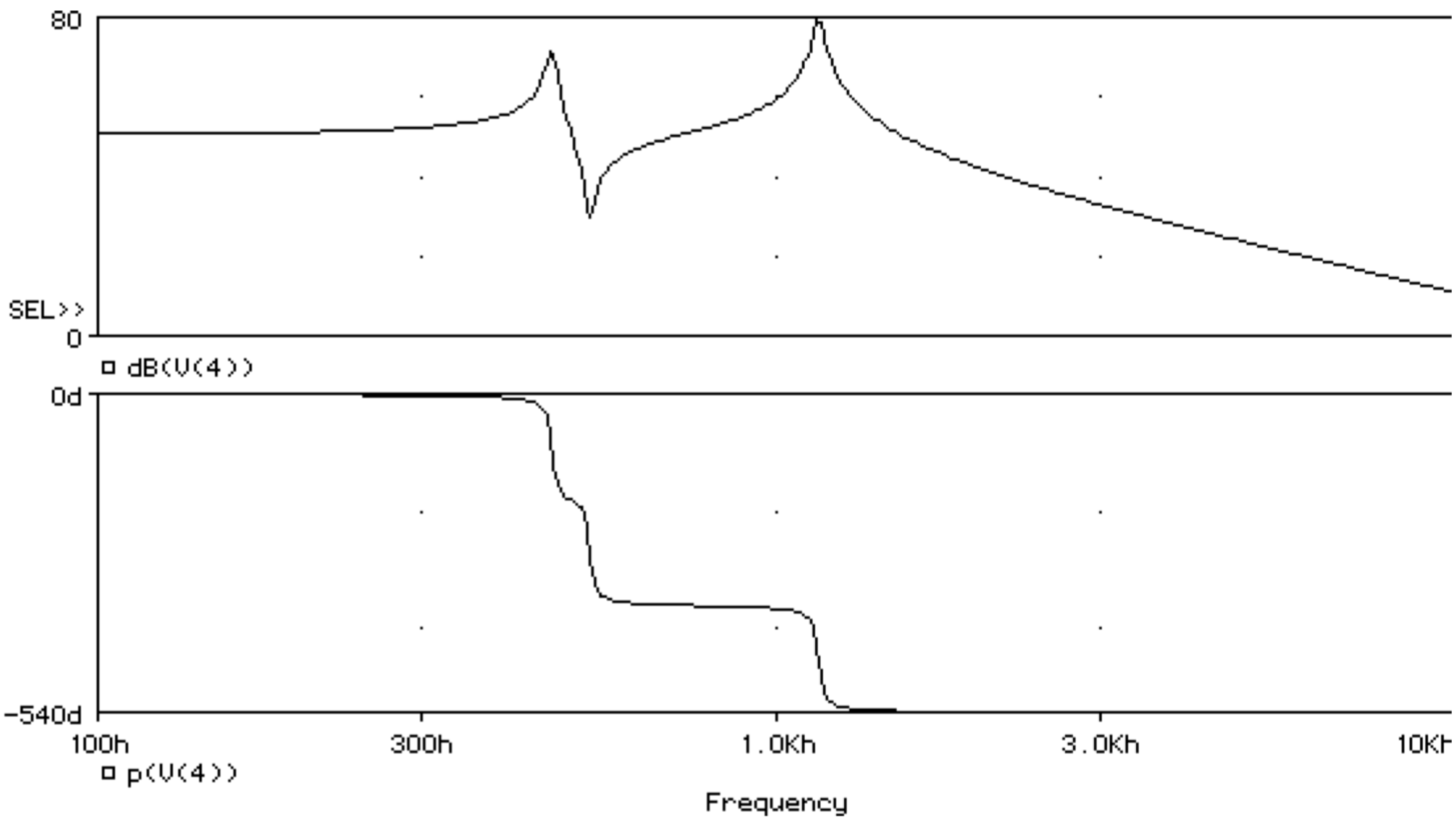
Given a nonlinear time-invariant circuit, as on the previous slide, we can get Spice to automatically perturb, linearize, and plot small-signal ac transfer functions:

- 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.

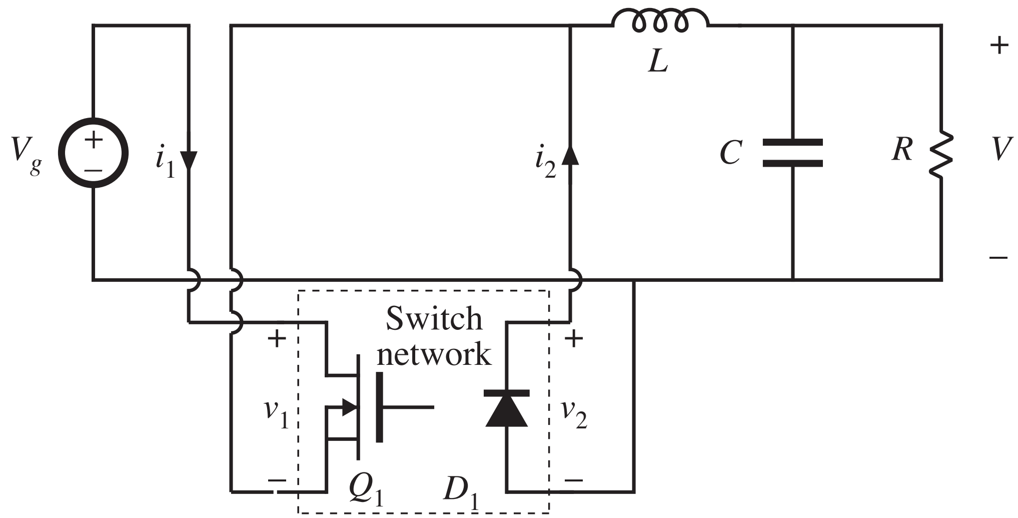
PROBE Output
SEPIC Example: Control-to-output transfer function

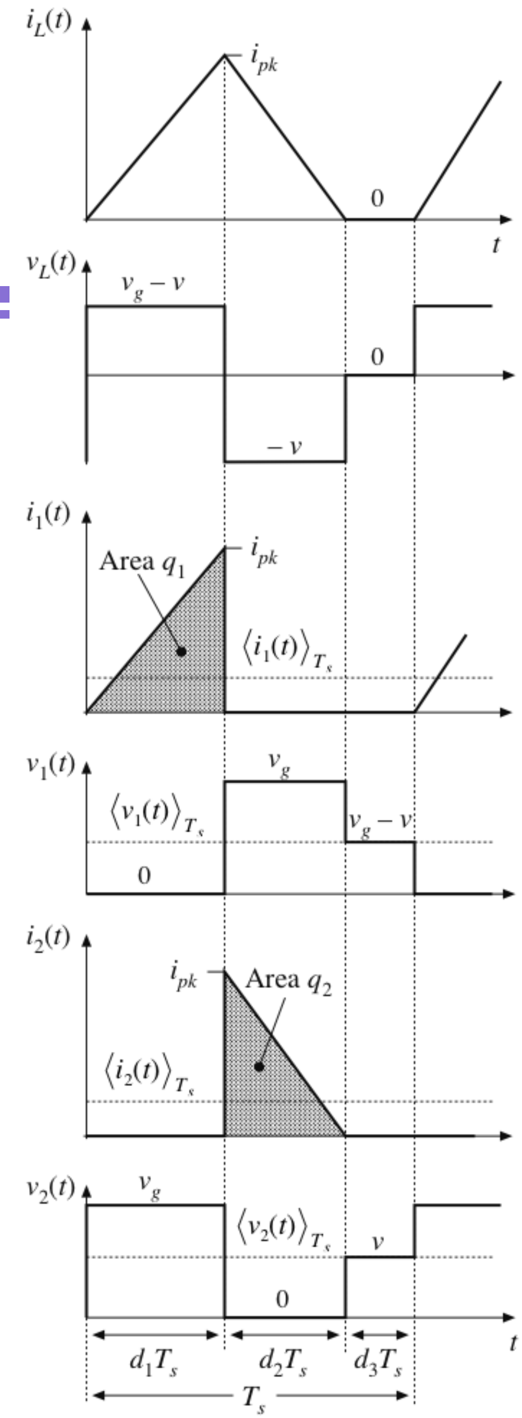
Magnitude

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

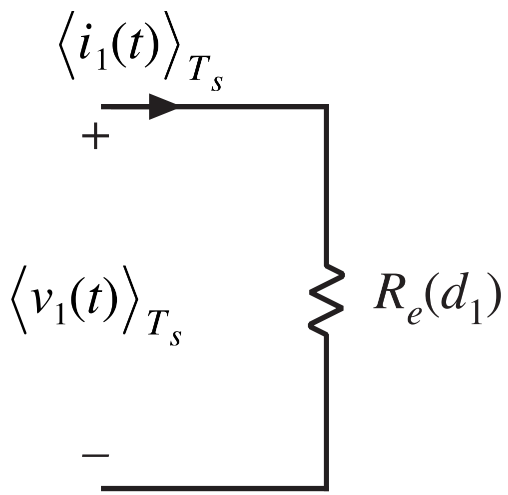
Input (transistor) port

Averaged equivalent circuit

$$\left\langle i_1(t) \right\rangle_{T_s} = \frac{d_1^2(t)\, T_s}{2L} \left\langle v_1(t) \right\rangle_{T_s}$$

$$\left\langle i_1(t) \right\rangle_{T_s} = \frac{\left\langle v_1(t) \right\rangle_{T_s}}{R_e(d_1)}$$

$$R_e(d_1) = \frac{2L}{d_1^2\, T_s}$$

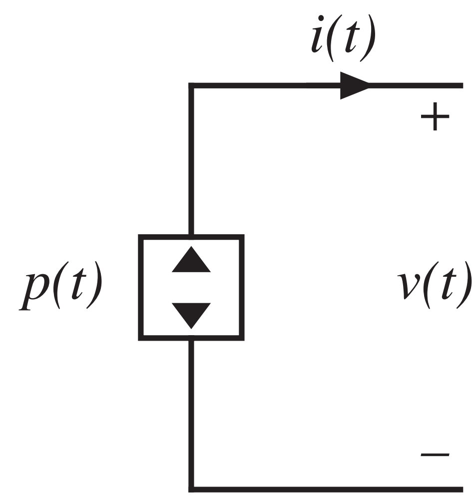


Output (diode) port

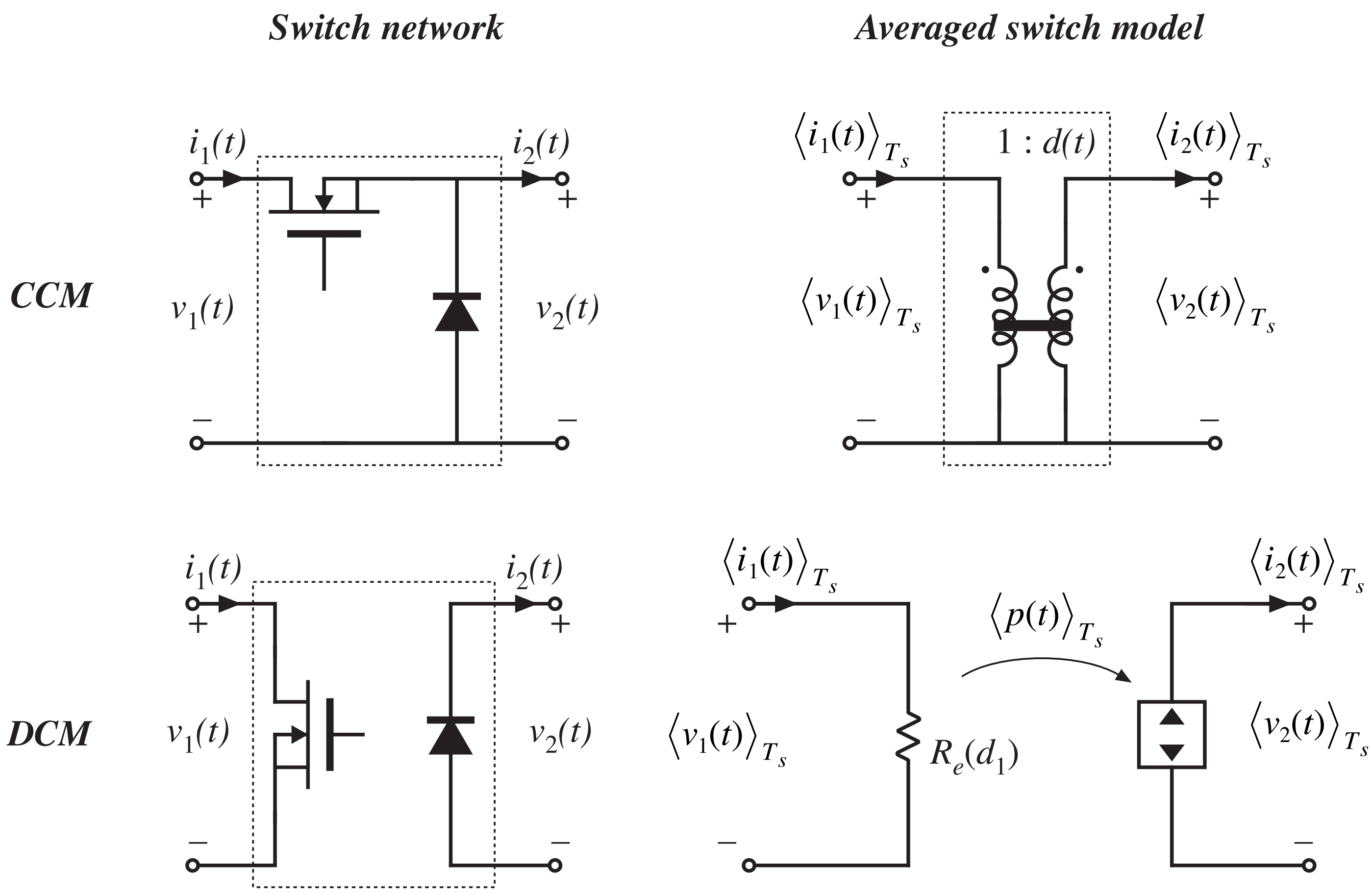
Averaged equivalent circuit

$$\left\langle i_2(t) \right\rangle_{T_s} = \frac{d_1^2(t)\, T_s}{2L} \frac{\left\langle v_1(t) \right\rangle_{T_s}^2}{\left\langle v_2(t) \right\rangle_{T_s}}$$

$$\left\langle i_2(t) \right\rangle_{T_s} \left\langle v_2(t) \right\rangle_{T_s} = \frac{\left\langle v_1(t) \right\rangle_{T_s}^2}{R_e(d_1)} = \left\langle p(t) \right\rangle_{T_s}$$



Averaged modeling of CCM and DCM switch networks



Spice model CCM-DCM1

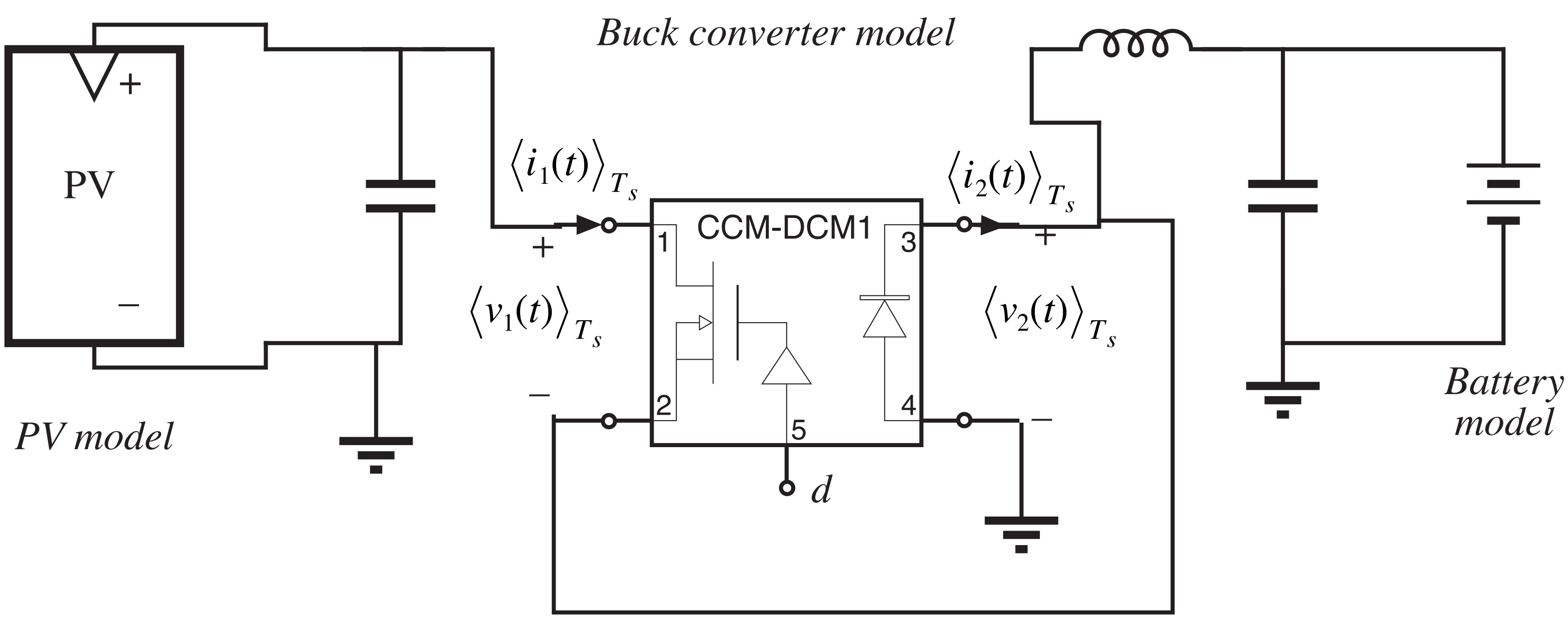
Combined CCM/DCM switch model

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

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

PSPICE 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 PSPICE model library elements are linked on course web page