ECEN 4517/5517

Power Electronics and Photovoltaic Power Systems Laboratory

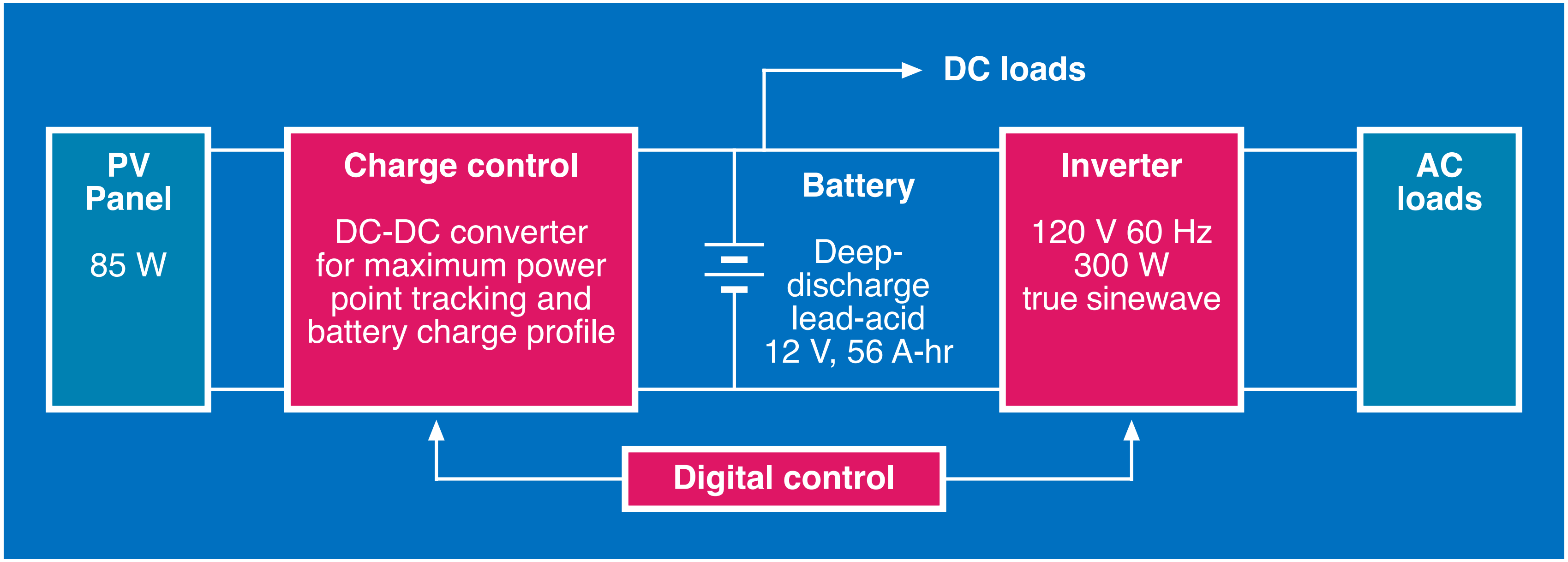
Lecture 4

Converter Modeling and Simulation

Announcements

- This week's lab: Continue Experiment 3-1
  - You have this and next week to finish Experiment 3-1
  - Get your converter running open-loop and take data outside
  - Next week finish Exp 3-1, including simulations
  - Exp 3-1 Lab Report due by 11:59 pm (MT) on Friday February 24, 2017
- After this: Experiment 3-2
  - Experiment 3-2 has a pre-lab (due 11:59 pm, Friday February 17, 2017)
  - Have 2 weeks to work on Experiment 3-2
  - Exp 3-2 Lab Report due by 11:59 pm (MT) on Friday March 10, 2017
- Following this: Experiment 4
  - Experiment 4 has a pre-lab (due 11:59 pm, Friday March 3, 2017)
  - Have 3 weeks to work on Experiment 4
  - Exp 4 Lab Report due by 11:59 pm (MT) on Friday April 7, 2017
- Quiz 1: Monday, February 27, 2017 (in class)

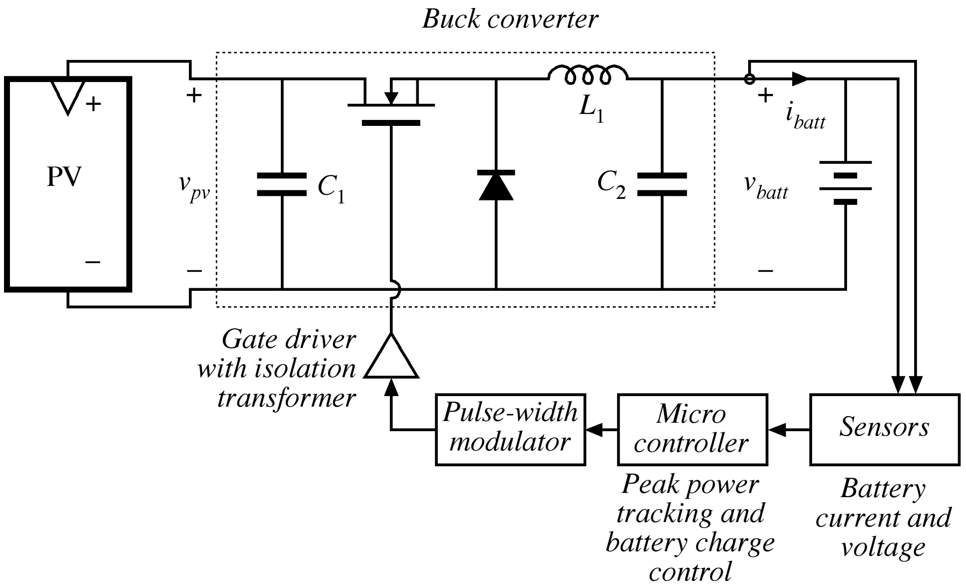
Experiments



- Exp 1 – PV panel and battery characteristics and direct energy transfer
- Exp 2 – TI MSP430 microcontroller introduction
- Exp 3-1, 3-2 – Buck dc-dc converter for PV MPPT and battery charge control
- Exp 4 – Step-up 12V-200V dc-dc converter
- Exp 5 – Single-phase dc-ac converter (inverter)
- Expo – Complete system demonstration

Experiments 3-1 and 3-2

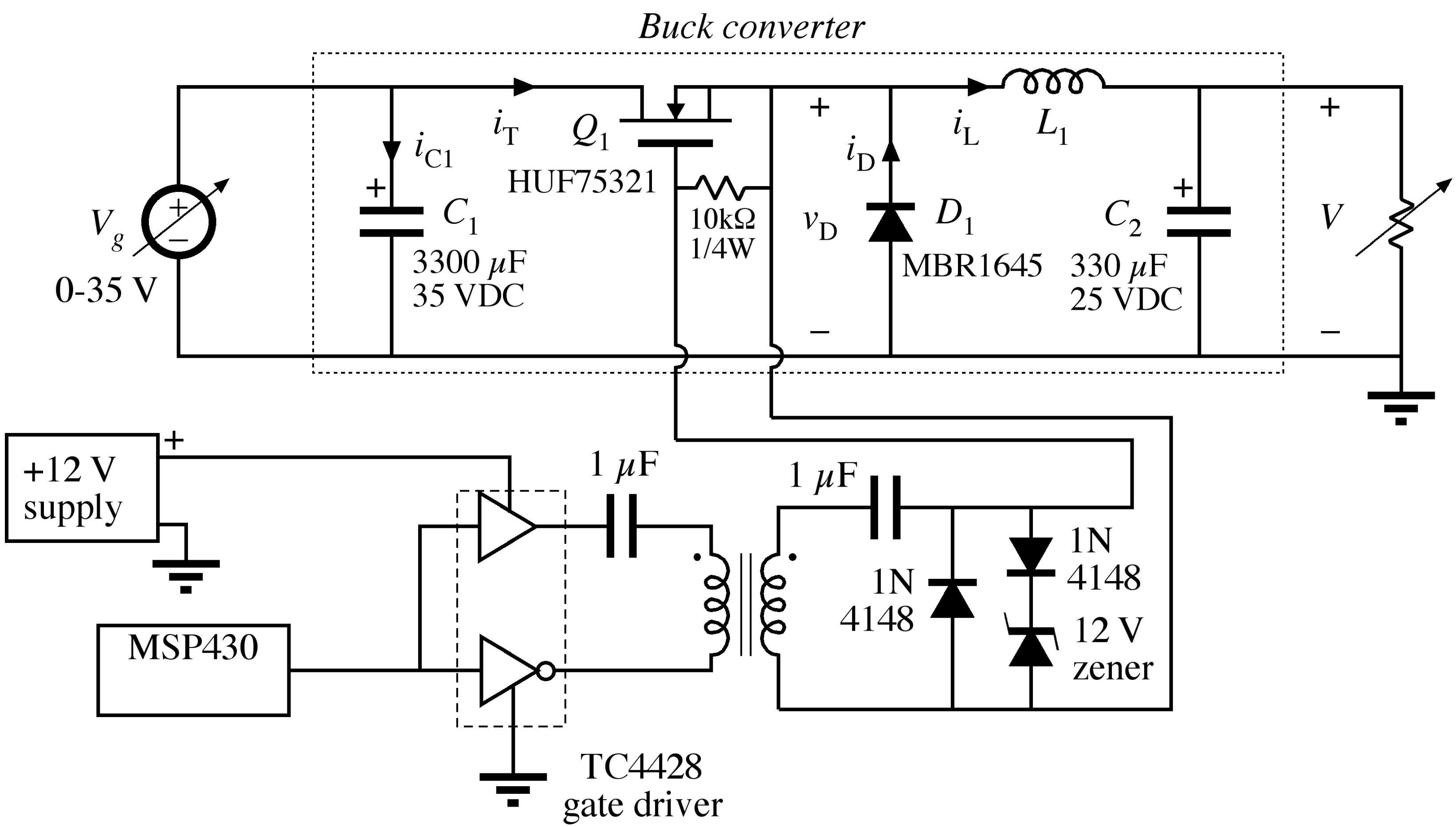
- Experiment 3-1
  - Demonstrate dc-dc converter power stage operating open loop, driven by MSP430 PWM output
  - Inside, with input power supply and resistive load
  - Outside, between PV panel and battery
  - DC system simulation



- Experiment 3-2
  - Demonstrate working sensor circuitry, interfaced to microprocessor
  - Demonstrate peak power tracker and battery charge controller algorithms, outside with converter connected between PV panel and battery

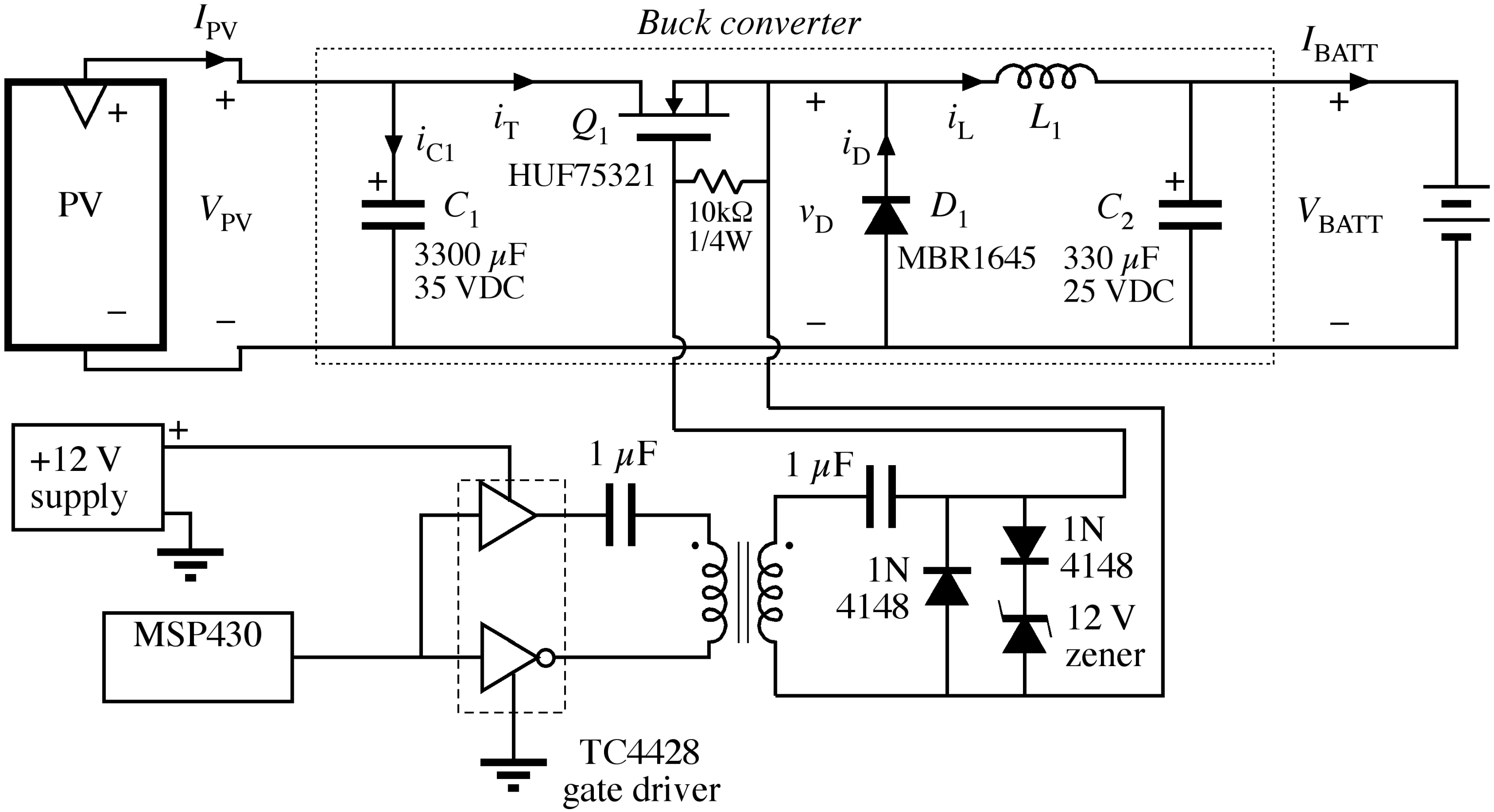
Experiments 3-1 Week 1

- Demonstrate dc-dc converter power stage inside



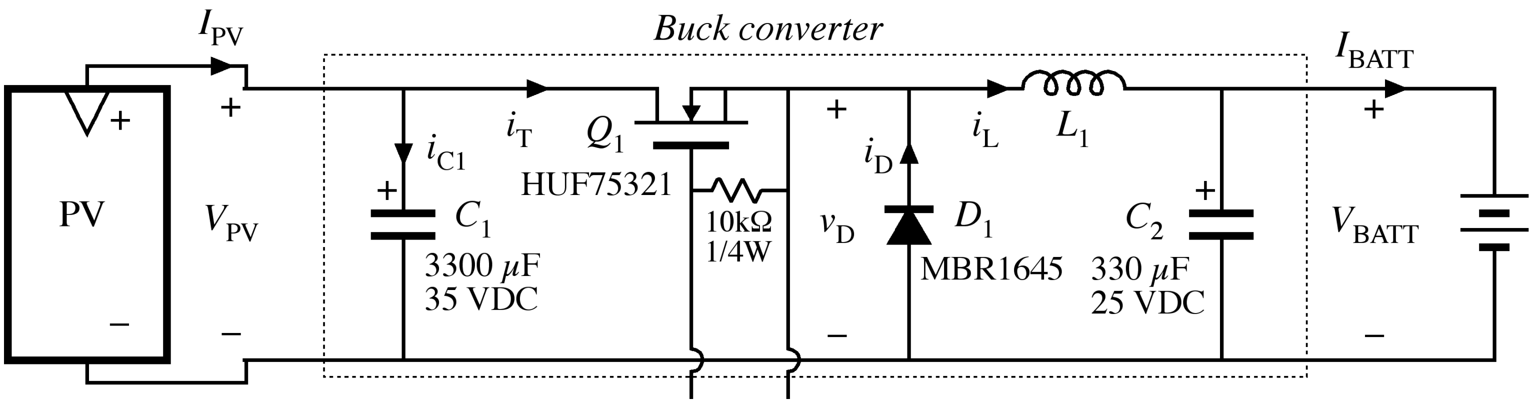
Experiments 3-1 Week 2

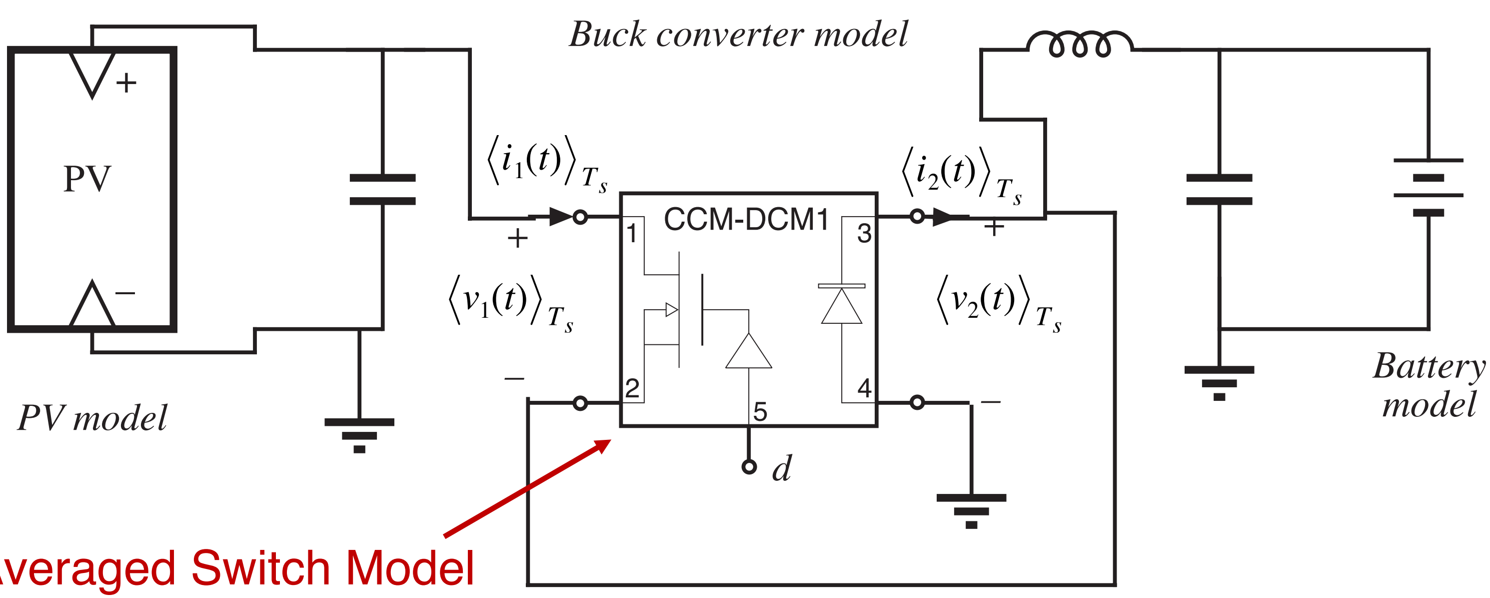
- Demonstrate dc-dc converter power stage outside



- Explore how duty ratio controls the PV and battery voltages and currents

Converter Modeling and Simulation



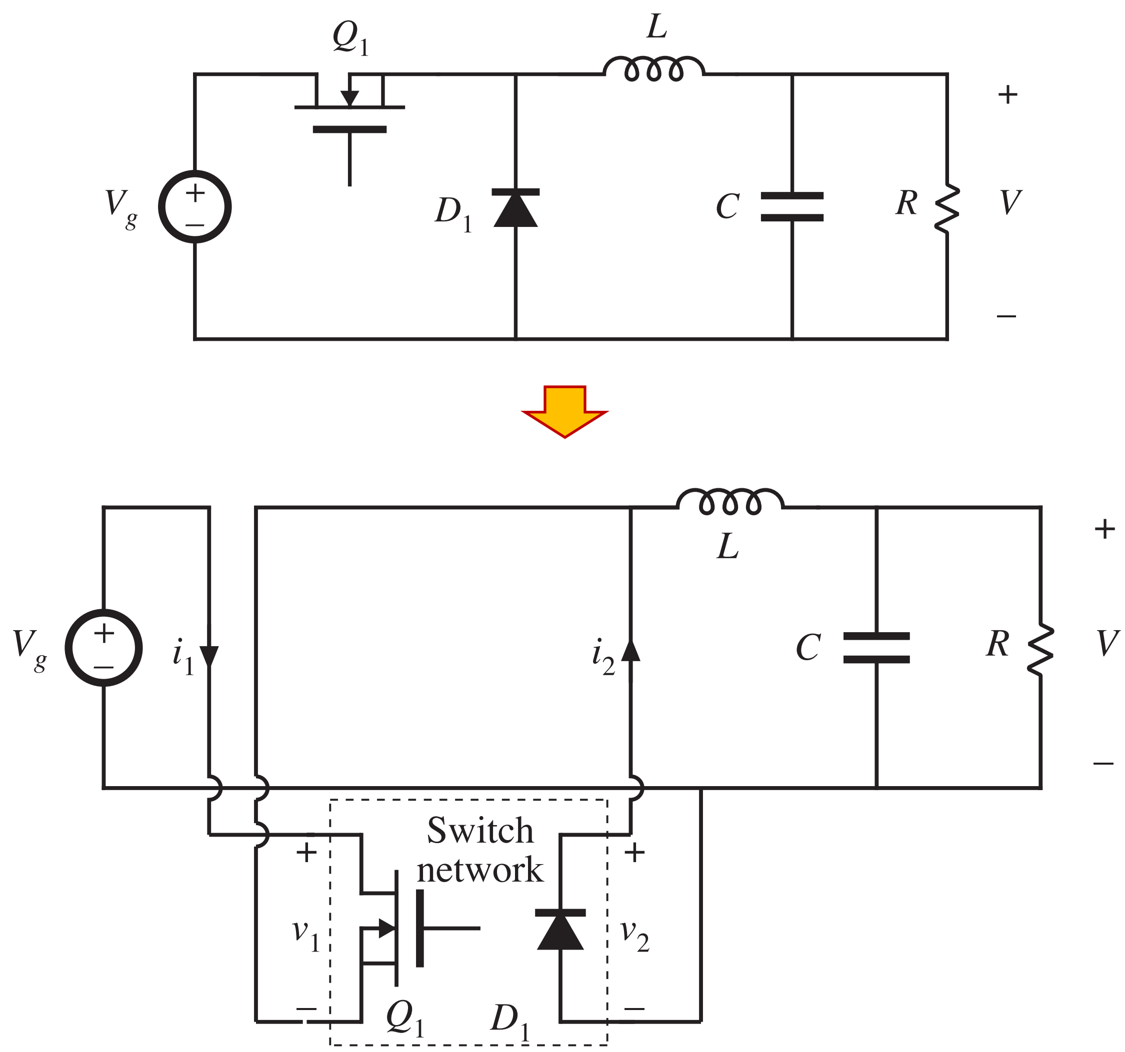


Averaged Switch Model

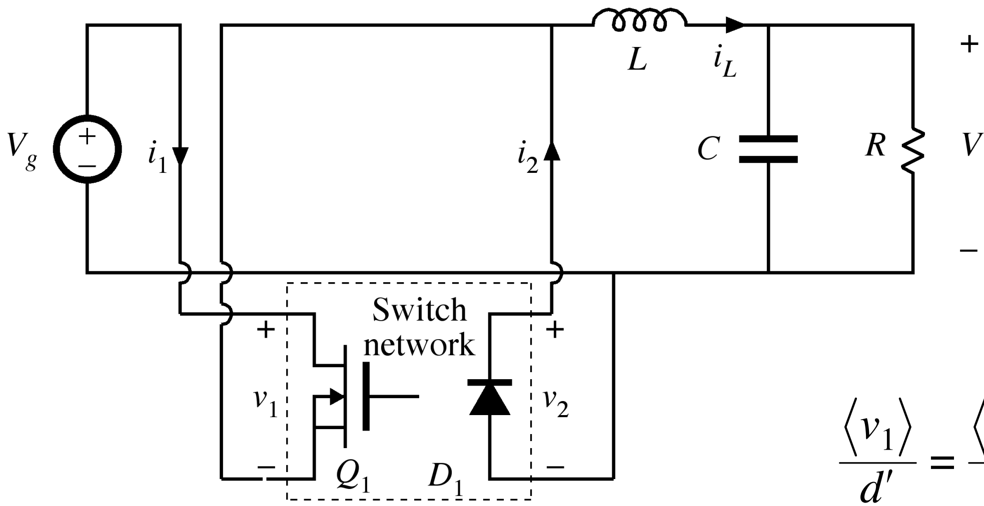
Average Switch Modeling

- Separate the switching elements from the remainder of the converter
- Define the terminal voltages and currents of the two-port switch network
- Derive relationships between the local average values of the switch network terminal voltages and currents

Example: Buck Converter



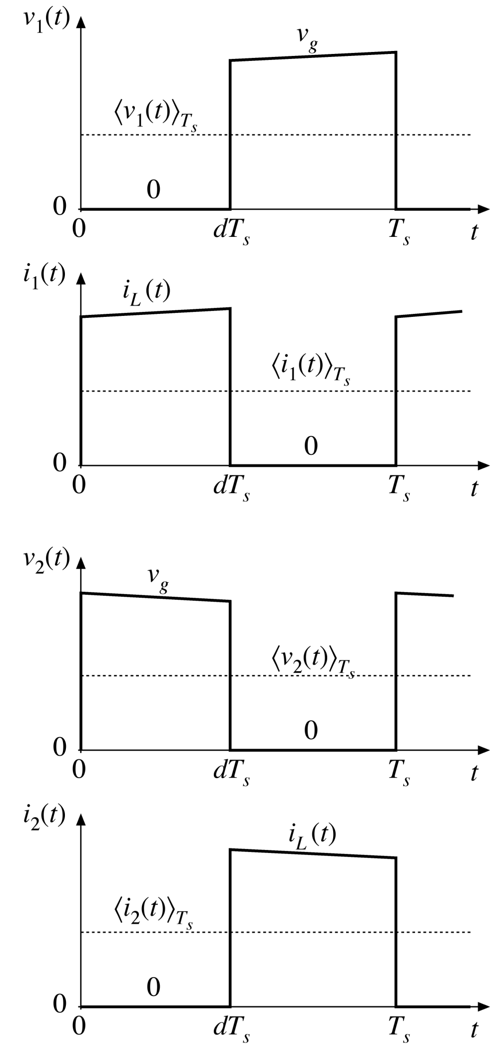
Average Switch Modeling in CCM



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

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

Continuous Conduction Mode (CCM) Operation



Relationship between average terminal waveforms:

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

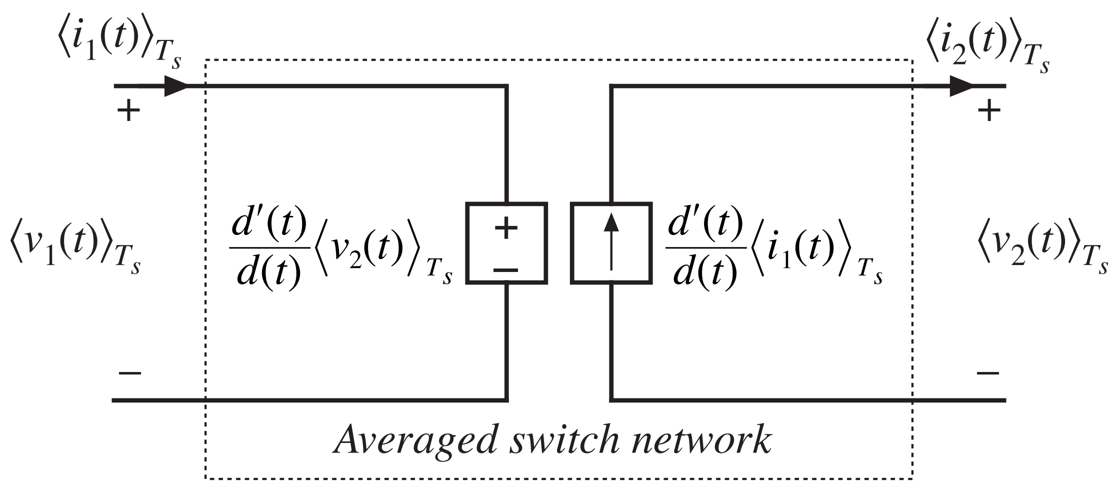
$$\langle i_2(t) \rangle_{T_s} = \frac{d'(t)}{d(t)} \langle i_1(t) \rangle_{T_s}$$

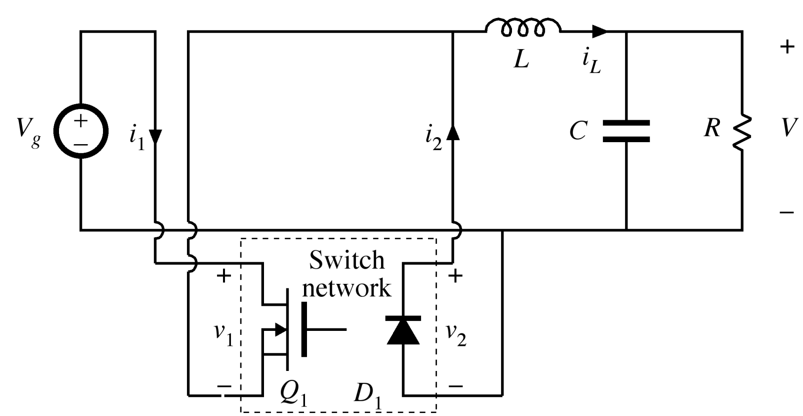
Averaged Model of Switch Network under CCM

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

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

Can model the switch network via averaged dependent sources



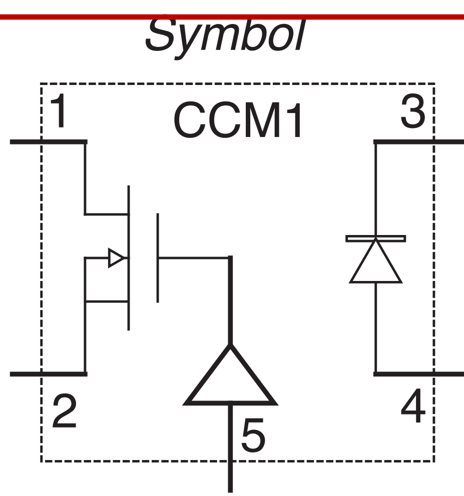


Averaged Switch Model in SPICE

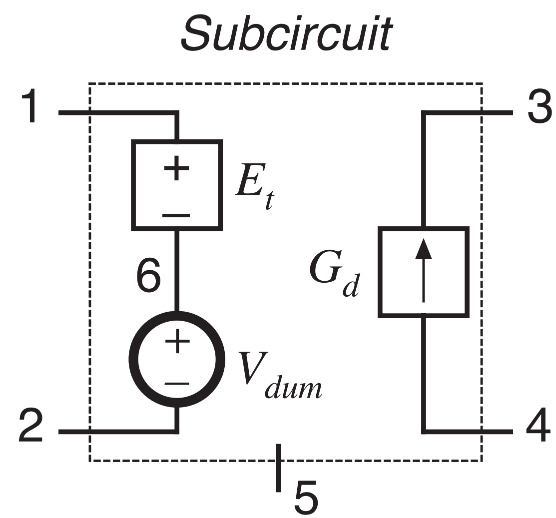
- We will use LTspice (a free version of SPICE) as the circuit simulator

```
.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
```

This CCM averaged switch model is available inside SPICE Library file switch.lib

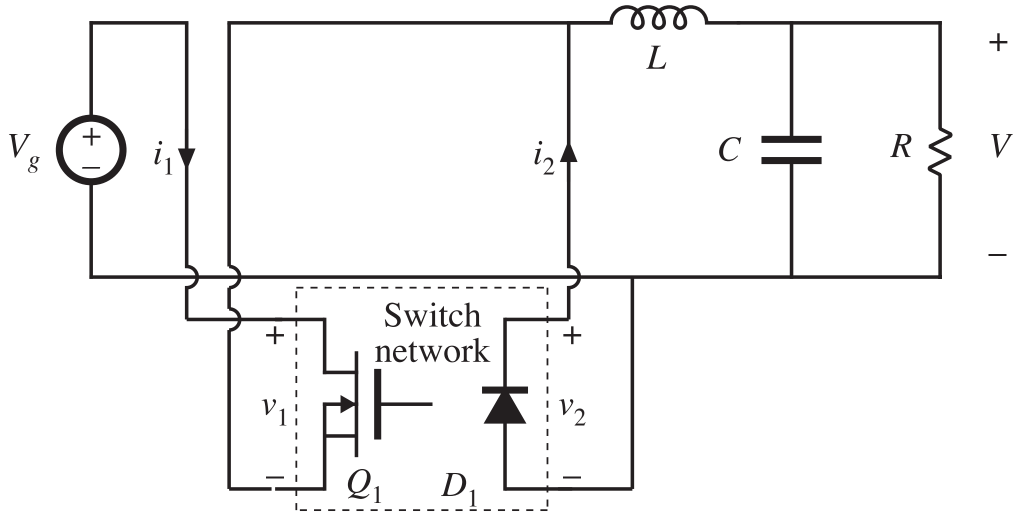


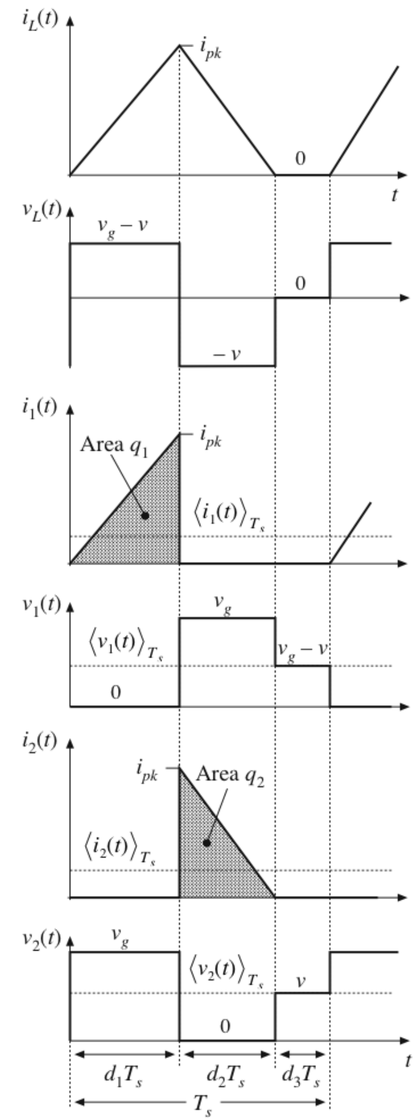
LTspice Symbol



Subcircuit

Average Switch Modeling in DCM

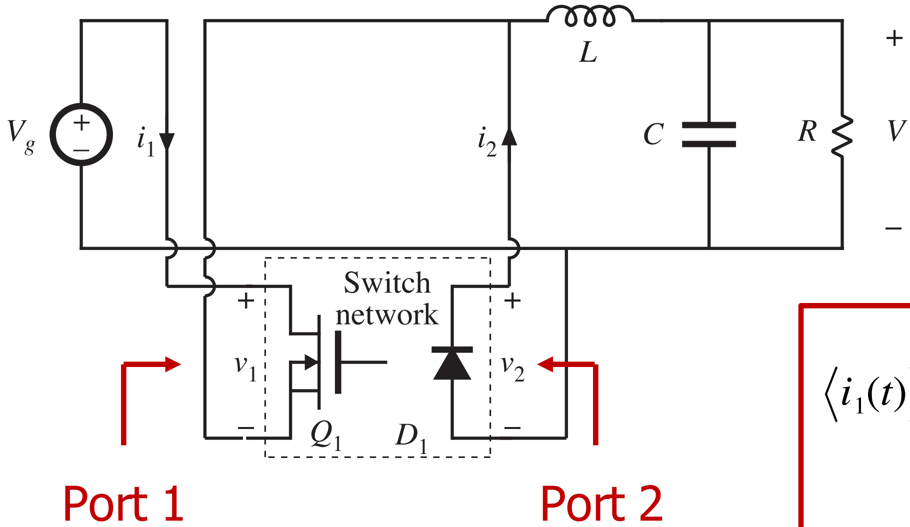


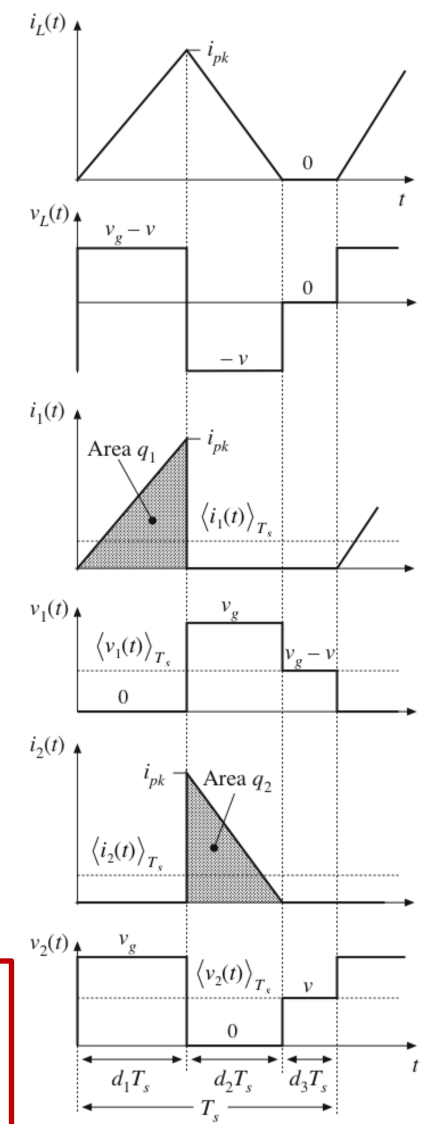


Discontinuous Conduction Mode (DCM) Operation

- Again find average values of switch network terminal voltages and currents
- Eliminate variables external to the switch network

Average Switch Modeling in DCM





Port 1

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

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

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

Port 2

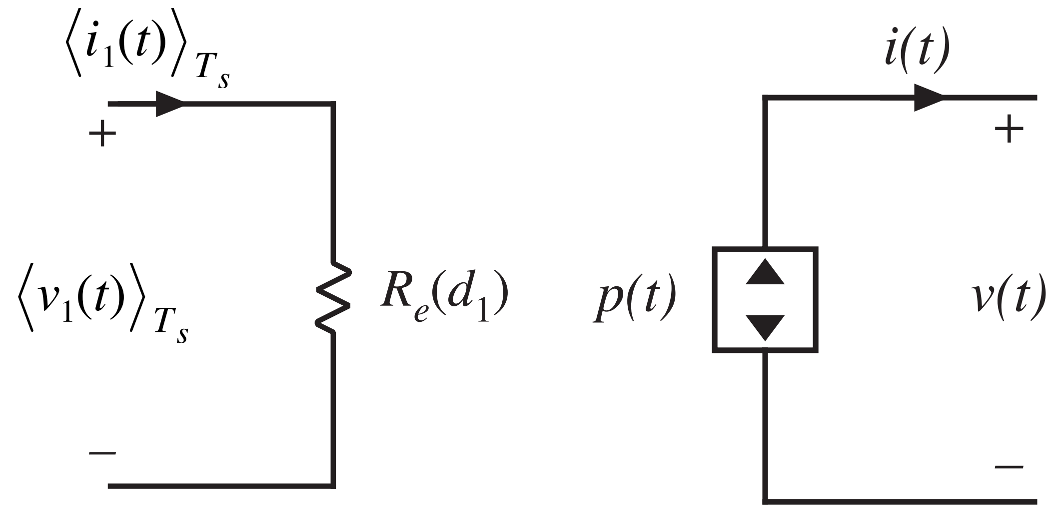
$$\left\langle i_2(t) \right\rangle_{T_s} \left\langle v_2(t) \right\rangle_{T_s} = \frac{\left\langle v_1(t) \right\rangle_{T_s}^2}{R_e(d_1)} = \left\langle p(t) \right\rangle_{T_s} \Rightarrow \left\langle i_2(t) \right\rangle_{T_s} = \frac{d_1^2(t)\, T_s}{2L} \frac{\left\langle v_1(t) \right\rangle_{T_s}^2}{\left\langle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

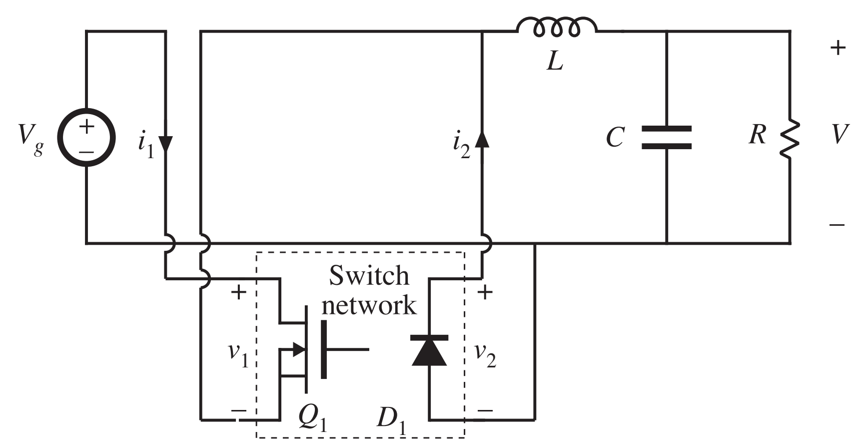
Averaged Model of Switch Network under DCM

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

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

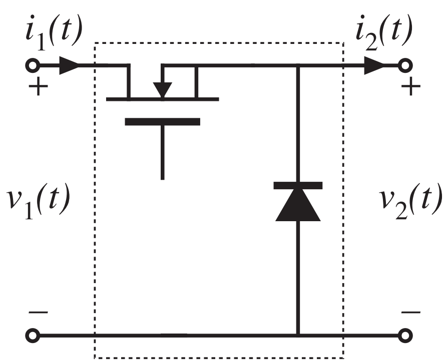
$$\left\langle i_2(t) \right\rangle_{T_s} \left\langle v_2(t) \right\rangle_{T_s} = \frac{\left\langle v_1(t) \right\rangle_{T_s}^2}{R_e(d_1)} = \left\langle p(t) \right\rangle_{T_s}$$



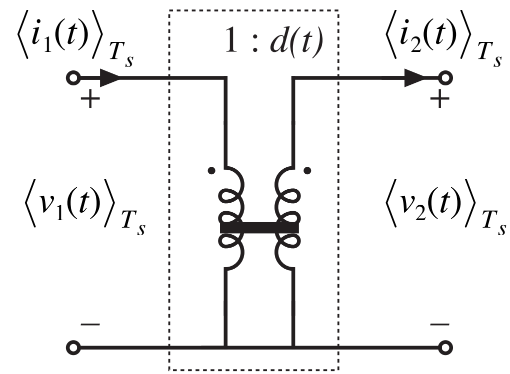


Summary of Averaged Switch Models

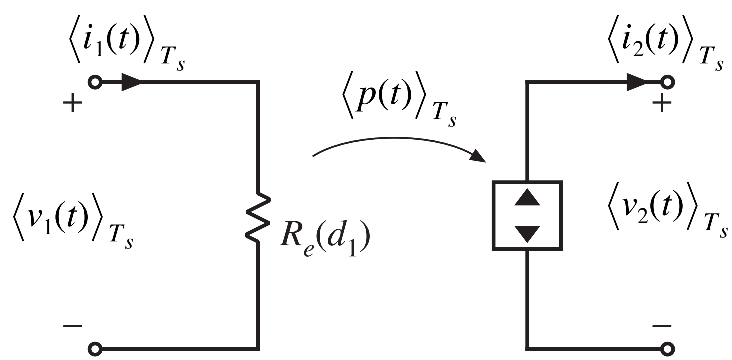
Switch Network



Averaged Switch Models



CCM



DCM

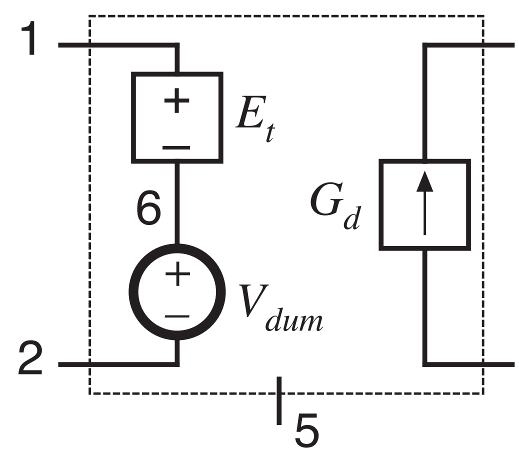
SPICE Model CCM-DCM1

```
**********************************************************
* 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={MIN((1-v(5))*v(v2)/v(5), i(Va)*2*L/(V(5)*V(5))*fs)}
Gd 4 3 value={MIN((1-v(5))*i(Va)/v(5), i(Va)*i(Va)*2*L*fs/(V(5)*V(5)*V(v2)))}
Ga 0 a value={MAX(i(Et),0)}
Va a b
Ra b 0 10k
Ef v2 0 value={MAX(V(3,4),0)}
Rb v2 0 1k
.ends
*$
**********************************************************
```

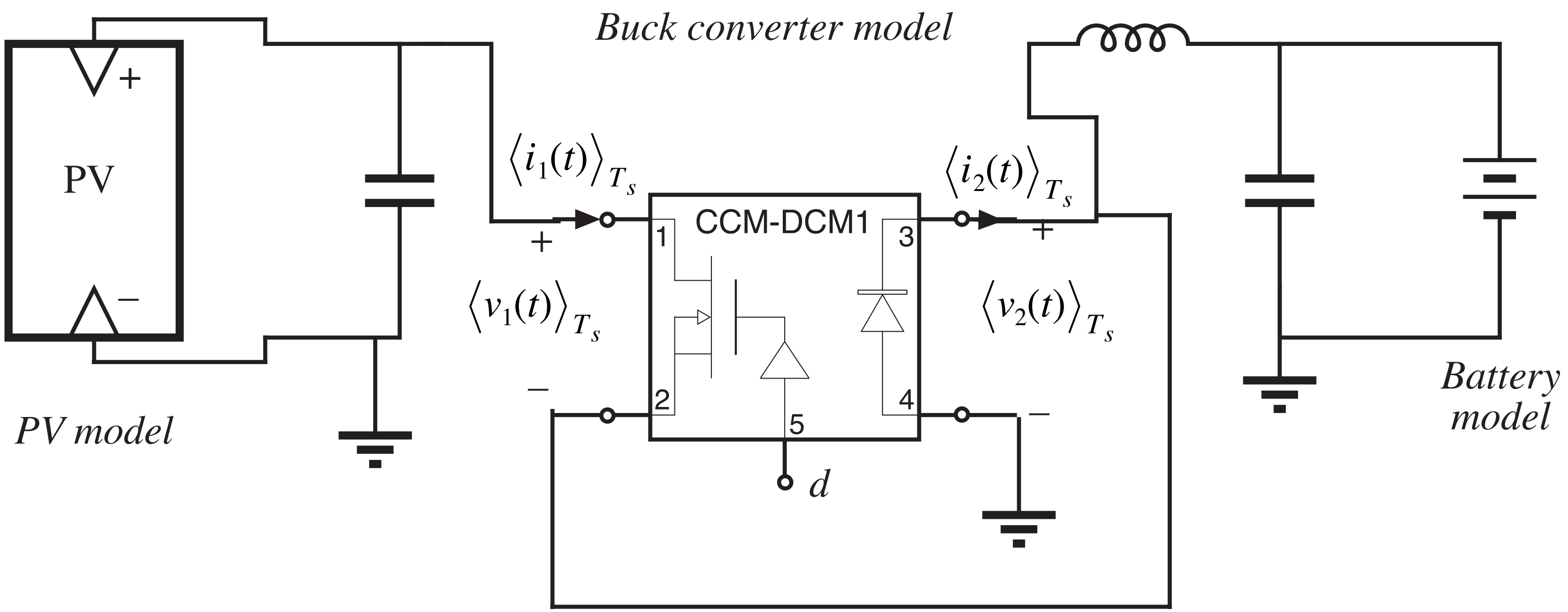
Combined CCM/DCM switch model available inside switch.lib

This averaged model automatically switches between CCM and DCM as necessary

Subcircuit



Simulation of Buck Converter in SPICE



- Replace buck converter switches with averaged switch model CCM-DCM1
- CCM-DCM1 and other SPICE model library elements are available from: http://ecee.colorado.edu/ecen4517/pspicelib/index.html
- Use your PV model from Experiment 1

Frequency Response (AC Analysis) in SPICE

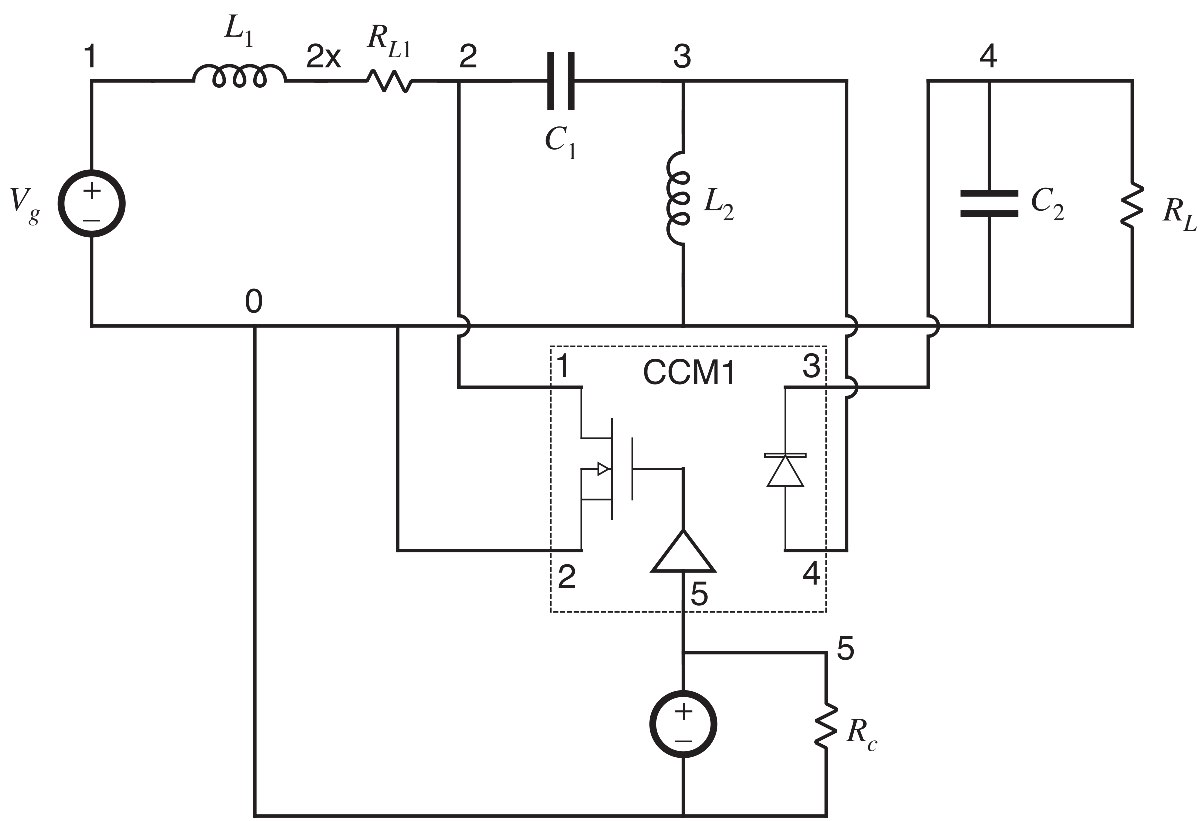
- Given a nonlinear time-invariant circuit, as on the previous slide, SPICE can automatically perturb, linearize, and plot small-signal ac transfer functions
  - Use DC sources to set up the correct quiescent operating conditions
  - Include an AC source having amplitude 1

- When you 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

SEPIC Frequency Response Example

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 of SEPIC in SPICE

Magnitude

Phase