Power Converter Simulation

ECE 482 Lecture 6
January 27, 2014

Announcements

- Lab report 1 due today
- This week: Continue Experiment 2
  - Boost open-loop construction and modeling

Analytical Loss Modeling

- High efficiency approximation is acceptable for hand calculations, as long as it is justified
  - Solve waveforms of lossless converter, then calculate losses
- Alternate approach: average circuit
  - Uses average, rather than RMS currents
  - Difficult to include losses other than conduction
- Argue which losses need to be included, and which may be neglected

Power Stage Losses

	MOSFETS	IGBTs	Diodes	Inductor	Capacitors
Conduction Losses	• R_{on}	• r_{ce} • V_{ce}	• V_F • R_d	• R_{dc}	• ESR
Frequency-Dependent Losses	• C_{oss}	• Current tailing	• C_d • Reverse-Recovery	• Skin Effect • Core Loss • Fringing • Proximity	• Dielectric Losses

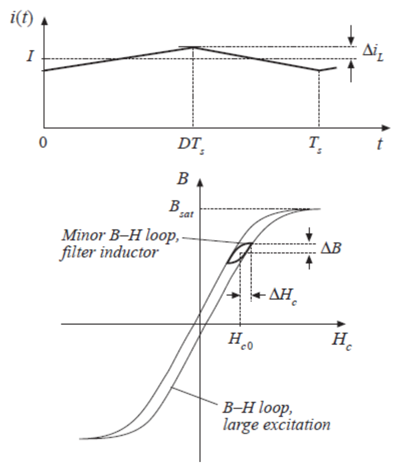
Inductor Core Loss

- Governed by Steinmetz Equation:

$$P_v = K_{fe} f_s^{\alpha} (\Delta B)^{\beta} \quad [\text{mW/cm}^3]$$

- Parameters K_{fe}, α, and β extracted from manufacturer data
- $\Delta B \propto \Delta i_L$ → small losses with small ripple

$$P_{fe} = P_v A_c l_m \text{ [mW]}$$



Steinmetz Parameter Extraction

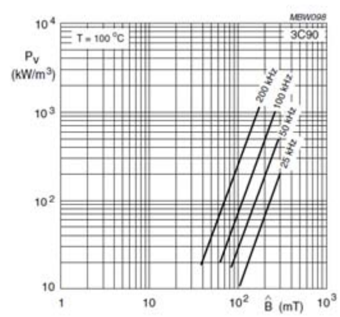


Fig.6 Specific power loss as a function of peak flux density with frequency as a parameter.

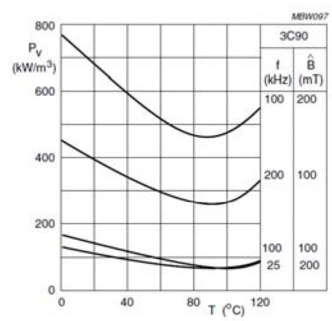
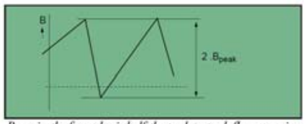


Fig.7 Specific power loss for several frequency/flux density combinations as a function of temperature.

Ferroxcube Curve Fit Parameters



B_{peak} *in the formulas is half the peak to peak flux excursion in the core.*

Power losses in our ferrites have been measured as a function of frequency (f in Hz), peak flux density (B in T) and temperature (T in °C). Core loss density can be approximated (2) by the following formula :

$$P_{core} = C_m \cdot f^{x} \cdot B_{peak}^{y} \cdot (ct_0 - ct_1 T + ct_2 T^2) \quad [3]$$

$$= C_m \cdot C_T \cdot f^{x} \cdot B_{peak}^{y} \quad [\text{mW/cm}^3]$$

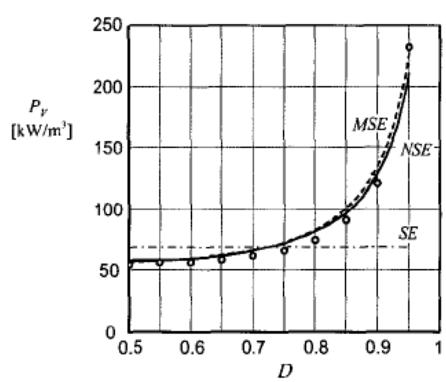
ferrite	f (kHz)	Cm	x	y	ct_2	ct_1	ct_0
3C30	20-100	$7.13.10^{-3}$	1.42	3.02	$3.65.10^{-4}$	$6.65.10^{-2}$	4
	100-200	$7.13.10^{-3}$	1.42	3.02	4.10^{-4}	$6.8 .10^{-2}$	3.8
3C90	20-200	$3.2.10^{-3}$	1.46	2.75	$1.65.10^{-4}$	$3.1.10^{-2}$	2.45
3C94	20-200	$2.37.10^{-3}$	1.46	2.75	$1.65.10^{-4}$	$3.1.10^{-2}$	2.45
	200-400	2.10^{-9}	2.6	2.75	$1.65.10^{-4}$	$3.1.10^{-2}$	2.45
3F3	100-300	$0.25.10^{-3}$	1.63	2.45	$0.79.10^{-4}$	$1.05.10^{-2}$	1.26
	300-500	2.10^{-5}	1.8	2.5	$0.77.10^{-4}$	$1.05.10^{-2}$	1.28
	500-1000	$3.6.10^{-9}$	2.4	2.25	$0.67.10^{-4}$	$0.81.10^{-2}$	1.14
3F4	500-1000	12.10^{-4}	1.75	2.9	$0.95.10^{-4}$	$1.1.10^{-2}$	1.15
	1000-3000	$1.1.10^{-11}$	2.8	2.4	$0.34.10^{-4}$	$0.01.10^{-2}$	0.67

Table 1: Fit parameters to calculate the power loss density

NSE/iGSE

- More complex empirical loss models exist, and remain valid for non-sinusoidal waveforms
- NSE/iGSE:

$$P_{NSE} = \left(\frac{\Delta B}{2}\right)^{\beta-\alpha} \frac{k_N}{T} \int_0^T \left|\frac{dB}{dt}\right|^{\alpha} dt$$



NSE/iGSE Shortcut for Squarewaves

- For square wave excitation, the improved loss model can be reduced to:

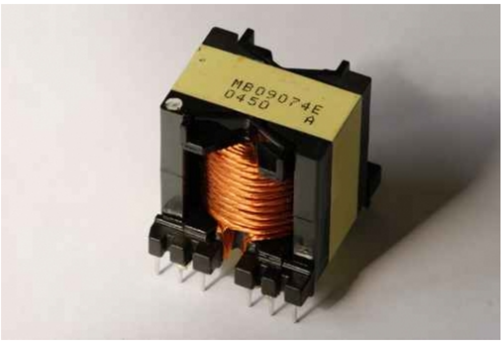
$$k_N = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos\theta|^\alpha d\vartheta} \quad (8)$$

$$P_{NSE} = k_N \ f^\alpha (\Delta B)^\beta \left(\left(\frac{2}{D}\right)^\alpha + \left(\frac{2}{1-D}\right)^\alpha (1-D) \right) \quad (9)$$

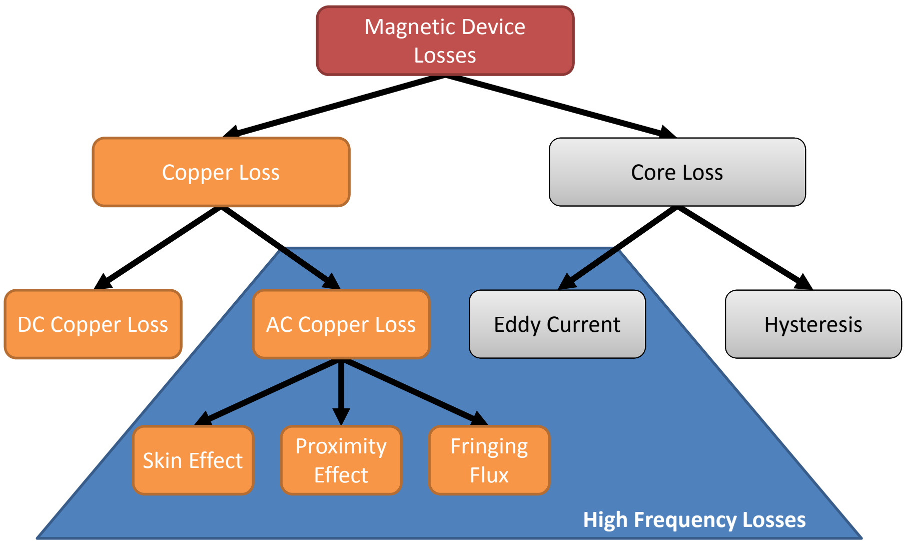
- Full Paper included on materials page of website

Van den Bossche, A.; Valchev, V.C.; Georgiev, G.B.; , "Measurement and loss model of ferrites with non-sinusoidal waveforms," *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual* , vol.6, no., pp. 4814- 4818 Vol.6, 20-25 June 2004 doi: 10.1109/PESC.2004.1354851

Inductor Design



Magnetics Losses



K_g and K_{gfe} Methods

- Two closed-form methods to solve for the optimal inductor design *under certain constraints/assumptions*
- Neither method considers losses other than DC copper and (possibly) steinmetz core loss
- Both methods particularly well suited to spreadsheet/iterative design procedures

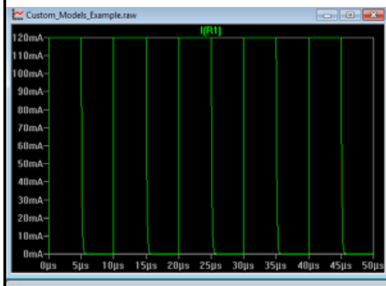
	K_g	K_{gfe}
Losses	DC Copper (specified)	DC Copper, SE Core Loss (optimized)
Saturation	Specified	Checked After
B_{max}	Specified	Optimized

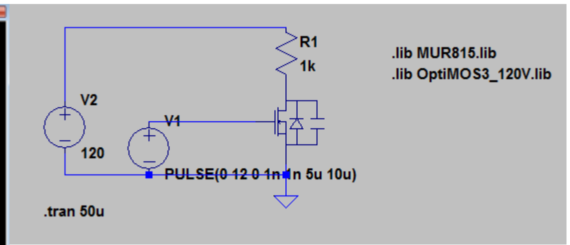
Simulation Modeling

Circuit Simulation

- Matlab, Simulink, LTSpice
  - Other tools accepted, but not supported
- Choose model type (switching, averaged, dynamic)
- Supplement analytical work rather than repeating it
- Show results which clearly demonstrate what matches and what does not with respect to experiments (i.e. ringing, slopes, etc.)

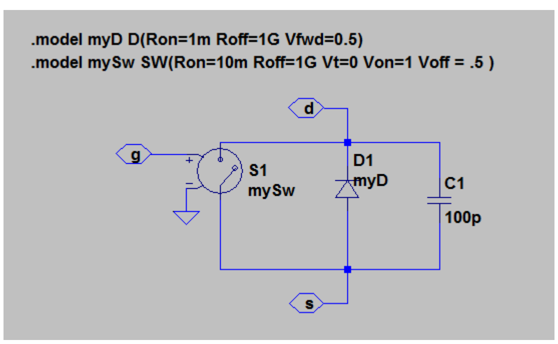
LTSpice Modeling Examples





- Example files added to course materials page

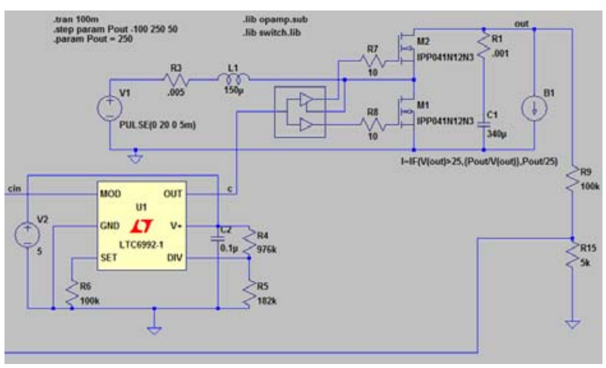
Custom Transistor Model



Manufacturer Device Model

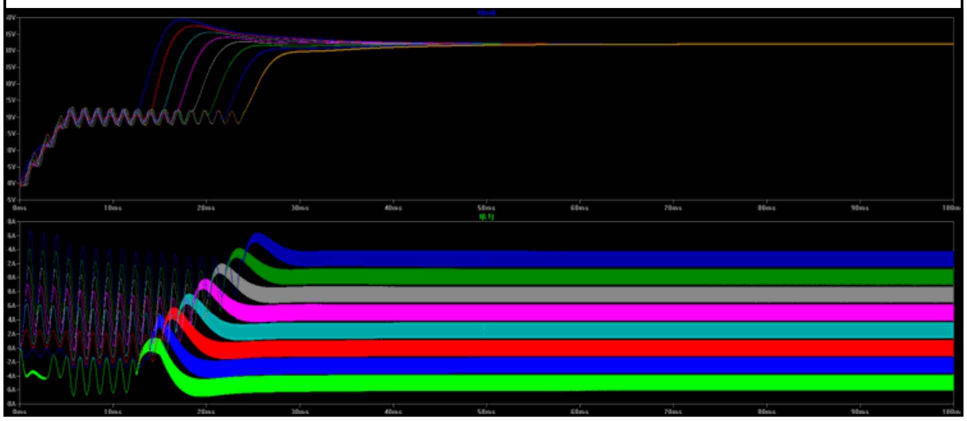
- Text-only netlist model of device including additional parasitics and temperature effects
- May slow or stop simulation if timestep and accuracy are not adjusted appropriately

Full Switching Simulation



Switching Model Simulation Results

- Simulation Time ≈ 15 minutes



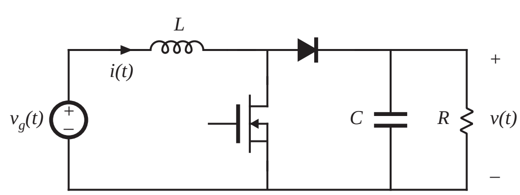
Full Switching Model

- Gives valuable insight into circuit operation
  - Understand expected waveforms
  - Identify discrepancies between predicted and experimental operation
- Slow to simulate; significant high frequency content
- Cannot perform AC analysis

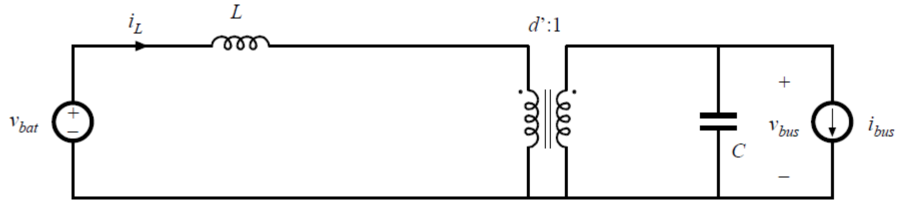
Averaged Switch Modeling: Motivation

- A *large-signal, nonlinear* model of converter is difficult for hand analysis, but well suited to simulation across a wide range of operating points
- Want an *averaged* model to speed up simulation speed
- Also allows linearization (AC analysis) for control design

Nonlinear, Large-Signal Equations



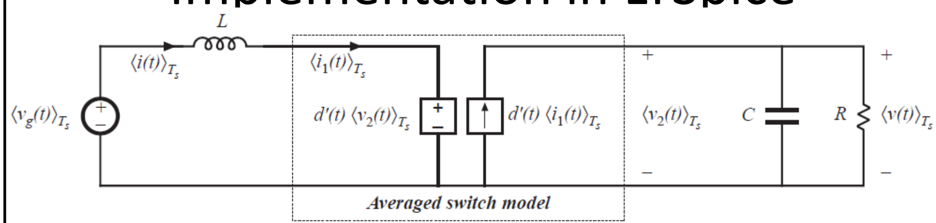
Nonlinear, Averaged Circuit

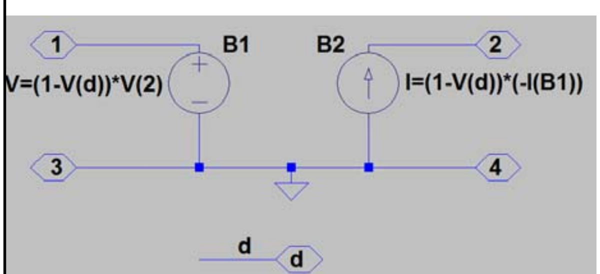


$$L\frac{d\langle i_L\rangle}{dt}=\langle v_{bat}\rangle-(1-d)\langle v_{bus}\rangle$$

$$C\frac{d\langle v_{bus}\rangle}{dt}=(1-d)\langle i_L\rangle-\langle i_{bus}\rangle$$

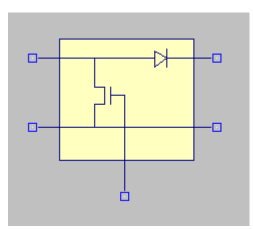
Implementation in LTSpice





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

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

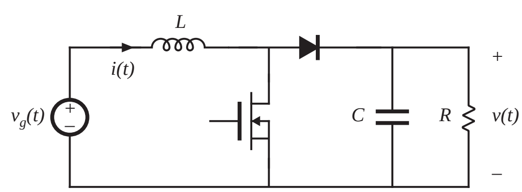


Circuit Averaging and Averaged Switch Modeling

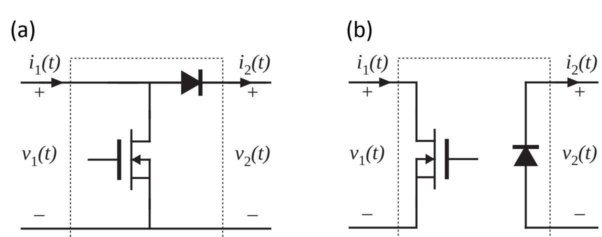
- Historically, circuit averaging was the first method known for modeling the small-signal ac behavior of CCM PWM converters
- It was originally thought to be difficult to apply in some cases
- There has been renewed interest in circuit averaging and its corrolary, averaged switch modeling, in the last two decades
- Can be applied to a wide variety of converters
  - We will use it to model DCM, CPM, and resonant converters
  - Also useful for incorporating switching loss into ac model of CCM converters
  - Applicable to 3ø PWM inverters and rectifiers
  - Can be applied to phase-controlled rectifiers
- Rather than averaging and linearizing the converter state equations, the averaging and linearization operations are performed directly on the converter circuit

Boost converter example

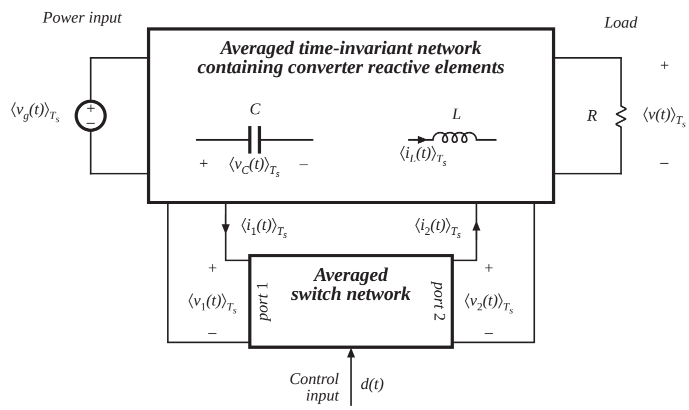
Ideal boost converter example



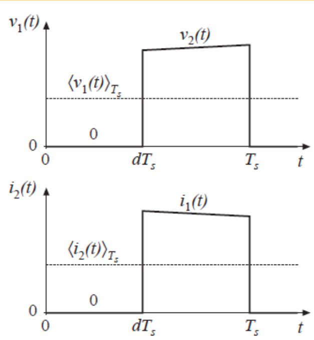
Two ways to define the switch network



Circuit Averaging



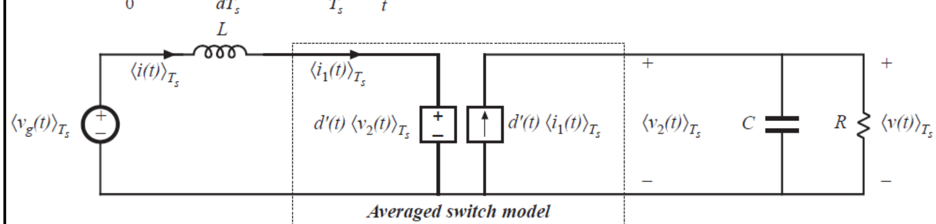
Compute average values of dependent sources



Average the waveforms of the dependent sources:

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

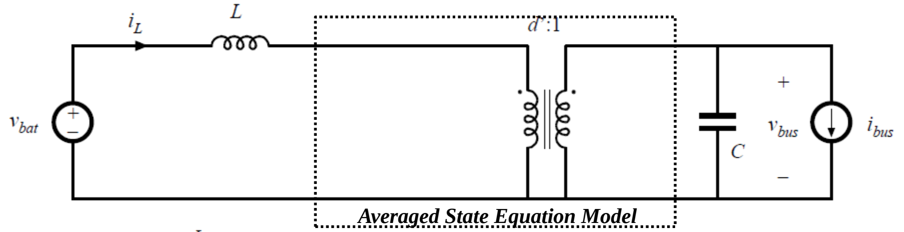
$$\left\langle i_2(t) \right\rangle_{T_s} = d'(t) \left\langle i_1(t) \right\rangle_{T_s}$$

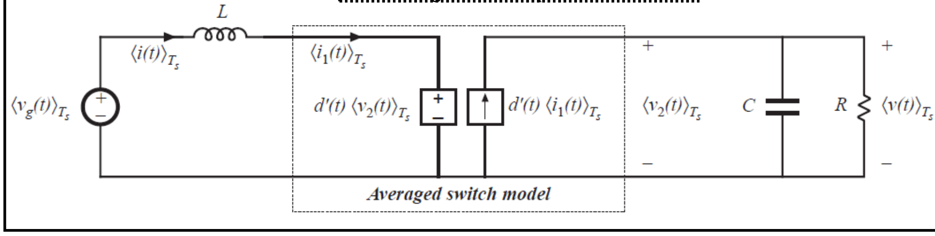


Summary: Circuit averaging method

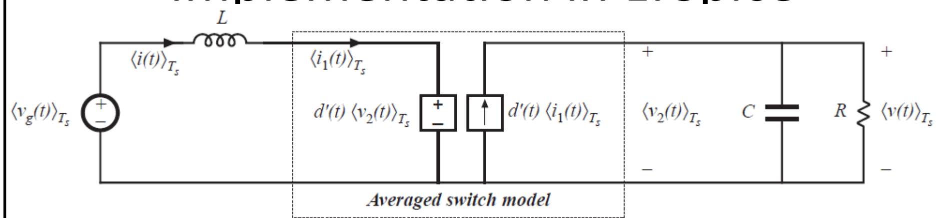
Model the switch network with equivalent voltage and current sources, such that an equivalent time-invariant network is obtained

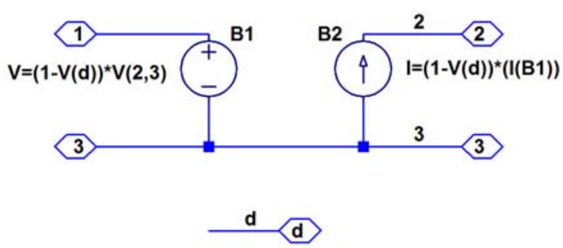
Average converter waveforms over one switching period, to remove the switching harmonics



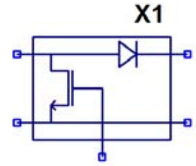


Implementation in LTSpice

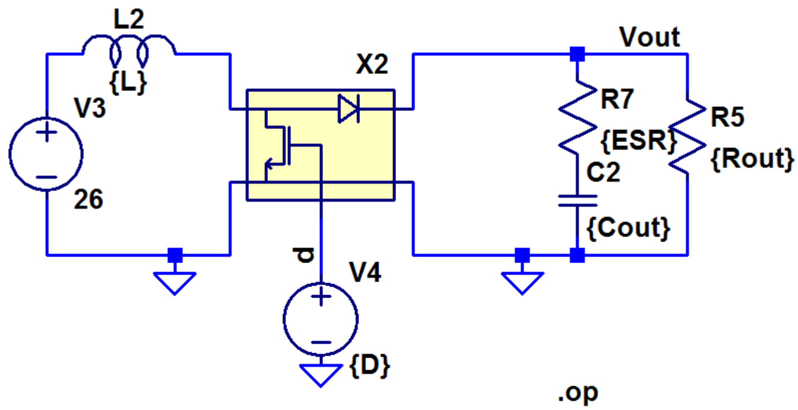




$$\langle v_1(t)\rangle_{T_s} = d'(t)\,\langle v_2(t)\rangle_{T_s}$$
$$\langle i_2(t)\rangle_{T_s} = d'(t)\,\langle i_1(t)\rangle_{T_s}$$

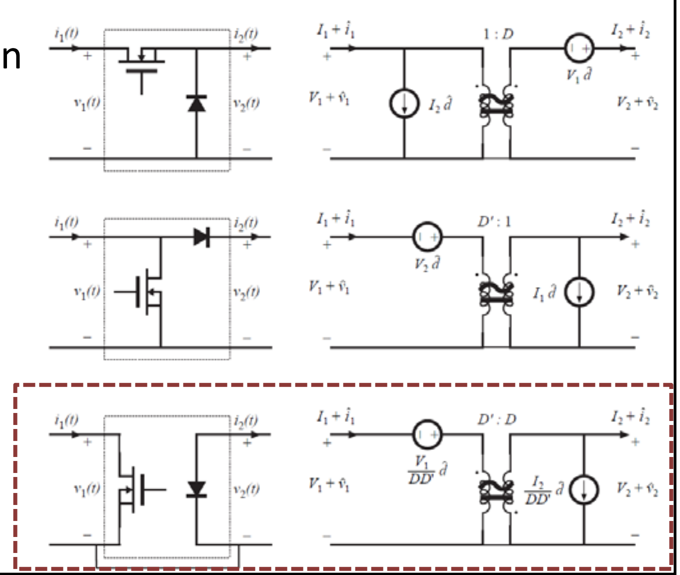


Averaged Switch Model



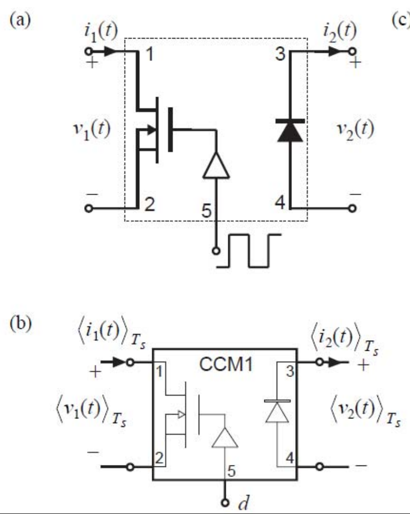
Three Basic Switch Cells

- Can perturb an linearize as normal for linear SSM
- Most general switch cell is included in library file, switch.lib



Switch.lib CCM1 Model

Generalized Equations: $\langle v_1(t)\rangle_{T_s} = \frac{d'(t)}{d(t)}\langle v_2(t)\rangle_{T_s}$ $\langle i_2(t)\rangle_{T_s} = \frac{d'(t)}{d(t)}\langle i_1(t)\rangle_{T_s}$



(c)

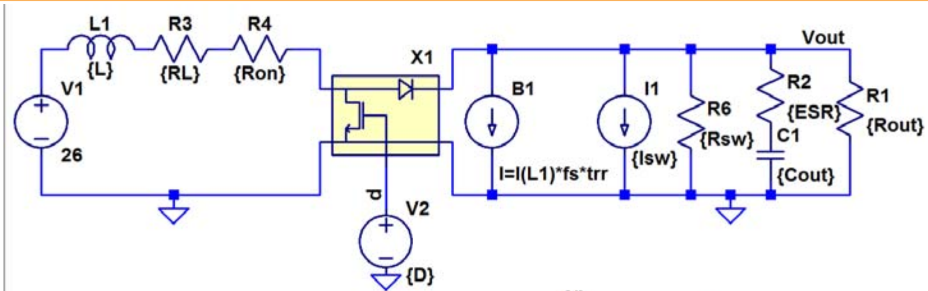
```
***************************************************************
* Subcircuit: CCM1
* Application: two-switch PWM converters
* Limitations: ideal switches, CCM only, no transformer
***************************************************************
* Parameters: none
***************************************************************
* Nodes:
* 1: transistor positive (drain for an n-channel MOS)
* 2: transistor negative  (source for an n-channel MOS)
* 3: diode cathode
* 4: diode anode
* 5: duty cycle control input
***************************************************************
.subckt CCM1 1  2  3  4  5
Et 1 2 value={(1-v(5))*v(3,4)/v(5)}
Gd 4 3 value={(1-v(5))*i(Et)/v(5)}
.ends
***************************************************************
```

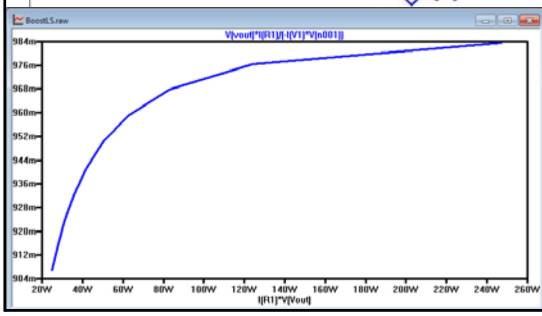
Fig. B.1 Averaged switch model CCM1: (a) the general two-switch network: (b) symbol for the averaged switch subcircuit model; (c) PSpice netlist of the subcircuit.

Averaged Switch Modeling: Further Comments

- Model is slightly different but can be produced in same manner for
  - Inclusion of loss models
  - Transformer isolated converters
  - Converters in DCM
- See book appendix B.2 for further notes

Averaged Model With Losses





.op
.param Rout = 10
.step param Rout 10 100 10

What known error will be present in loss predictions with this model?