# 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

| | | |
|---|---|---|
| 8. Jan. 27<br>Simulation of Power Converters<br>Lecture 5 handout slides<br>Experiment 1 Report due | 9. Jan. 29<br>Lab 2 (cont): Steady-State Modeling and Efficiency Analysis of Boost Converter | Jan. 31<br>Average Current Mode Control |
| 10. Feb. 3<br>Feedback Loop Design | 11. Feb. 5<br>Lab 3: Closed-Loop Operation of Boost Converter<br>Prelab 3 due | Feb. 7<br>Experiment 2 Report Due |

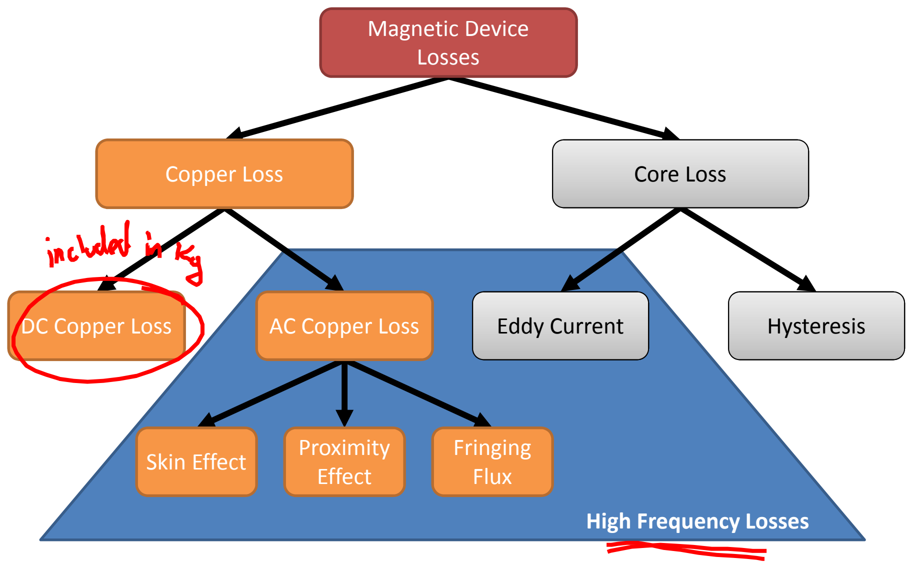
## Analytical Loss Modeling

- 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 | • $R_{on}$ | • $r_{ce}$<br>• $V_{ce}$ | • $V_F$<br>• $R_d$ | • $R_{dc}$ | • ESR |
| Frequency-Dependent Losses | • $C_{oss}$ | • Current tailing | • $C_d$<br>• Reverse-Recovery | • Skin Effect<br>• Core Loss<br>• Fringing<br>• Proximity | • Dielectric Losses |

# Magnetics Losses



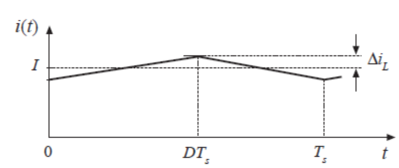

# Inductor Core Loss

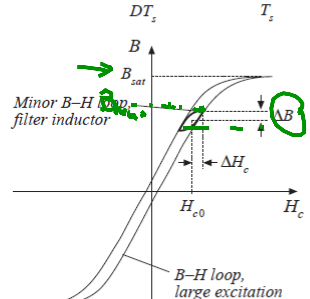
- Governed by Steinmetz Equation:

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

- Parameters $K_{fe}$, $\alpha$, and $\beta$ extracted from manufacturer data
- $\Delta B \propto \Delta i_L \rightarrow$ small losses with small ripple

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



# Steinmetz Parameter Extraction

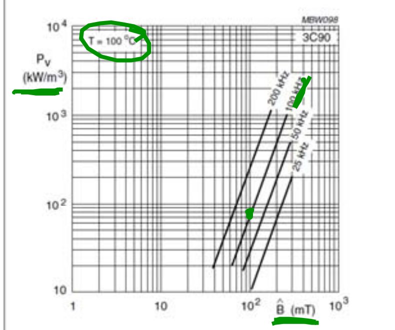



Fig.6 Specific power loss as a function of peak flux density with frequency as a parameter.

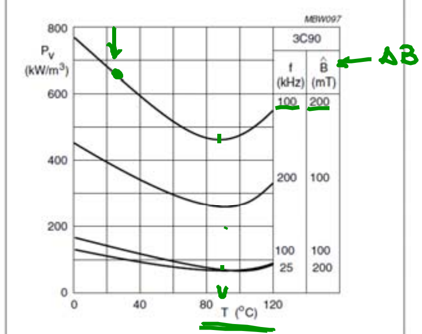
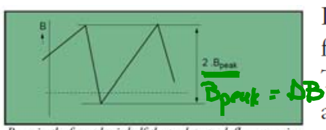



Fig.7 Specific power loss for several frequency/flux density combinations as a function of temperature.

# 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 :

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

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

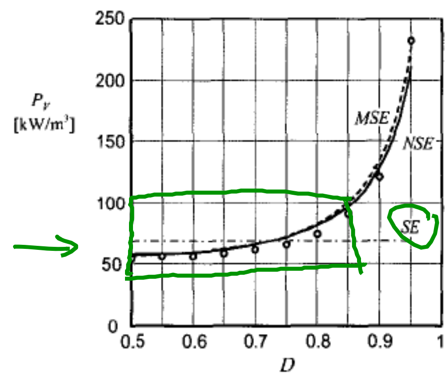
| ferrite | f (kHz) | Cm | x | y | $ct_2$ | $ct_1$ | $ct_0$ |
|---|---|---|---|---|---|---|---|
| 3C30 | 20-100 | $7.13.10^{-3}$ | 1.42 | 3.02 | $3.65.10^{-4}$ | $6.65.10^{-2}$ | 4 |
| | 100-200 | $7.13.10^{-3}$ | 1.42 | 3.02 | $4.10^{-4}$ | $6.8 .10^{-2}$ | 3.8 |
| 3C90 | 20-200 | $3.2.10^{-3}$ | 1.46 | 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:

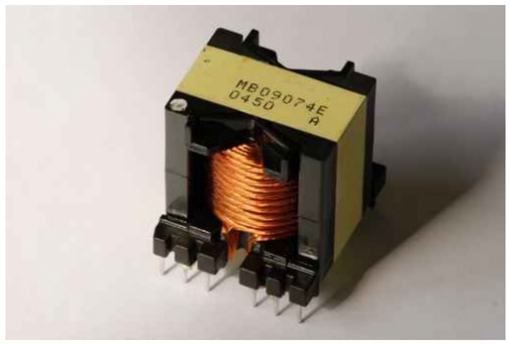
$$k_N = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos\theta|^{\alpha} d\vartheta} \quad (8)$$

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

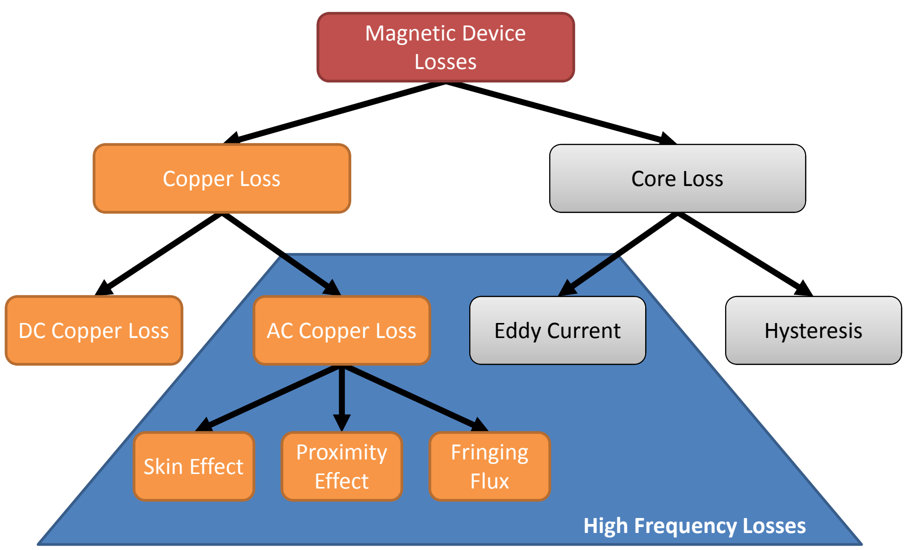
- Full Paper included on materials page of website

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 |
| | | |

# $K_g$ Method Derivation

The four constraints:

$$nI_{max} = B_{max} A_c \mathcal{R}_g = B_{max} \frac{\ell_g}{\mu_0}$$

$$L = \frac{n^2}{\mathcal{R}_g} = \frac{\mu_0 A_c n^2}{\ell_g}$$

$$K_u W_A \geq n A_W$$

$$R = \rho \frac{n\,(MLT)}{A_W}$$

These equations involve the quantities

$A_c$, $W_A$, and $MLT$, which are functions of the core geometry,

$I_{max}$, $B_{max}$ , $\mu_0$, $L$, $K_u$, $R$, and $\rho$, which are given specifications or other known quantities, and

$n$, $\ell_g$, and $A_W$, which are unknowns.

Elimination of $n$, $\ell_g$, and $A_W$ leads to

$$\frac{A_c^2 W_A}{(MLT)} \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u}$$

$K_g$

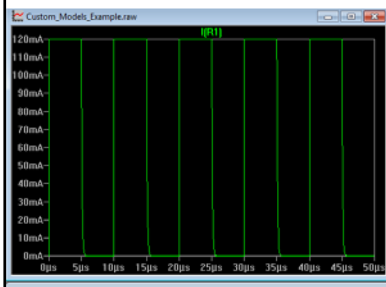
# Simulation Modeling

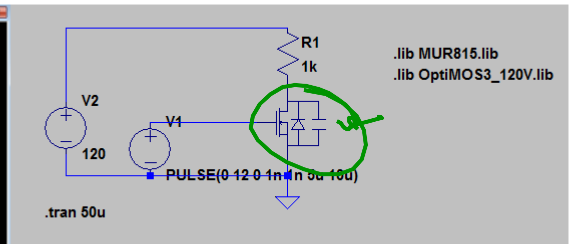
15

# 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.)

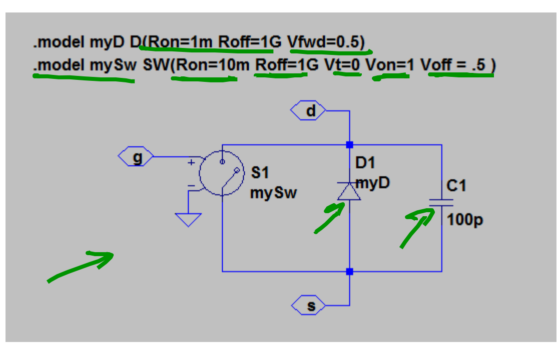
# LTSpice Modeling Examples




- Example files added to course materials page

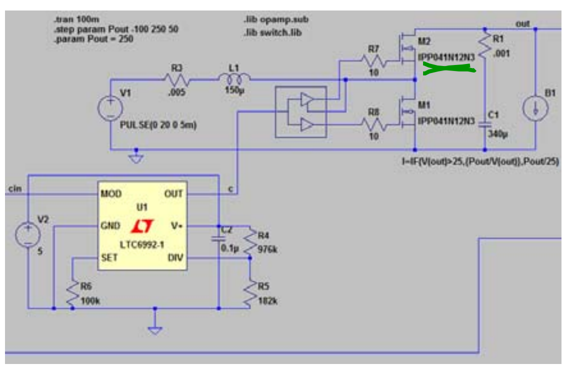
# Custom Transistor Model



# Manufacturer Device Model

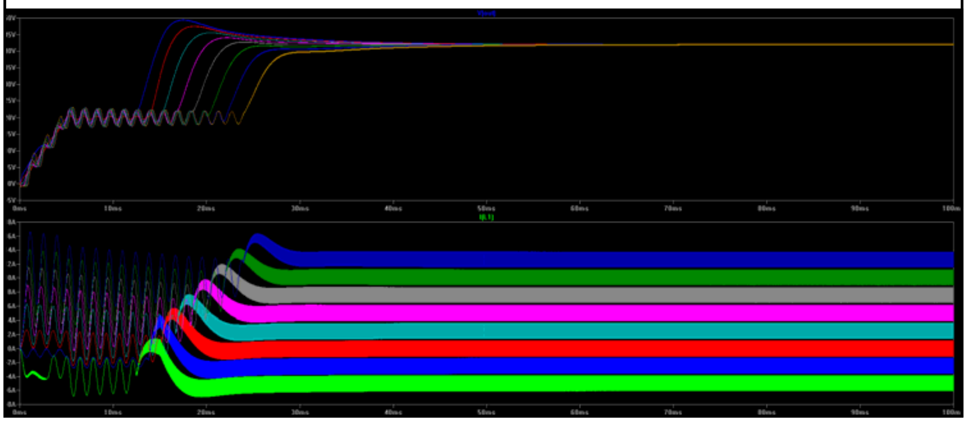
- Text-only netlist model of device including additional parasitics and temperature effects
- May slow or stop simulation if timestep and accuracy are not adjusted appropriately

# Full Switching Simulation



## Switching Model Simulation Results

- Simulation Time ≈ 15 minutes



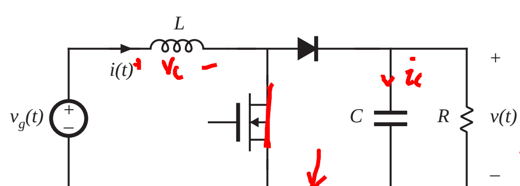
## Full Switching Model

- 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




$$\langle v_L\rangle = L\frac{d\langle i_L\rangle}{dt} = d(t)\langle v_g(t)\rangle + d'(t)\left(\langle v_g(t)\rangle - \langle v(t)\rangle\right)$$

$$\langle i_c\rangle = C\frac{d\langle v(t)\rangle}{dt} = -\frac{\langle v\rangle}{R}d(t) + d'(t)\left(\langle i_L(t)\rangle - \frac{\langle v(t)\rangle}{R}\right)$$

DC

DC only

$$0 = V_g - D'V$$

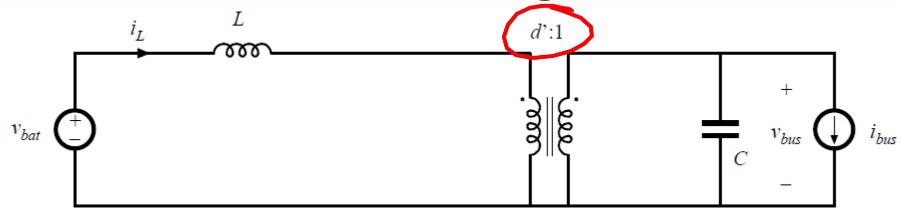
$$0 = D'I_L - \frac{V}{R}$$

Averaged AC

$$L\frac{d\hat{i}_L}{dt} = \hat{v}_g - D'\hat{v} + V\hat{d}$$

$$C\frac{d\hat{v}}{dt} = -\frac{\hat{v}}{R} + D'\hat{i}_L - I_L\hat{d}$$

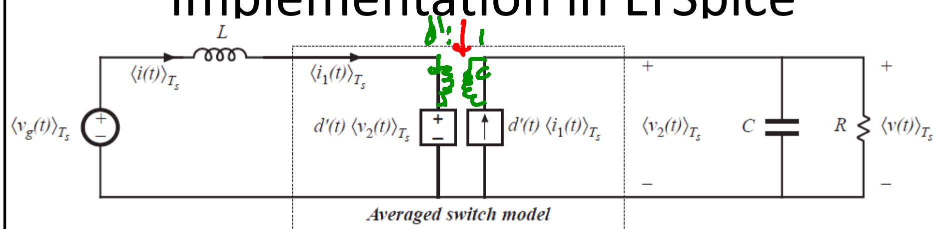
# Nonlinear, Averaged Circuit

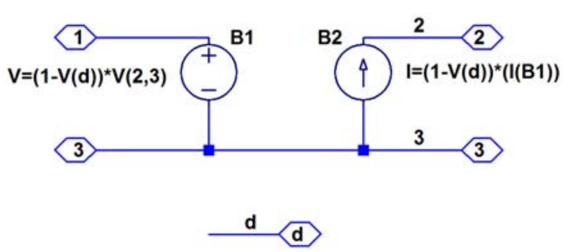



$$L\frac{d\langle i_L\rangle}{dt} = \langle v_{bat}\rangle - (1-d)\langle v_{bus}\rangle$$

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

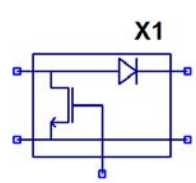
# Implementation in LTSpice



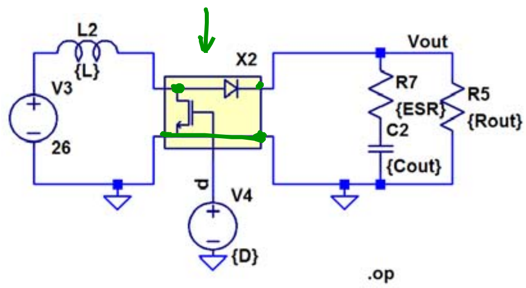




$$\langle v_1(t)\rangle_{T_s} = d'(t)\,\langle v_2(t)\rangle_{T_s}$$

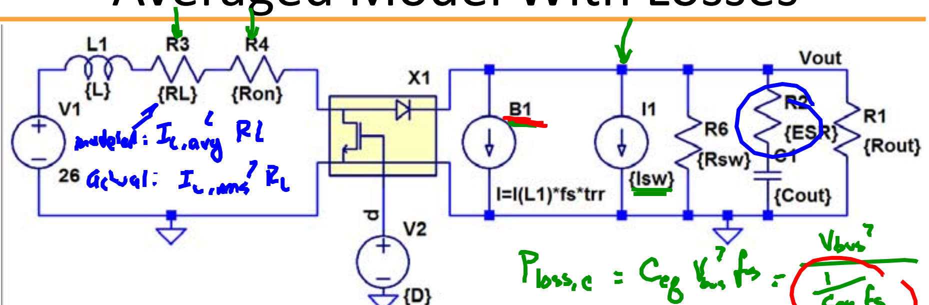
$$\langle i_2(t)\rangle_{T_s} = d'(t)\,\langle i_1(t)\rangle_{T_s}$$



# Averaged Switch Model

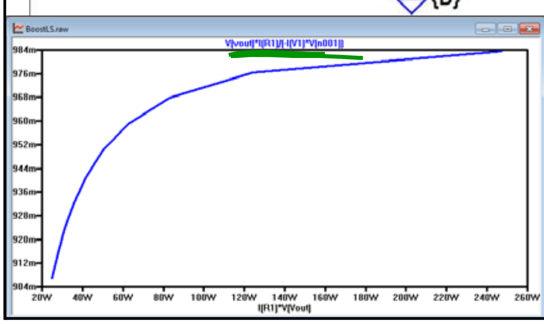



# Averaged Model With Losses




$P_{loss,c} = C_{eq} V_{bus}^2 f_s = \frac{V_{bus}^2}{\frac{1}{C_{eq} f_s}}$ ($R_{sw}$)

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




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

$P_{rr} = V_{out} f_s [I_L t_{rr} + Q_r]$ ($I_L \cdot \Delta I_L$)

$I_{sw} = f_s Q_r$