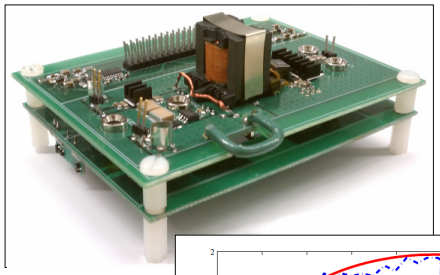
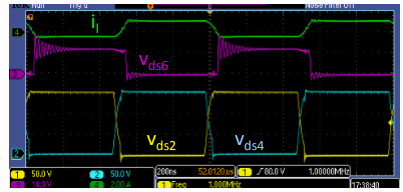
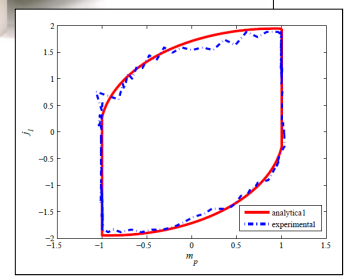
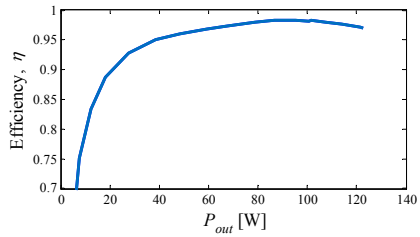
DAB: Experimental Results









D. Costinett, D. Maksimovic, and R. Zane, "Design and control for high efficiency in high step-down dual active bridge converters operating at high switching frequency," IEEE Trans. Power Electron., vol. PP, no. 99, p. 1, 2012.

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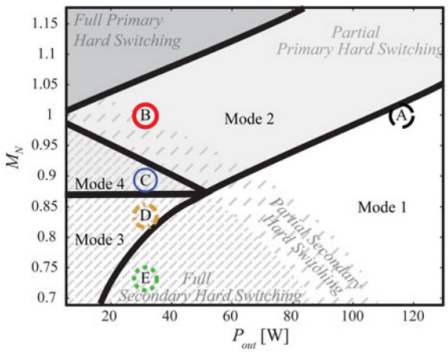
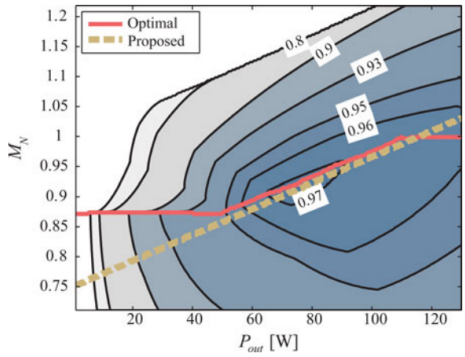
Soft Switching Range with Varying V_{out}





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Application Example: Automotive

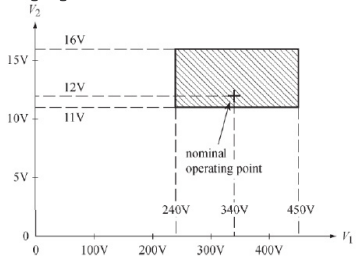
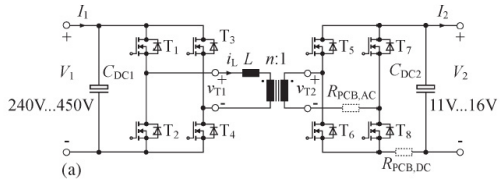


Fig. 1. Converter operating voltage ranges required for automotive application.



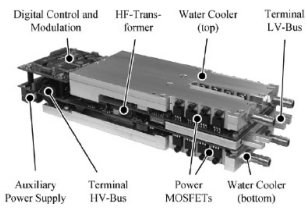


Fig. 3. Automotive DAB converter (273 × 90 × 53 mm).

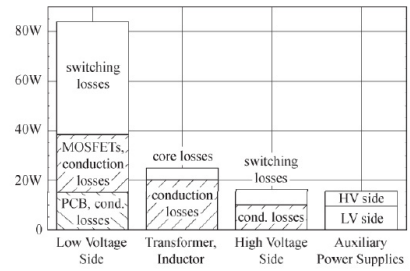


Fig. 13. Calculated distribution of the power losses for operation at $V_1 = 340$ V, $V_2 = 12$ V, and $P_2 = 2$ kW.

*F. Krismer, J.W.Kolar, "Accurate Power Loss Model Derivation of a High-Current Dual Active Bridge Converter for an Automotive Application, IEEE Trans. On Industrial Electronics, March 2010

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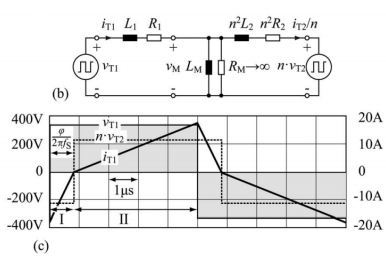
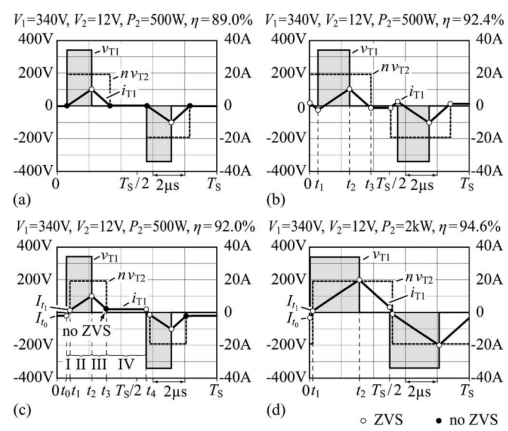
Alternate Modulation Schemes





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Efficiency Results

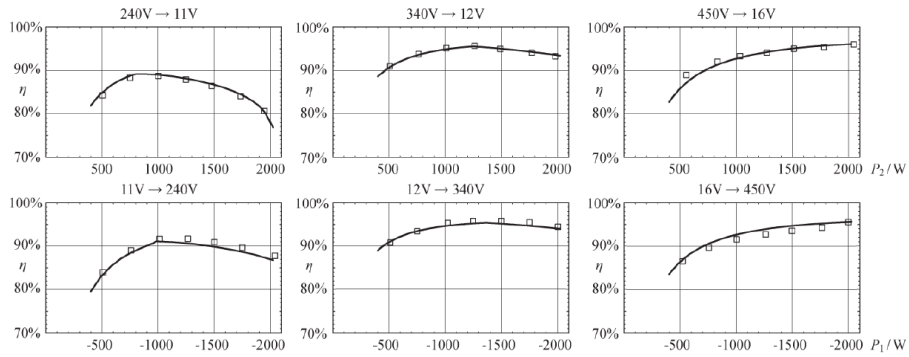
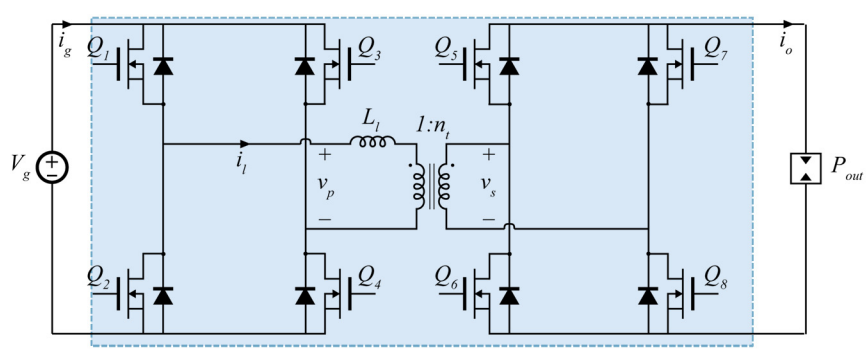
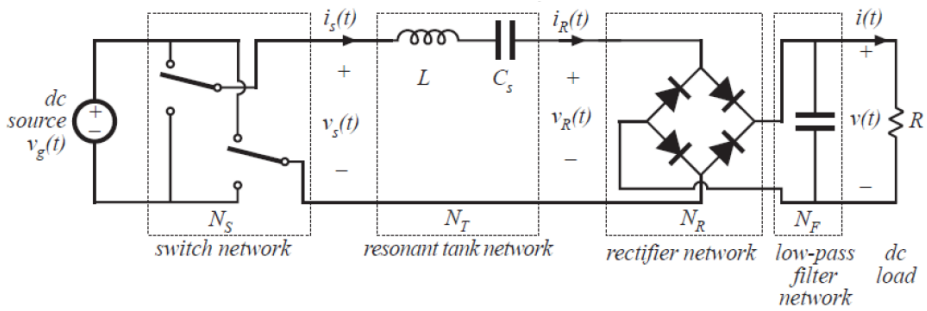


Fig. 12. (Solid lines) Predicted efficiencies and (□) measured efficiencies for different operating conditions. The efficiencies are calculated with the improved DAB loss model which includes all methods discussed in Section IV.

Transformer Saturation

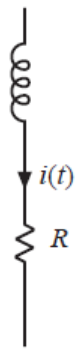


Next: SRC



Magnetics Losses

Magnetics Winding Loss (DC)



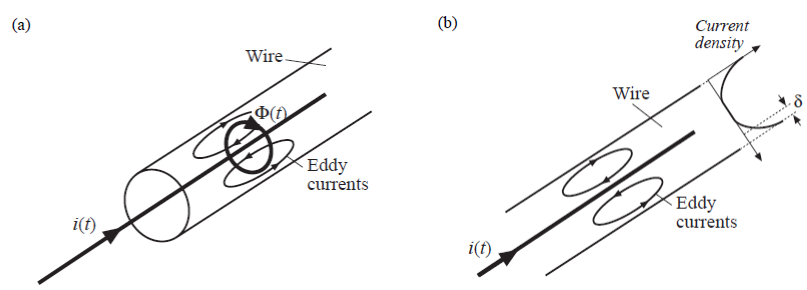
- DC Resistance given by

$$R_{DC} = \rho \frac{l_b}{A_w}$$

- At room temp, ρ = 1.724·10^{-6} Ω-cm
- At 100°C, ρ = 2.3·10^{-6} Ω-cm
- Losses due to DC current:

$$P_{cu,DC} = {I_{L,rms}}^2 R_{DC}$$

Skin Effect in Copper Wire



- Current profile at high frequency is exponential function of distance from center with characteristic length δ

Skin Depth

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$

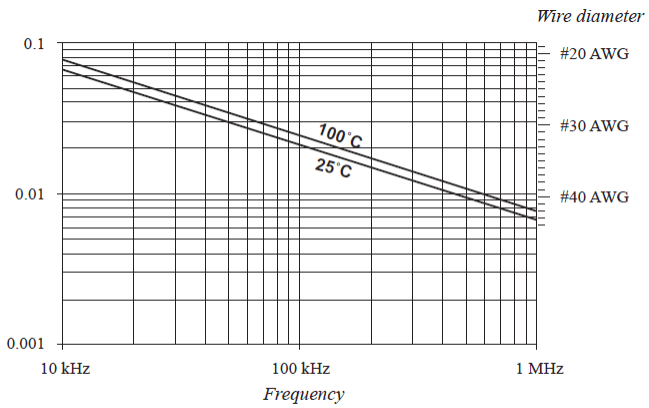
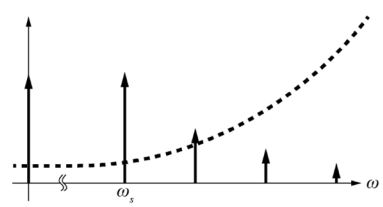
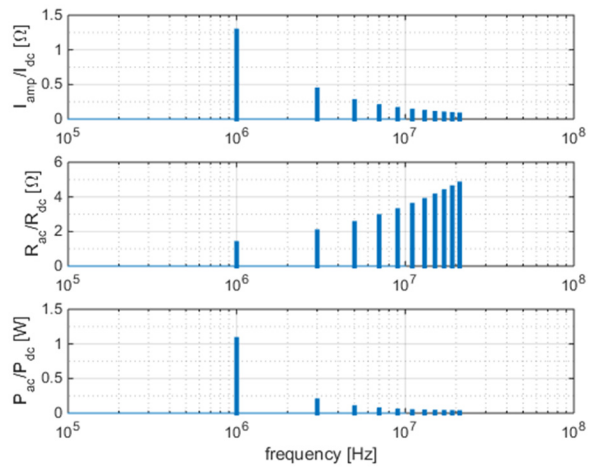


Fig. 13.23 Penetration depth δ, as a function of frequency *f*, for copper wire.

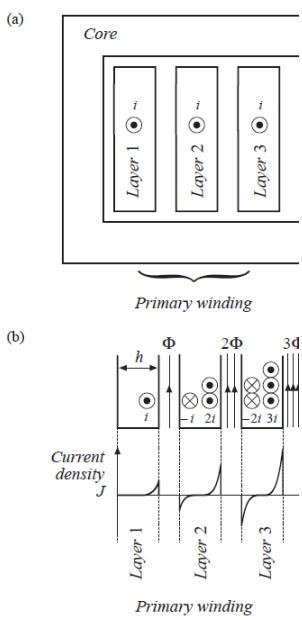
Skin Depth Calculations



Example Calculation



Proximity Effect



- In *foil* conductor closely spaced with $h >> \delta$, flux between layers generates additional current according to Lentz's law.

$$P_1 = {I_{L,rms}}^2 R_{ac}$$

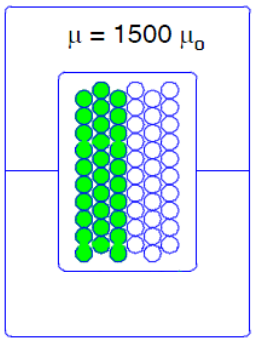
- Power loss in layer 2:

$$P_2 = {I_{L,rms}}^2 R_{ac} + \left(2I_{L,rms}\right)^2 R_{ac}$$

$$P_2 = 5P_1$$

See *Fundamentals of Power Electronics*, Section 13.4

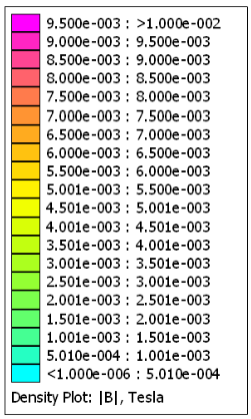
Simulation Example



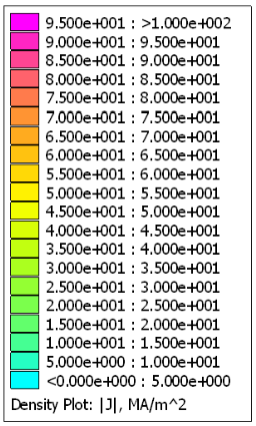
- AWG#30 copper wire
  - Diameter d = 0.294 mm
  - $d = \delta$ at around 50 kHz
- 1:1 transformer
  - Primary and secondary are the same, 30 turns in 3 layers
- Sinusoidal currents, $I_{1rms} = I_{2rms} = 1$ A

Numerical field and current density solutions using FEMM (Finite Element Method Magnetics), a free 2D solver, http://www.femm.info/wiki/HomePage

Flux density magnitude

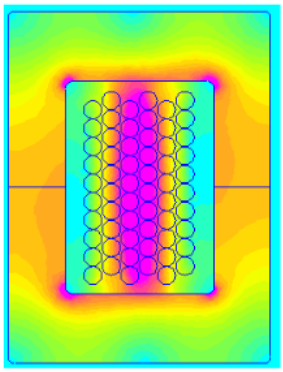


Current density magnitude

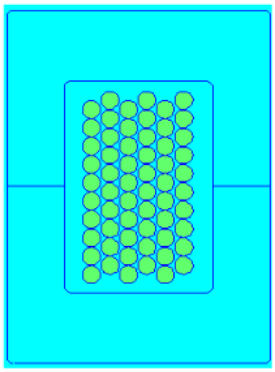


Frequency: 1 kHz

Flux density

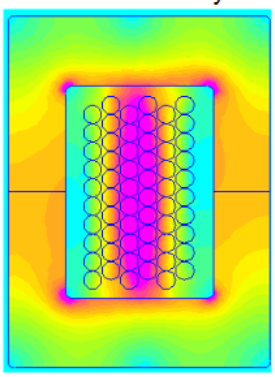


Current Density

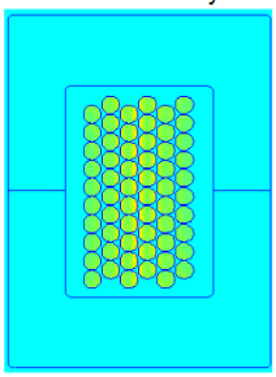


Frequency: 100 kHz

Flux density



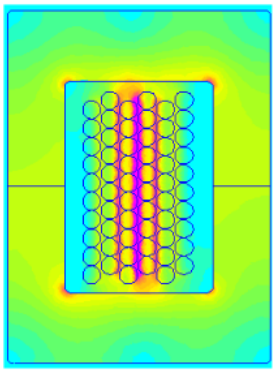
Current Density



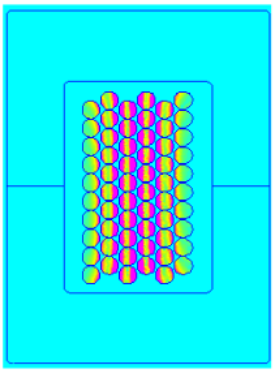
Total copper losses 1.8 larger than at 1 kHz

Frequency: 1 MHz

Flux density



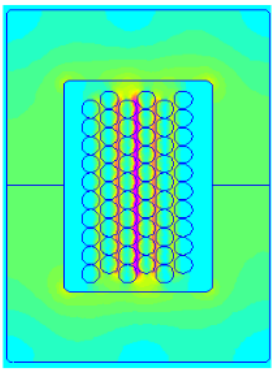
Current Density



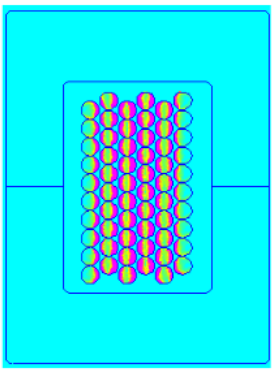
Total copper losses 20 times larger than at 1 kHz

Frequency: 10 MHz

Flux density

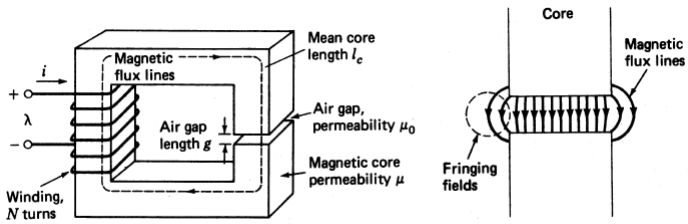


Current Density



Very significant proximity effect
Total copper losses = 65 times larger than at 1 KHz

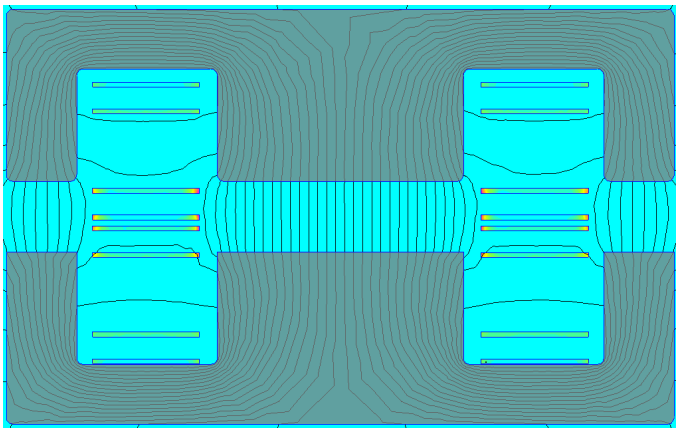
Fringing



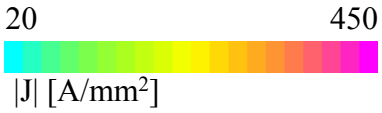
A simple magnetic circuit with an air gap

- Near air gap, flux may bow out significantly, causing additional eddy current losses in nearby conductors

Finite Element Simulation

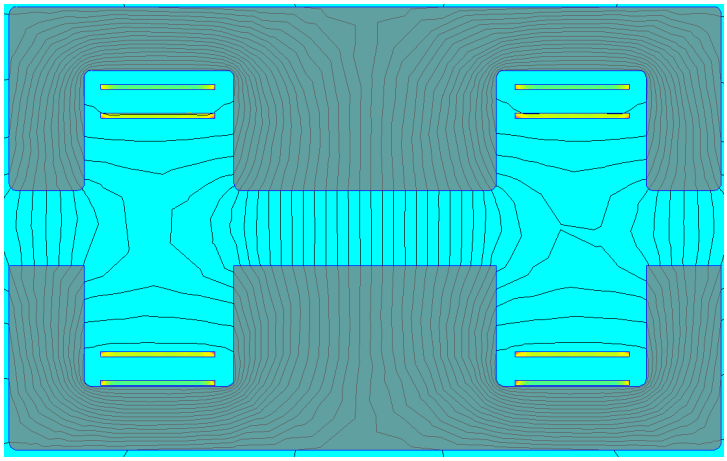


$P_{cond} = 330$ W



http://www.femm.info/wiki/HomePage

Removing Copper From Fringing Field



$P_{cond} = 180$ W

15 280

|J| [A/mm^2]

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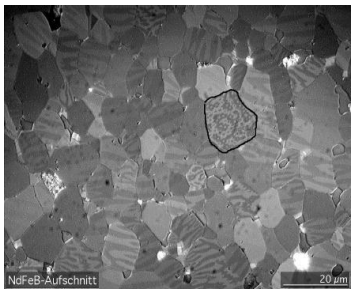
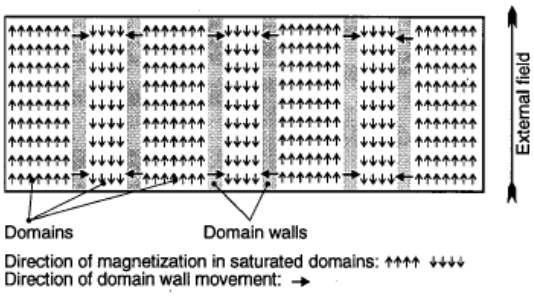
Physical Origin of Core Loss

- Magnetic material is divided into "domains" of saturated material
- Both Hysteresis and Eddy Current losses occur from domain wall shifting





Reinert, J.; Brockmeyer, A.; De Doncker, R.W.; , "Calculation of losses in ferro- and ferrimagnetic materials based on the modified Steinmetz equation,"

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Inductor Core Loss

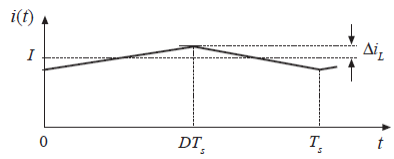
- Governed by Steinmetz Equation:

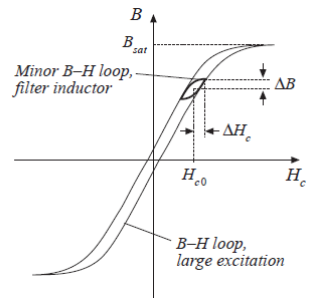
$$P_v = K_{fe} f_s^{\alpha} (\Delta B)^{\beta} \quad [\text{mW/cm}^3]$$

- Parameters K_{fe}, α, and β extracted from manufacturer data

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

- Only valid for sinusoidal waveforms





Steinmetz Parameter Extraction

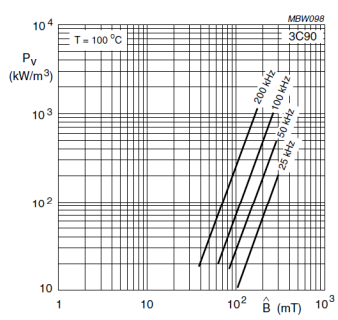


Fig.6 Specific power loss as a function of peak flux density with frequency as a parameter.

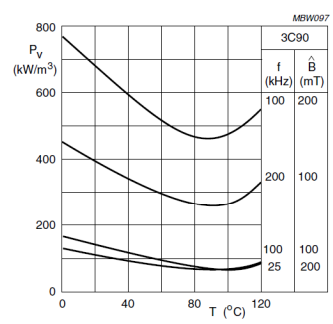


Fig.7 Specific power loss for several frequency/flux density combinations as a function of temperature.

Non-Sinusoidal Waveforms

- Modified Steinmetz Equation (MSE)
  - "Guess" that losses depend on $^{dB}/_{dt}$
  - Calculate $\langle {}^{dB}/_{dt} \rangle$ and find frequency of equivalent sinusoid

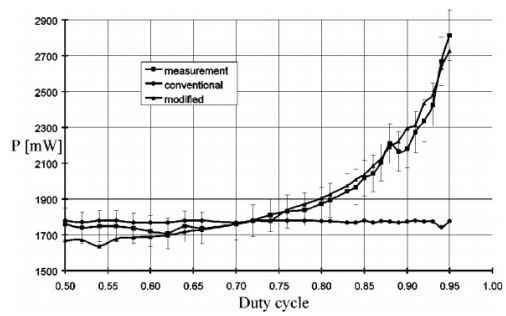


Fig. 8. Comparison between measurement and calculation as a function of duty cycle.

Albach ,Durbau and Brockmeyer, 1996
Reinert, Brockmeyer, and Doncker, 1999

NSE/iGSE

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

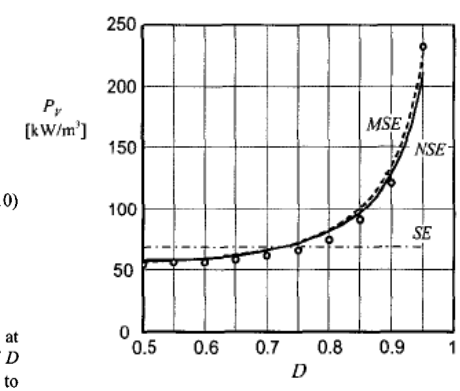
$$k_N = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos\theta|^{\alpha} d\vartheta}$$

Simple Formula for Square-wave voltages:

$$P_{NSE} = k_N \, (2f)^{\alpha} (\Delta B)^{\beta} \left(D^{1-\alpha} + (1-D)^{1-\alpha}\right) \qquad (10)$$

where f is the operating frequency;
$\Delta B / 2$ is the peak induction;
D is the duty ratio of the square wave voltage.

Note: The second and third harmonics are dominant at moderate values of duty ratio D. For extreme values of D (95%), a higher value of α could give better matching to the actual losses.



Van den Bossche, A.; Valchev, V.C.; Georgiev, G.B.; , "Measurement and loss model of ferrites with non-sinusoidal waveforms,"
K. Venkatachalam; C. R. Sullivan; T. Abdallah; H. Tacca, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters"

Additional Approaches

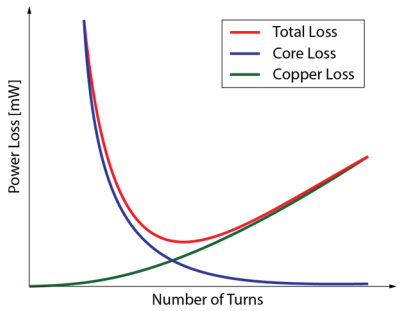
- History of Core Loss Approximation Techniques:

https://engineering.dartmouth.edu/inductor/Sullivan_APEC_2012_core_loss%20overview_with_references.pdf

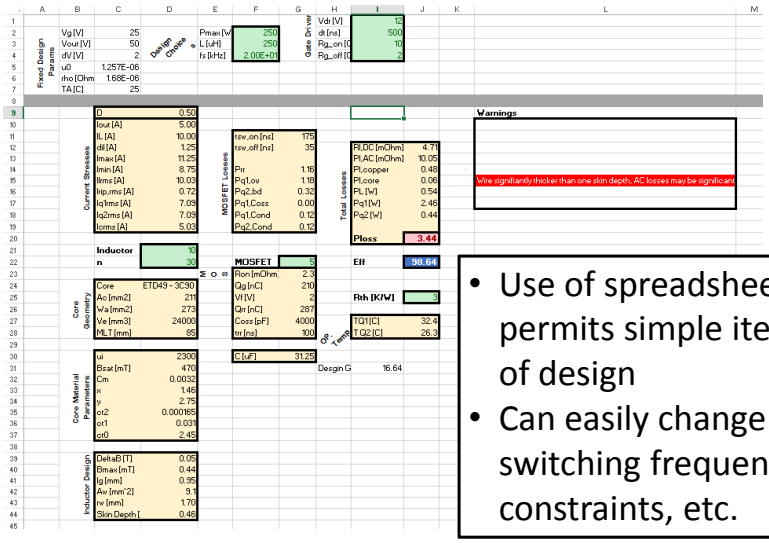
- Seminar on magnetic loss modeling:

https://www.pes.ee.ethz.ch/uploads/tx_ethpublications/APEC2012_MagneticTutorial.pdf

Minimization of Losses



Spreadsheet Design



- Use of spreadsheet permits simple iteration of design
- Can easily change core, switching frequency, loss constraints, etc.

Matlab (Programmatic) Design

```
function [n, lg, Pq1, Pq2, Pl, eta, Cmin ] = TestBoostDesign(Pmax, fs, L, dt, core_geom, core_mat, MOSFET)
%TestBoostDesign calculate boost conveter efficiency and temperature rise
%for various designs
%   fs  = switching frequency (in Hz)
%   L = inductance (in Henries)
%   n = number of turns on inductor
%   dt = switching dead time (in seconds)
%   core_geom = core geometry, chosen from 'EFD25', 'ETD29', 'ETD39', 'ETD44', or 'ETD49'
%   core_mat = core material, chosen from '3F3', '3C90', or '3F4'
%   MOSFET = MOSFET selection, chosen from 'AOT', 'FDP', 'IPP2', 'IRF',
%   'CSD' or 'IPP0'

Vg = 25;
Vout = 50;
Iout = Pmax/Vout;
Ts = 1/fs;
D = 1-Vg/Vout;
dVout = 2;
Vdr = 12;

Rgon = 10;
Rgoff = 2;

rho = 1.724e-6; %ohms*cm
u0 = 4*pi*1e-7;

%% Inductor Datasheet Parameters
switch core_geom
    case 'EFD25'
        MLT = 46.4; %mm
        Ac = 58; %mm^2
        Ve = 3300; %mm^3
        Wa = 40.2; %mm^2
```

- Matlab, or similar, permits more powerful iteration and plotting/insight into design variation