



# TINY BOX CHALLENGE

## Competition Specifications

The **winning converter** will be the unit which achieves the **highest power density**, i.e. fits in the smallest rectangular volume, while meeting the following specifications.

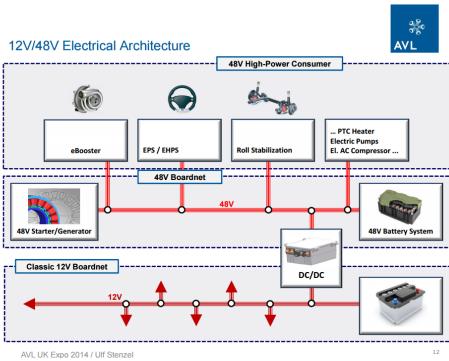
Parameter	Requirement	Comment
Voltage Input	60 Vdc, 10 Ω series resistor	
Maximum Output Power	60 W	
Output Voltage	12 ± 1 Vdc	
Input Ripple Current	< 5%	Measured as $I_{pk,pk}/I_{avg}$ from the DC supply, in steady state, at full output power
Output Ripple Voltage	< 2%	Measured as $V_{pk,pk}/V_{avg}$ from the DC supply, in steady state, at full output power
TPE Efficiency	> 90%	Measured using TPE method <sup>1</sup>
No-load Power Loss	< 3W	Measured with load disconnected, but output voltage within specified range
Volume	< 6 in <sup>3</sup>	Volume of minimum rectangle enclosing power stage

<sup>1</sup>Tennessee Power Electronics (TPE) efficiency is a weighted power efficiency defined as:

$$\eta_{TPEF} = 0.1\eta_{Po=15W} + 0.15\eta_{Po=30W} + 0.25\eta_{Po=45W} + 0.5\eta_{Po=60W}$$

## Example Applications

### EV 48V Architectures

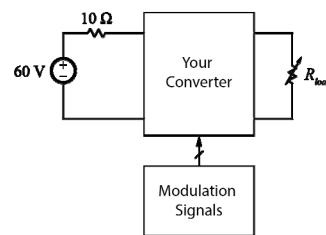


### Data Centers / Telecom

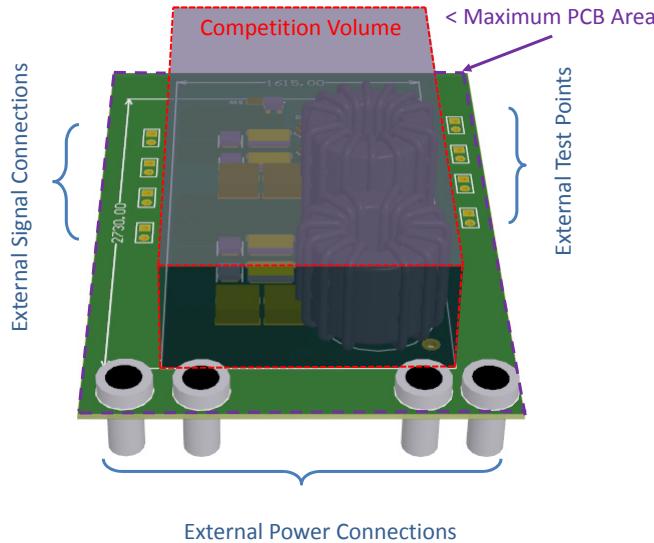


NXP Semi, "Semiconductors – enablers of future mobility concepts", 2011  
 Audi, "Electric biturbo and hybridization", 2014  
 AVL, "48V Mild Hybrid Systems"

## Testing Setup



## How Volume is Measured



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## Schedule

20. Oct. 3	Oct. 5	Oct. 7
Magnetics Loss Analysis <i>Tiny Box Challenge Begins</i>	<i>WbW 2016</i>	<i>Fall Break</i>
21. Oct. 10	Oct. 12	22. Oct. 14 <i>Homework 6 Due</i>
23. Oct. 17 <i>TBC Paper Design Comparison Report Due</i>	24. Oct. 19	25. Oct. 21 <i>Homework 7 Due</i>
26. Oct. 24 <i>TBC Final Paper Design Report Due</i>	27. Oct. 26	28. Oct. 28
29. Oct. 31 <i>TBC PCB Layout Due</i>	30. Nov. 2 <i>WbPDA 2016</i>	Nov. 4 <i>Homework 8 Due</i>
31. Nov. 7 <i>WbPDA 2016</i>	32. Nov. 9 <i>WbPDA 2016</i>	33. Nov. 11 <i>Homework 9 Due</i>
34. Nov. 14	35. Nov. 16	36. Nov. 18 <i>Homework 10 Due</i>
37. Nov. 21	38. Nov. 23 <i>TBC Testing Report Due</i>	Nov. 25 <i>Thanksgiving Break</i>

## Additional Details

- Full competition specifications and example testing report on course webpage
- No regulation requirements
- First Deliverable: Monday October 17<sup>th</sup>
  - Design comparison of 4 topologies

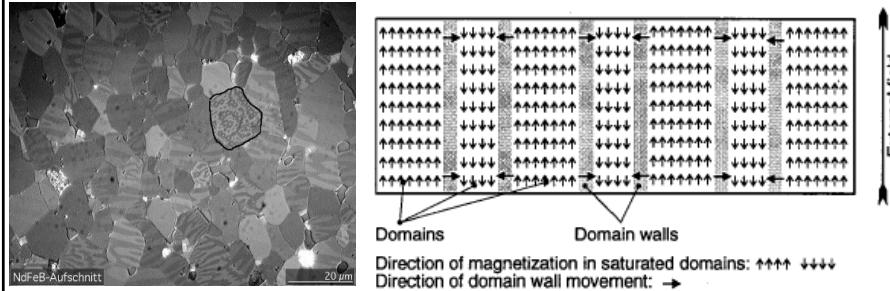


## Magnetics Losses



## 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

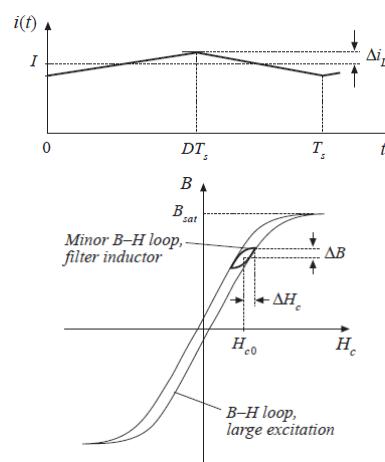
- Governed by Steinmetz Equation:

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

- Parameters  $K_{fe}$ ,  $\alpha$ , and  $\beta$  extracted from manufacturer data

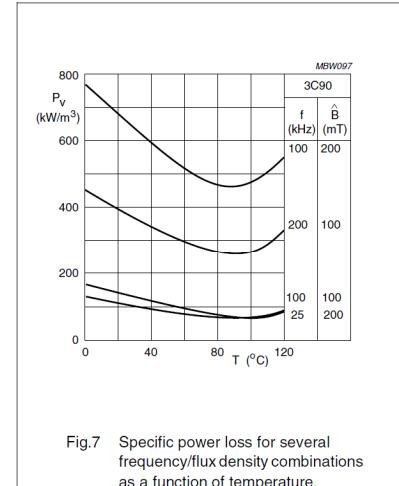
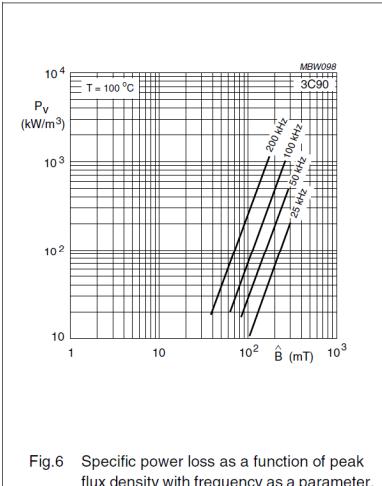
$$P_{fe} = P_v A_c l_m \text{ [mW]}$$

- Only valid for sinusoidal waveforms



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## Steinmetz Parameter Extraction



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## Non-Sinusoidal Waveforms

- Modified Steinmetz Equation (MSE)
  - “Guess” that losses depend on  $\frac{dB}{dt}$
  - Calculate  $\langle \frac{dB}{dt} \rangle$  and find frequency of equivalent sinusoid

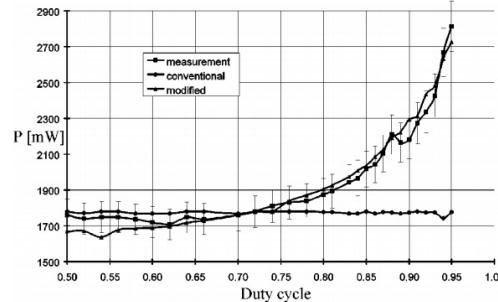


Fig. 8. Comparison between measurement and calculation as a function of duty cycle.

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

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## NSE/iGSE

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

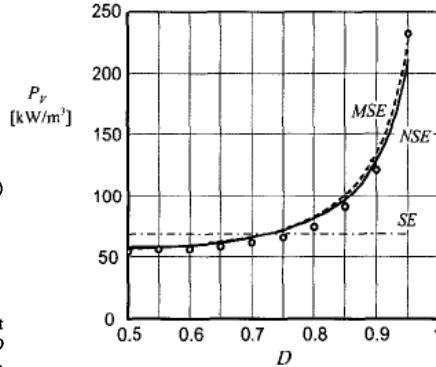
$$k_N = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos \theta|^\alpha d\vartheta}$$

**Simple Formula for Square-wave voltages:**

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

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  $\alpha$  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"

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## Additional Approaches

- History of Core Loss Approximation Techniques:

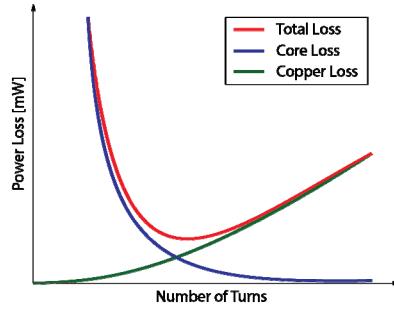
[https://engineering.dartmouth.edu/inductor/Sullivan\\_APEC\\_2012\\_core\\_loss\\_overview\\_with\\_references.pdf](https://engineering.dartmouth.edu/inductor/Sullivan_APEC_2012_core_loss_overview_with_references.pdf)

- Seminar on magnetic loss modeling:

[https://www.pes.ee.ethz.ch/uploads/tx\\_ethpublications/APEC2012\\_MagneticTutorial.pdf](https://www.pes.ee.ethz.ch/uploads/tx_ethpublications/APEC2012_MagneticTutorial.pdf)

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## Minimization of Losses



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## Spreadsheet Design

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	A	B	C	D	E	F	G	H	I	J	K	L	M
2	V <sub>s</sub> [V]	25	P <sub>max</sub> [W]	250	V <sub>b</sub> [V]	12	P <sub>g_on</sub> [W]	10					
3	V <sub>out</sub> [V]	50	I <sub>s</sub> [A]	250	I <sub>b</sub> [A]	500	P <sub>g_off</sub> [W]	2					
4	dV/dt	2	L <sub>s</sub> [ $\mu$ H]	2.00E+01	f <sub>s</sub> [Hz]								
5	i <sub>0</sub>	1.257E-06											
6	r <sub>ho</sub> [Ohm]	1.68E-06											
7	T <sub>A</sub> [C]	25											
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- Use of spreadsheet permits simple iteration of design
- Can easily change core, switching frequency, loss constraints, etc.

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## Matlab (Programmatic) Design

```

1  function [n, lg, Pg1, Pg2, P1, eta, Cmin ] = TestBoostDesign(Pmax, fs, L, dt, core_geom, core_mat, MOSFET)
2  %TestBoostDesign calculate boost converter efficiency and temperature rise
3  %for various designs
4  % fs = switching frequency (in Hz)
5  % L = inductance (in Henries)
6  % n = number of turns on inductor
7  % dt = switching dead time (in seconds)
8  % core_geom = core geometry, chosen from 'EFD25', 'ETD29', 'ETD39', 'ETD44', or 'ETD49'
9  % core_mat = core material, chosen from '3F3', '3C90', or '3F4'
10 % MOSFET = MOSFET selection, chosen from 'AOT', 'FDP', 'IPP2', 'IRF',
11 'CSD' or 'IPPO'
12
13 Vg = 25;
14 Vout = 50;
15 Iout = Pmax/Vout;
16 Ts = 1/fs;
17 D = 1-Vg/Vout;
18 dVout = 2;
19 Vds = 12;
20
21 Rgon = 10;
22 Rgoff = 2;
23
24 rho = 1.724e-6; %chms*cm
25 u0 = 4*pi*1e-7;
26
27 %% Inductor Datasheet Parameters
28 switch core_geom
29 case 'EFD25'
30     MLT = 46.4; %mm
31     Ac = 58; %mm^2
32     Ve = 3300; %mm^3
33     Wa = 40.2; %mm^2

```

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



## Planar Inductors

