WINDING LOSSES IN HIGH FREQUENCY TRANSFORMERS

presented by

Weyman Lundquist

WEST COAST MAGNETICS
1 . 8 0 0 . 6 2 8 . 1 1 2 3

WINDING LOSS COMPONENTS

Resistive loss

Eddy-current loss

$$P_{total} = I_{dc}^2 R_{dc} + I_{ac,rms}^2 R_{dc} + P_{skin} + P_{proximity}$$

dc loss

$$P_{dc} = I_{dc}^2 R_{dc}$$

ac loss

$$P_{ac} = I_{ac,rms}^2 R_{ac}$$

"ac resistance"

$$R_{ac} = \frac{P_{ac}}{I_{ac,rms}^2}$$

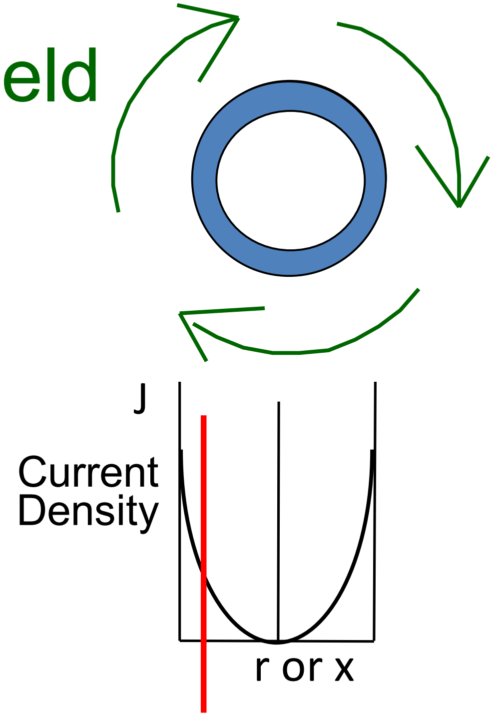
Source: J. Pollock Thayer School of Engineering at Dartmouth

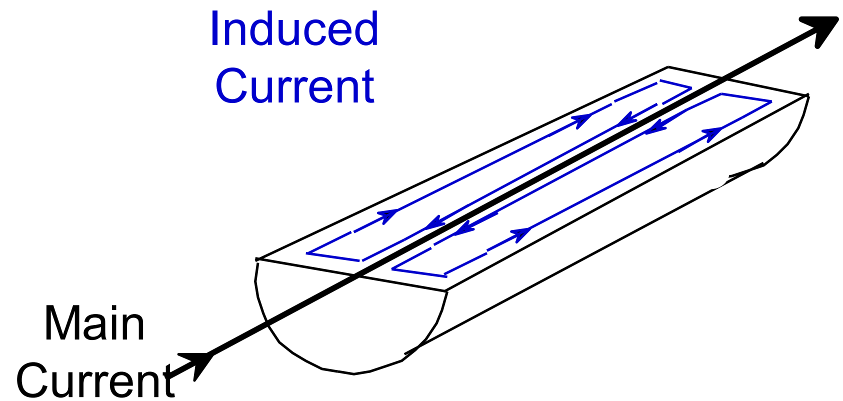
SKIN EFFECTS

B-Field

Skin depth

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





- Skin Effect
  - An isolated conductor carrying high-frequency current which generates a field in itself that forces the current to flow near the surface of the conductor.
  - Skin depth is the distance below the surface of an infinitely thick plane conductor where the field magnitude and current density decrease to 1/*e* of those at the surface

Source: J. Pollock, Thayer School of Engineering at Dartmouth

DEFINITION OF SKIN DEPTH

Skin depth is the distance beneath the surface of a conductor where the current density has fallen to 37 percent of its value at the surface.

$$\Delta = \left(\frac{6.62}{\sqrt{f}} \right) * K$$

$$Where:$$

$$\Delta = skindepth(cm)$$

$$f = frequency(Hz)$$

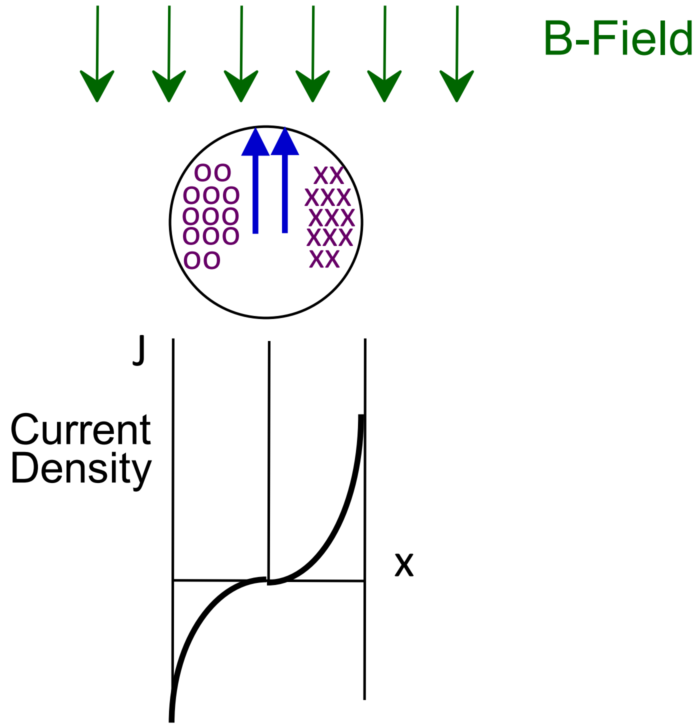
$$K = 1(copper)$$

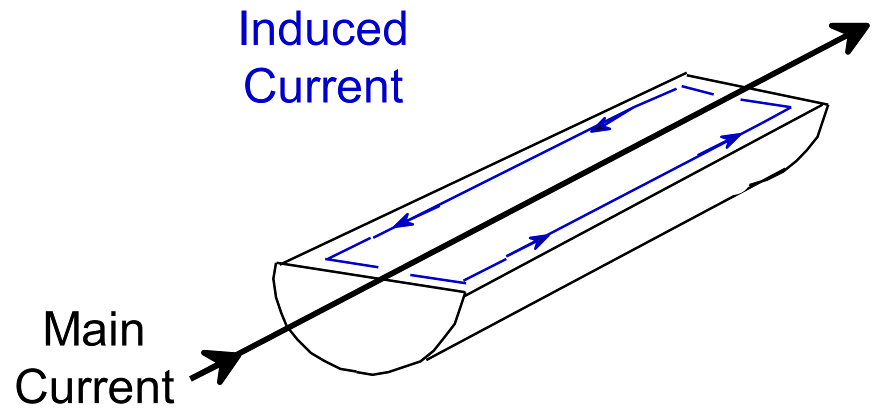
SKIN DEPTH VS. FREQUENCY, COPPER

SKIN DEPTH VS. FREQUENCY: COPPER

Frequency (kHz)	Skin Depth (cm)	Skin Depth (in)	Wire Gauge Dia < Skin Depth
1	0.2093	0.0824	12
2.5	0.1324	0.0521	16
5	0.0936	0.0369	19
10	0.0662	0.0261	22
25	0.0419	0.0165	26
50	0.0296	0.0117	29
100	0.0209	0.0082	32
200	0.0148	0.0058	35
300	0.0121	0.0048	37
400	0.0105	0.0041	38
500	0.0094	0.0037	39
750	0.0076	0.0030	41
1000	0.0066	0.0026	42
1500	0.0054	0.0021	44
2000	0.0047	0.0018	45
3000	0.0038	0.0015	47
5000	0.0030	0.0012	49

PROXIMITY EFFECT



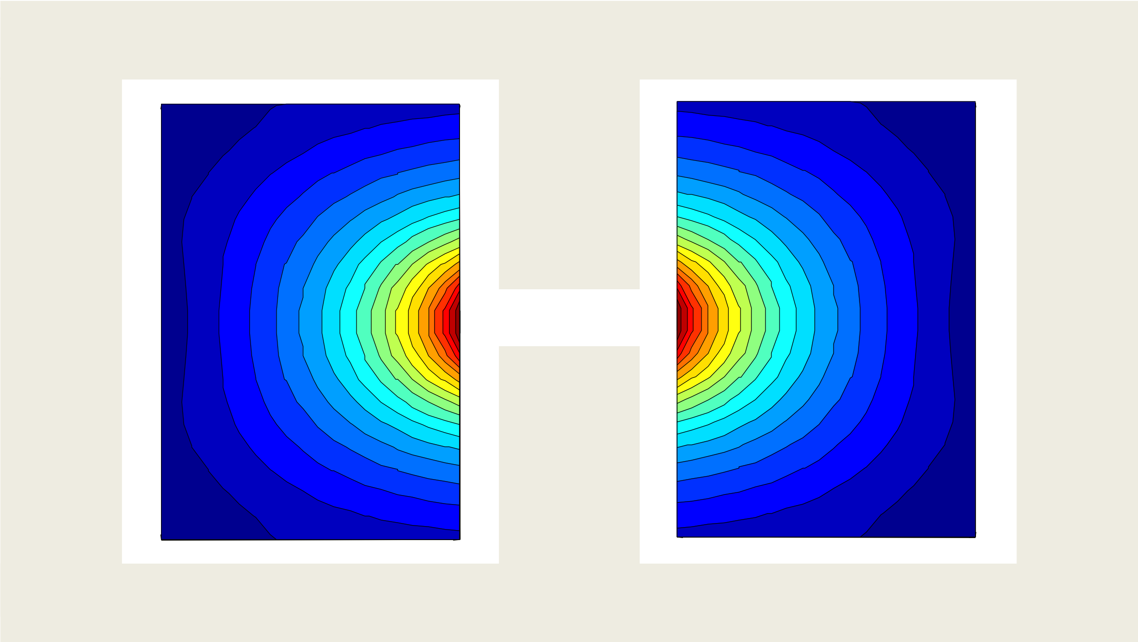


- Proximity Effect
  - An isolated conductor is placed in an uniform external field
  - External field results from other wires and windings near the conductor

Source: J. Pollock, Thayer School of Engineering at Dartmouth

IN GAPPED INDUCTORS THE FRINGING FIELD INDUCES AC LOSSES

Fringing Field Around the Gap



Magnitude of B

Legend:

Red – strong field

Blue – weak field

Lines – constant field magnitude

Note: the strength of the fringing field is a function of the ripple current shape and magnitude.

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Source: J. Pollock, C. Sullivan, Thayer School of Engineering at Dartmouth

OPTIONS FOR MANAGING HIGH FREQUENCY WINDING LOSSES

- Wind each winding in single or half layers.
- Use litz wire to minimize AC losses.
- Use an ungapped core topology.
- Choose a geometry with a larger window cross section, or a cross section which is more optimal for high frequency transformers.
- IN ALL CASES WE STILL NEED A METHOD TO DETERMINE WINDING LOSSES, BECAUSE DC WINDING LOSSES ARE NORMALLY LESS THAN AC WINDING LOSSES IN THIS CLASS OF TRANSFORMER

ESTIMATING WINDING LOSSES IN TRANSFORMERS, THE DOWELL METHOD

PRACTICAL METHODS FOR ESTIMATING WINDING LOSSES IN TRANSFORMERS: THE DOWELL METHOD

Assumptions/Simplifications

- Convert conductors to an equivalent rectangular foil
- Foil fills the winding window.
- Does not apply to litz windings
- Two winding transformer only
- Sinusoidal excitatiion

Sources of Error

- Field not parallel to layer surface
- Converting round wires to equivalent foils
- Neglecting edge effects
- Does not consider skin effects

Advantages

- Very simple to perform
- Accuracy good enough for most designs

ESTIMATING WINDING LOSSES IN TRANSFORMERS:
LITZ OPT

Assumptions/Simplifications

Squared field derivative method is very accurate.

Limitations:

Does not accommodate multifilar designs.
Does not accommodate foil windings.

Advantages

Litz wire losses can be estimated.
No limit on the number of windings.
User can specify current waveform.
User can specify winding placement.
Allowance for gap effects.
Easy to use.

Developed by:

Jennifer Pollock and Charles Sullivan
Thayer School of Engineering at Dartmouth

Available as a Matlab download or run on-line at:

http://power.thayer.dartmouth.edu

LITZ OPT PROGRAM OPTIONS

CURRENT WA VEFORM

A. Sinusoidal: the waveform is modeled as a sinusoid.

B. Piece-wise linear: the user specifies the exact shape of the current waveform in each winding.

APPROXIMATION METHOD:

A. One dimensional: quick and easy, but less accurate.

B. Two dimensional: more accurate.

WINDING PLACEMENT

A. Standard layered: Litz opt will choose the winding placement in a standard layered geometry.

B. Specific geometry: The user chooses precisely where to place each winding.

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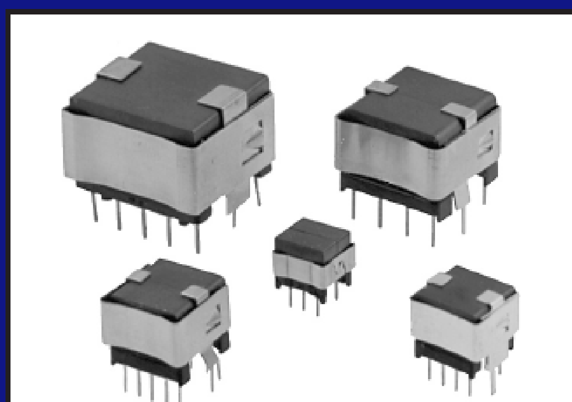
DESIGN EXAMPLE: FULL BRIDGE INPUT, PUSH PULL OUTPUT

Design Specifications:
- 85 Vdc input
- 48 Vdc output
- 250 kHz frequency
- 95 watts power
- EMI critical
- Minimize footprint

Choose WCM403 EP20 Geometry

SWITCH MODE TRANSFORMERS
WCM 403 Series



PRODUCT DESCRIPTION

West Coast Magnetics' 403 series transformers are ideal for switch mode power supply applications where very low emitted electromagnetic radiation is a priority. This type of transformer is also used in broadband small signal transmission applications. The cubic shape of the 403 series core and bobbin provides exceptional shielding and facilitates high PCB packing densities.

FEATURES - BENEFITS

RoHS compliant

Very low EMI • High PCB packing densities • Standard gapped cores from stock • Design assistance from West Coast Magnetics • Adaptable to UL,CSA,VDE safety agency requirements • SMD mounting available for small sizes

DESIGN EXAMPLE: FULL BRIDGE INPUT, PUSH PULL OUTPUT

DESIGN CONSTANTS

Size Code	SMD	A_L ungapped	A_L single gap	Ae core area (mm^2)	le magnetic path length (mm)	Ve core volume (mm^3)	Wa bobbin winding area (mm^2)	WaAc core area x winding area (mm^4)	Bobbin window width (mm)	Bobbin window height (mm)	Mean length per turn (mm)
EP 7	Yes	750min	63	10.7	15.7	162	3.8	39	3.2	1.3	18.0
EP 10	Yes	750min	63	11.3	19.2	217	11.4	129	5.4	2.1	21.3
EP 13	Yes	1600± 25%	100	19.5	24.2	472	13.8	269	7.4	1.9	23.8
EP 17	NA	2500±25%	100	33.7	28.5	966	18.8	637	9.3	2.0	28.7
EP 20	NA	4000±25%	160	78.7	39.8	3100	33.2	2590	11.9	2.8	40.8

OUTPUT POWER VS FREQUENCY OF OPERATION (WATTS)

Size Code	25 kHz	50 kHz	100 kHz	250 kHz	500 kHz
EP 7	1.0	1.3	1.7	2.7	3.1
EP 10	2.9	3.9	5.1	8.0	9.0
EP 13	5.4	7.3	9.7	23.9	17.2
EP 17	11.6	15.4	20.4	31.9	35.9
EP 20	32.8	43.7	58.8	91.2	103.0

DESIGN EXAMPLE: FULL BRIDGE INPUT, PUSH PULL OUTPUT

Rth = 29 degrees C per watt

Allow 1 Watt total losses

Budget 500 mW core and 500 mW copper.

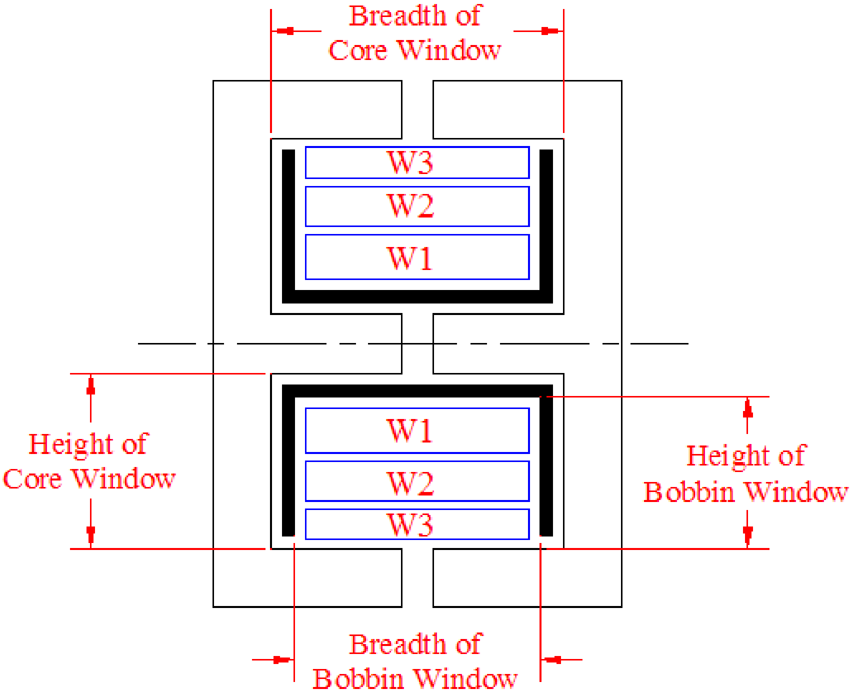
At 85 Vdc in we need 15 turns using Mag Inc P material to meet our core loss budget. .

We will use a 9 turn secondary which will get us to 48 Vdc at a duty cycle just under 50%.

Run LitzOpt to determine copper losses.

Choose 2 dimensional, piece-wise linear current waveform standard layered geometry.

LITZOPT INPUT PAGE: WINDING PICTORIAL



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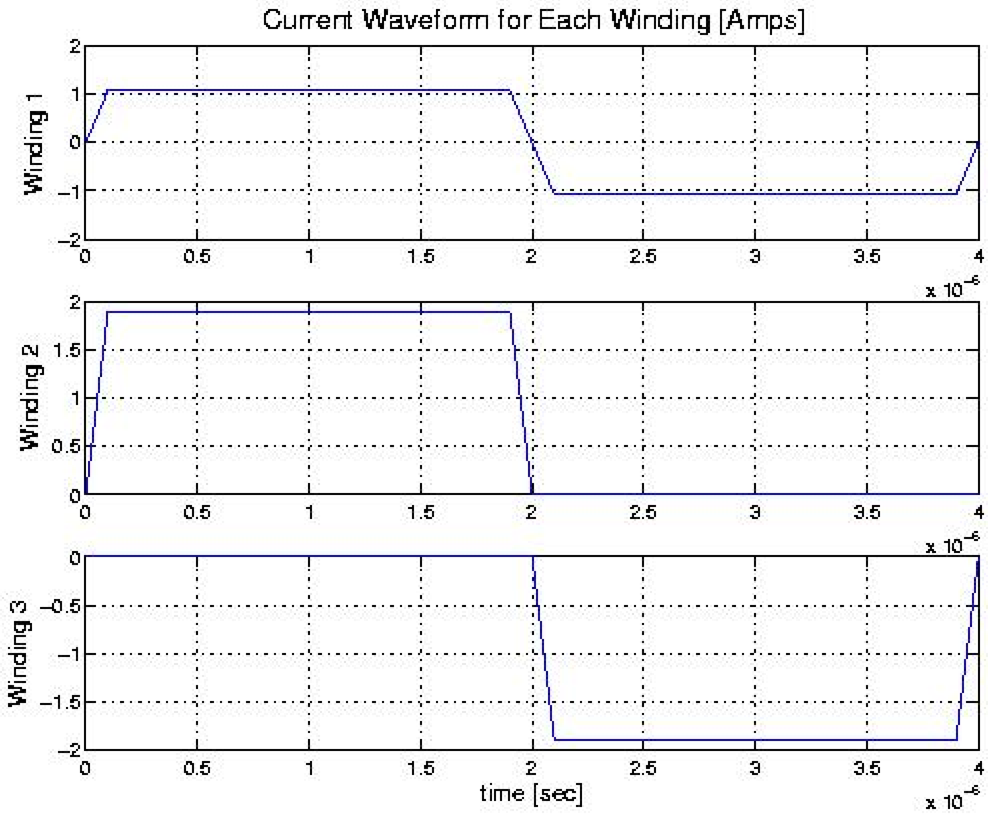
LITZ OPT INPUT DATA

Variable	Value	Units
Temperature	25	Degrees C
Maximum Achieveable Packing Factor	.33	
Breadth of Core Window	13.97	mm
Height of Core Window	3.56	mm
Breadth of Bobbin Window	11.90	mm
Height of Bobbin Window	2.80	mm
Number of Windings	3	
Number of Time Segments	6	
Centerpost Diameter	8.99	mm
Winding Wire Insulation Build	Single Build Insulation Heavy Build Insulation	

LITZ OPT: CURRENT WAVEFORMS



MORE LITZ OPT INPUT DATA

Winding Information				
Number of Turns				
Time Segments	**Current**	**W1**	**W2**	**W3**
Microseconds	at	I, amps	I, amps	I, amps
dt1	Start of dt1	0	0	0
	End of dt1			
		1.07	1.9	0
dt2	Start of dt2			
	End of dt2			
		1.07	1.9	0
dt3	Start of dt3			
	End of dt3			
		0	9	0
dt4	Start of dt4			
	End of dt4			
		-1.07	0	-1.9
dt5	Start of dt5			
	End of dt5			
		-1.07	0	-1.9
dt6	Start of dt6			
	End of dt6	0	0	0

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LITZ OPT RESULTS

Design	Gauge (W1)	Gauge (W2)	Gauge (W3)	Relative Cost	Loss in Watts	NumStrands (W1)	NumStrands (W2)	NumStrands (W3)
d1	32	32	32	0.0243	1.02	1	1	1
d2	32	32	32	0.0389	0.686	1	2	2
d3	32	32	32	0.0389	0.686	1	2	2
d4	34	32	32	0.0271	0.957	2	1	1
d5	34	32	32	0.0417	0.622	2	2	2
d6	34	32	32	0.0417	0.622	2	2	2
d7	36	34	34	0.0583	0.46	5	4	4
d8	38	36	36	0.0919	0.32	13	9	9
d9	38	36	36	0.0981	0.302	13	10	10
d10	38	36	36	0.0981	0.302	13	10	10
d11	40	38	38	0.159	0.214	32	23	23
d12	42	40	40	0.222	0.174	57	46	46
d13	44	44	44	0.368	0.164	90	113	113
d14	46	46	46	0.734	0.162	141	177	177
d15	48	48	48	2.03	0.161	221	278	278

Last Step: Choose Litz and Check Fit:

We will choose with 23/38 for each leg of the secondary and 32/40 for the primary.

Total winding losses are 214 mW, less than our budgeted 500 mW.

Diameter 23/38 served litz = 0.71 mm
Diameter 32/40 served litz = 0.66 mm

Width Primary = Dia. x (turns+1) = 11.8 mm
Width each Secondary = Dia. x (turns+1) = 7.4 mm
Height = Sum of winding heights plus thickness of 4 layers of tape = (0.71+0.71+.66)+(3x0.09) = 2.35 mm

DESIGN EXAMPLE: FULL BRIDGE INPUT, PUSH PULL OUTPUT

Bobbin Dimensions are 11.9 mm by 2.8 mm

Primary width: 11.8 mm, fits in one layer.
Each half of the secondary is 7.4 mm wide, fits easily.
Total winding height is 2.35 mm or 83.9% of the bobbin height. This exceeds 80% and should be reduced.

Total winding losses are 214 mW, far less than our budgeted 500 mW so we can reduce the litz stranding to achieve a better fit.

I chose to use 32/40 litz on all the windings. It is possible to go back into Litz Opt and determine losses for this choice of litz, but this is not necessary because:

a. copper losses are well below our budget.
b. litz stranding chosen is finer which will result in lower AC winding losses.

DESIGN EXAMPLE: FULL BRIDGE INPUT, PUSH PULL OUTPUT

FINAL WINDING SPECIFICATION:

W1= Secondary 1 = 9 turns 32/40 spread evenly in one layer across the bobbin.

W2 = Primary = 15 turns 32/40 in one layer, close wound.

W3 = Secondary = 9 turns 32/40 spread evenly in one layer across the bobbin.

COMPLETED TRANSFORMER:

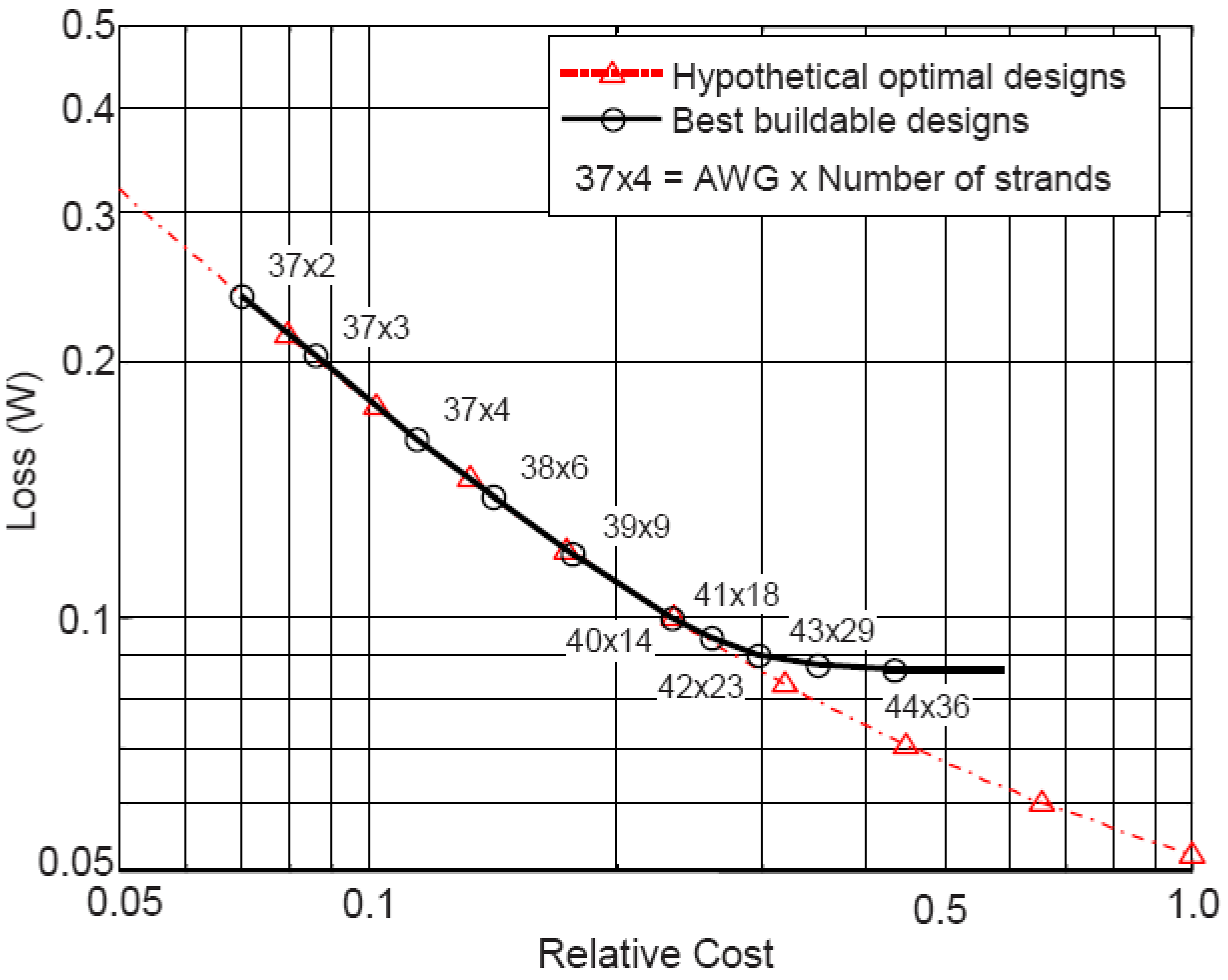
Package Size = 1.08” length by 1.00” width by 0.815” height.

Power: 95 Watts

Frequency 250 kHz

Hot spot temperature rise less than 40 C, no forced air.

COST VS. LOSS TRADEOFF: LITZ WIRE STRANDING



CONCLUSIONS

- For transformers operating at switch mode frequencies, the AC winding losses can exceed DC winding losses significantly.
- There are a limited number of tools available to the transformer designer for quick and accurate prediction of winding losses.
- LitzOpt is a freeware program which allows the user to create quick and accurate winding loss calculations with a high degree of flexibility.

ACKNOWLEDGEMENTS

The presenter gratefully acknowledges the work of the following individuals:

- Charles Sullivan, Professor of Electrical Engineering, Thayer School of Engineering at Dartmouth
- Jennifer Pollock, PhD Candidate, Thayer School of Engineering at Dartmouth College

Shape Opt design tool available at: **http://power.thayer.dartmouth.edu**