Reinventing Inductors:
Economical Gap Foil Technology Lowers Power Loss & Creates Energy Savings

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Introduction

The process of power conversion is used in an extremely large number of devices that perform a wide variety of functions. Identifying ways to improve the magnetics of power electronics has the potential to provide ground breaking reduction in energy costs. Indeed, inductors are often one of the largest, most expensive and volumetrically inefficient items in a power converter.

Two principal mechanism for loss in magnetic components are:

- Core losses
  - Magnetic properties of the core material
- Winding losses
  - AC & DC resistance in the conductive material

New Inductor Technology: Cut Foil

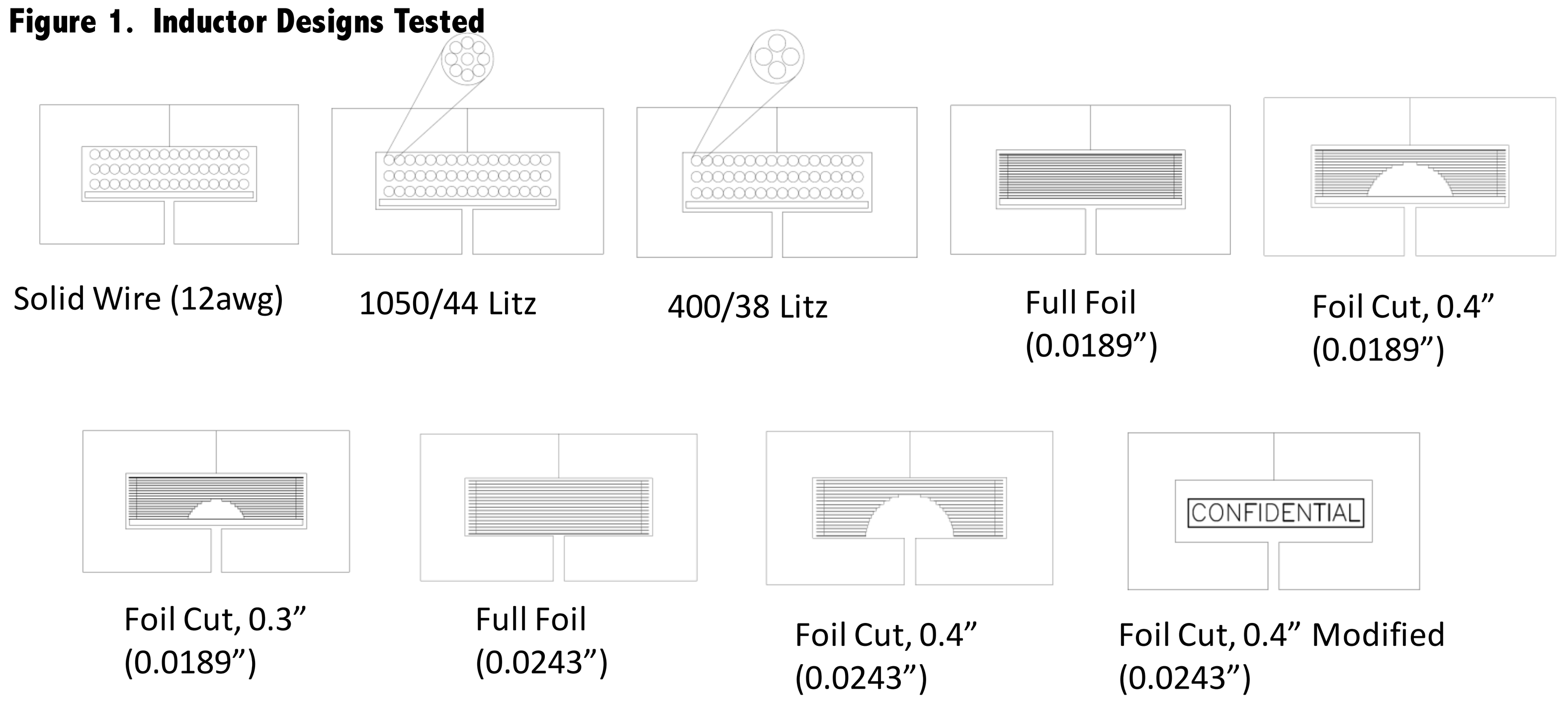
In general minimizing losses is a trade off. For instance, reducing AC resistance by the use of Litz wire can drastically increases DC resistance. While foil windings provide improvement due to their low DC characteristics, the AC resistance is relatively high. West Coast Magnetics (WCM), in collaboration with Dartmouth College has developed a new method of reducing overall winding losses in inductors that significantly reduces AC resistance with only a small increase in DC resistance using gap foil designs (see Figure 1, Foil Cut Inductors)[1-5].

Experimental Design

Nine different winding styles were explored (Fig 2). Conventional windings chosen were typical of best practice techniques and included 12 awg solid wire, full foil in two thicknesses, as well as 800/38 Litz (400/38 bifilar) and 3150/44 (1050/44 trifilar). Four different shaped foil windings were chosen to be representative of the potential shaped foil technology.

In order to compare various types of windings, the same low loss gapped ferrite E core for all the inductor designs.

Figure 1. Inductor Designs Tested



Results

A. DC Resistance

DC resistance was measured for each inductor design when connected to a voltmeter and current generator.

Table 1. DC Resistance

Winding Type	Rdc (mOhm)
12 awg Solid Wire	4.28
Litz 1050/44 trifilar	7.68
Litz 400/38 bifilar	7.24
Full Foil (0.0189")	2.44
WCM Foil cut, 0.4" cutout (0.0198")	3.46
WCM Foil cut, 0.3" cutout (0.0189")	2.75
Full foil (0.0243")	2.16
WCM Foil cut, 0.4" cutout (0.0243")	2.66
WCM Foil cut, 0.4" cutout modified (0.0243")	3.90

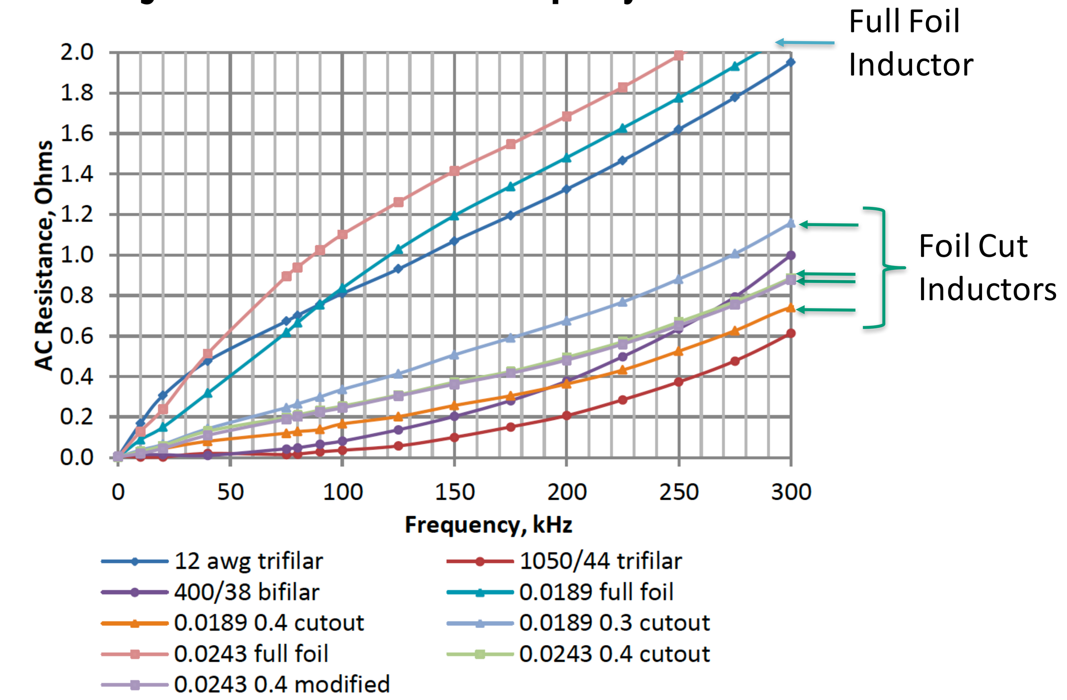
B. AC Resistance

Testing was conducted using an Agilent 4285A Precision LCR Meter for values between 75 kHz to 1 MHz. The HP/Agilent 4275A LCR meter was used for frequencies between 10 kHz to 75 kHz.

Figure 2 is a portion between the ranges of 0-300 kHz. When the frequency of an inductor is increased, the AC resistance follows as well. Their slope would be dependent on the winding style chosen.

AC resistance shows a substantial decrease over the frequency range from the traditional full foil inductor.

Figure 2. AC Resistance *vs.* Frequency



C. Power Loss

Power loss in the winding is derived by both AC and DC resistances as depicted in this following equation:

$$Loss\ (Watts) = (I_{dc})^2 * (R_{dc}) + (I_{ac,rms})^2 * (R_{ac})$$

Where Idc is direct current, Rdc is DC Resistance, Iac,rms is the AC ripple current, and Rac is the AC Resistance.

The data was based off of a 30 amp DC current which was chosen because it was close to the level supportable by the core and gap geometry without saturating the core. Tests were performed 10 kHz, 20 kHz, 40 kHz, 80 kHz, and 100 kHz. Representative data at 20 kHz and 80 kHz are shown in Figure 3 and 4.

Figure 3. Loss vs. Ripple, 20 kHz

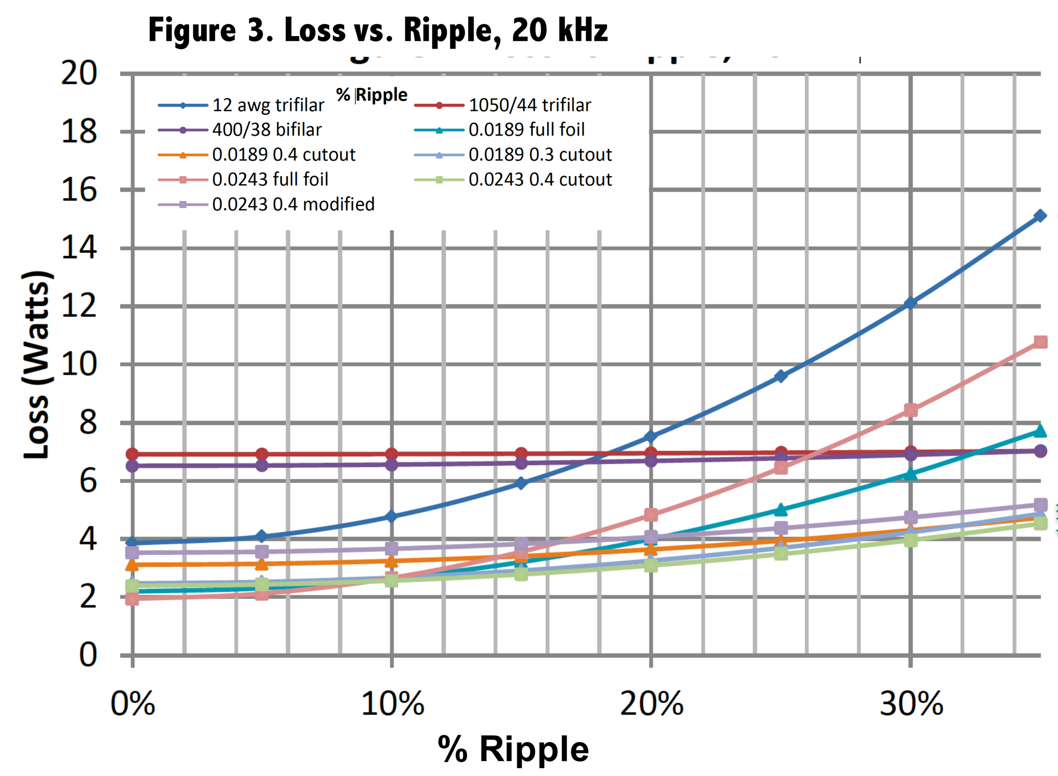
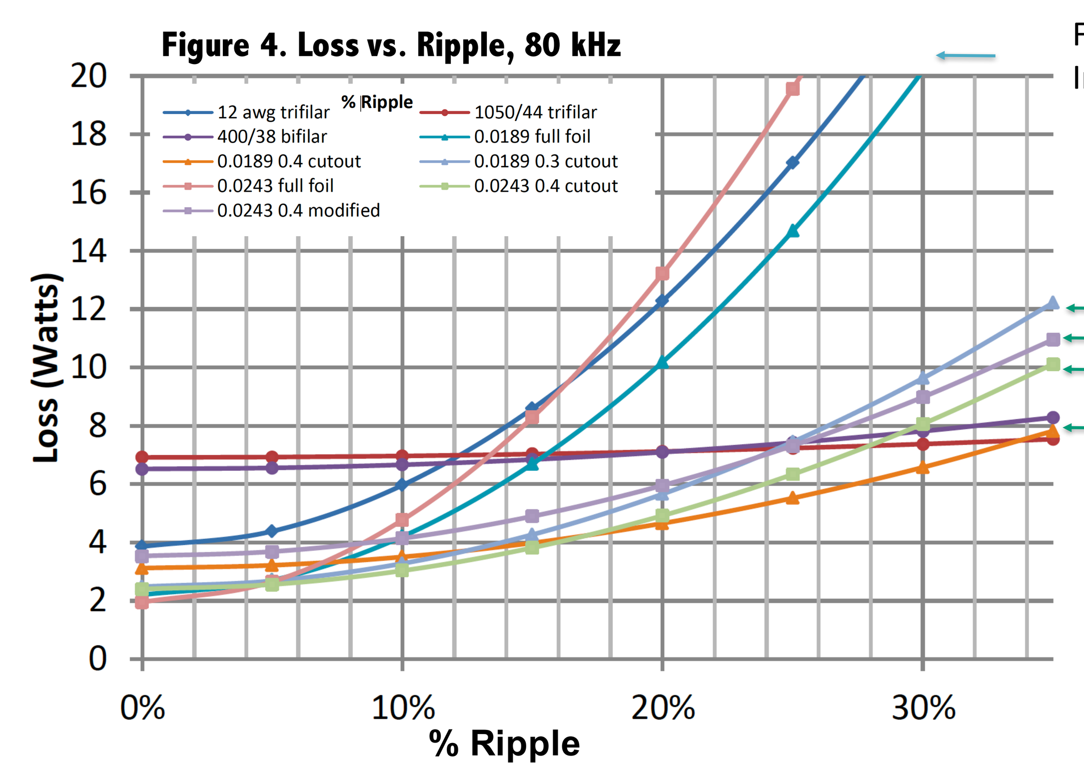


Figure 4. Loss vs. Ripple, 80 kHz



The new WCM foil cut technology showed a large decrease in power loss compared to the original full foil design. Comparing the 0.0243" full foil with the 0.0243" 0.4" modified cutout at 30% ripple, the great decrease in loss is easily recognizable (Table 2).

Table 2. Total Winding Loss at 30% Ripple

Frequency	Conventional Full Foil (loss, Watts)	WCM Design 0.4" Modified Cut Foil (loss, Watts)	Percent Decrease
10 kHz	5.43	4.07	25%
20 kHz	8.42	4.74	44%
40 kHz	15.82	6.50	59%
80 kHz	27.32	8.98	67%
100 kHz	31.70	10.14	68%

Offering a good compromise between cost and performance, 400/38 Litz bifilar was a good comparison to the new foil cut technology. On average, the 0.0243" 0.4" modified design showed a decrease of 44%, 39%, 27%, 17%, and 16% at 10 kHz, 20 kHz, 40 kHz, 80 kHz, and 100 kHz, respectively.

The new foil cut technology demonstrated that it would be a less expensive option to achieve higher efficiency when compared to the 400/38 bifilar Litz.

D. Cost Comparison

Offering similar performance results, the new foil cut technology offers a less expensive alternative. Factoring in a production run of 1000 parts, the 0.0243" 0.4" modified cutout would total $3,760 vs. $19,993 or $10,101 for the 1050/44 or 400/38 Litz winding alternative in material cost. The advantage of using foil cut technology is that cut copper

Table 3. Cost Breakdown per 1000 Parts

	$/lb Copper	$/lb Copper Recovered	Copper Weight (lb)	Bobbin	3M56 Tape	3M Turfquin	Cost for Parts (Copper Only)	Recovered Copper	Total Cost
12 awg	$5.06	-	488.02	$3.06	$100	-	$2470	-	$5,630
1050/44 Litz	$49.74	-	388.41	$3.06	$100	-	$16,883	-	$19,933
400/38 Litz	$19.81	-	350.36	$3.06	$100	-	$6,941	-	$10,101
Full Foil (0.0189")	$4.91	$4.00	873.25	-	-	$332	$4,288	-	$6,860
0.4" Cutout (0.0189")	$4.91	$4.00	873.25	-	-	$332	$4,288	$356	$7,324
0.3" Cutout (0.0189")	$4.91	$4.00	873.25	-	-	$332	$4,288	$356	$5,904
Full Foil (0.0243")	$5.18	$4.00	1142.48	-	-	$332	$5,918	-	$6,260
0.4" Cutout (0.0243")	$5.18	$4.00	1142.48	-	-	$332	$5,918	$1,135	$5,125
0.4" Cutout modified (0.0243")	$5.18	$4.00	1142.48	-	-	$332	$5,918	$2,500	**$3,760**

Conclusions

- West Coast Magnetics has shown that it is possible to create an inductor winding with very low DC and AC resistance at a cost lower than conventional alternatives including Litz, solid wire, and full foil.
  - A 70% decrease in power loss was achieved compared to the traditional full foil designs.
- Component cost savings and overall energy savings are easily achievable with the new foil cut winding technology.
- At frequencies of 10 kHz and above, and medium to high ripple current conditions, this new technology outperforms all of the conventional alternatives with measurably and in some cases dramatically lower overall winding loss.

Acknowledgement

West Coast Magnetics would like to acknowledge Dr. Charles R. Sullivan in the guidance of choosing various foil cut out designs.

References

1. R. Goldhahn, "Low AC Resistance Foil Inductor," West Coast Magnetics.
2. J. D. Pollock, C. R. Sullivan, "Modelling Foil Winding Configurations with Low AC and DC Resistance," Thayer School of Engineering at Dartmouth College.
3. J. Pollock, C. R. Sullivan, "Gapped-Inductor Foil Windings with Low AC and DC Resistance," *IEEE Industry Applications Conference*, 2004.
4. US Patent 11/547.831
5. Provisional Patent PCT/US/44297