Low AC Resistance Foil Cut Inductor

West Coast Magnetics

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***Abstract*—New foil cut inductors reduce AC resistance in gapped inductors while maintain a low DC resistance as well. This decrease in AC resistance will increase the efficiency of the inductor and decrease power losses. This new foil cut technology is examined in a 110 uH center leg gap inductor using various cut out shapes as well as different winding styles to gather comparative data. Maintaining a low cost and high efficiency are two primary goals for the new winding design.**

I. INTRODUCTION

Power electronics are used in many applications all over the world. Identifying a way to improve these devices would be ground breaking and a great way to reduce costs through energy savings. The use of power electronics would be greatly improved because inductors are often one of the largest and most expensive items in a power converter.

Inductor efficiency is limited by the loss of the inductor which is caused by core losses and winding losses. Core loss can be reduced through material choice whereas winding losses require a little more finesse. To decrease the loss in the winding, both AC and DC resistances must be reduced.

West Coast Magnetics has developed a new method of reducing overall winding losses in inductor, utilizing a new foil cut technology developed by the Thayer School of Engineering at Dartmouth. Typically, foil windings are a great improvement over standard wire wound inductors due to their low DC characteristics. The downside is that the AC resistance in foil windings is relatively high in comparison to the other winding styles. This paper dives into the comprehensive testing of the foil cut windings and compares them to the traditional windings styles of magnet wire and litz-wire.

II. SET UP

A. Inductor Design

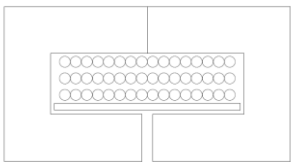
In order to compare various types of windings, this experiment used the same low loss gapped ferrite E core for all the experiments. The core was E71/33/32 geometry and the material was Ferroxcube 3C90. The center leg was gapped to a total of 2.64mm where each core half was gapped 1.32mm to maintain a centered air gap. Testing was conducted using the same core for all the windings, and the windings were all 16 turn windings. This insured that all the variables except for the winding itself were fixed.

Nine different winding styles were explored; one solid wire, two litz variants, two full foil variants, and four foil shape cutout variants. Each winding has a total of sixteen turns on a rectangular bobbin which maximized the winding window. Each winding also spans 1.55” across the bobbin maintaining similar cross sections. The bobbin was made of 0.05” thick fiberglass. The inductors created were designed for operations up to 30 Amps DC with a maximum of 35% AC ripple with an inductance value of 110 uH.

The first winding consisted of a solid 12 gauge magnet wire. This was wound trifilar in three layers and connected in parallel. Two served litz wire winding styles were employed using different wire strands. The first stranding was 1050/44 served litz, the second was 400/38 served litz. The 1050/44 served litz was wound trifilar whereas the 400/38 was wound bifilar to accommodate the 1.55” winding length. Both windings were wound in four layers.

Two full foil windings were used as a baseline to compare the new foil cut technology windings. The copper foils used were 0.0189” and 0.0243” thick; both 1.55” in width. The insulating material between each layer was 0.003”x1.69” Nomex. The foil cut outs were 0.4” and 0.3” radius circles. The center of the semicircle cut was the center of the air gap along the edge closest to the winding. The modified 0.4” cutout employs a technique to save copper by keeping the width across each layer the same while shaping the foil around the center gap and away from the corners to reduce AC resistance.

Conventional windings were chosen which were typical of best practice techniques. The conventional windings 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.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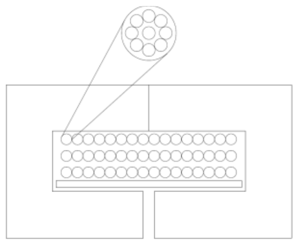
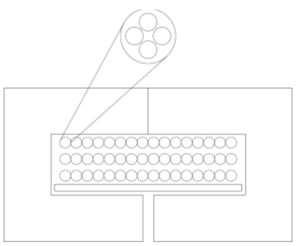

1050/44 Litz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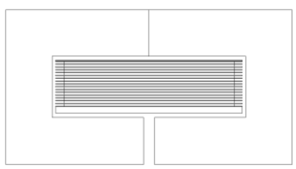
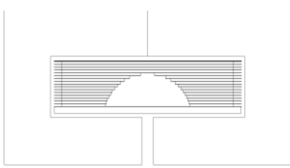
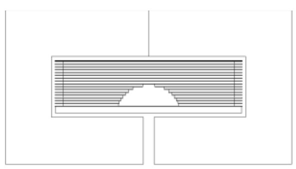
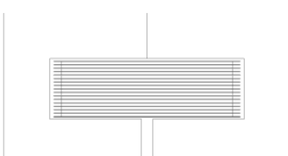
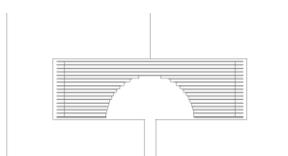

Full Foil (0.0189")


0.4" cutout (0.0189")


0.3" cutout (0.0189")


Full foil (0.0243")


0.4" cutout (0.0243")

0.4" cutout modified (0.0243")

III. RESULTS

A. DC Resistance

To obtain the DC resistance, parts were connected to a voltmeter and current generator (see Figure 1). Using Ohm's law, $V = I * R$, the resistance can be determined.

Figure 1: Circuit Diagram

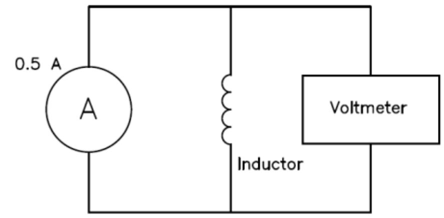


Table 1: DC Resistance

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
0.4" cutout (0.0189")	3.46
0.3" cutout (0.0189")	2.75
Full Foil (0.0243")	2.16
0.4" cutout (0.0243")	2.66
0.4" cutout modified (0.0243")	3.90

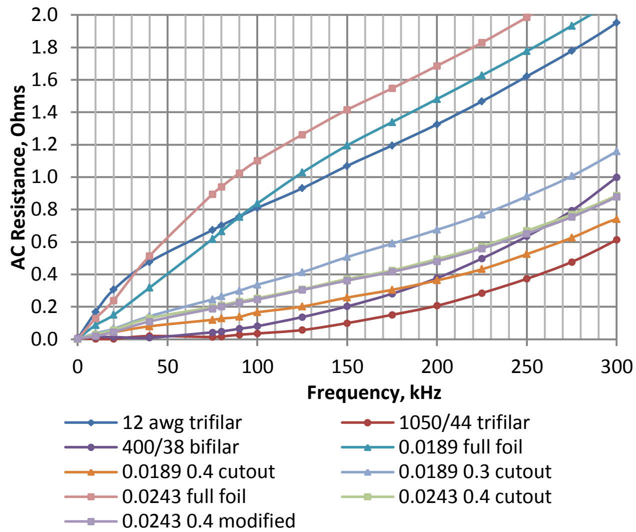
B. AC Resistance

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.

Lead exits for all inductors were all cut to 3.0" from the edge of bobbin and tinned 0.5". The foil cut inductors required two lead exits for the start leads which exited outwards away from the core gap and were joined in parallel outside of the winding.

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.

Figure 2: AC Resistance vs Frequency



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

C. Power Loss

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

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

Where I_{dc} is direct current, R_{dc} is DC Resistance, $I_{ac,rms}$ is the AC ripple current, and R_{ac} 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. The following graphs are results based off of 10 kHz, 20 kHz, 40 kHz, 80 kHz, and 100 kHz (Figures 3 to 7, respectively):

Figure 3: Loss vs Ripple, 10 kHz

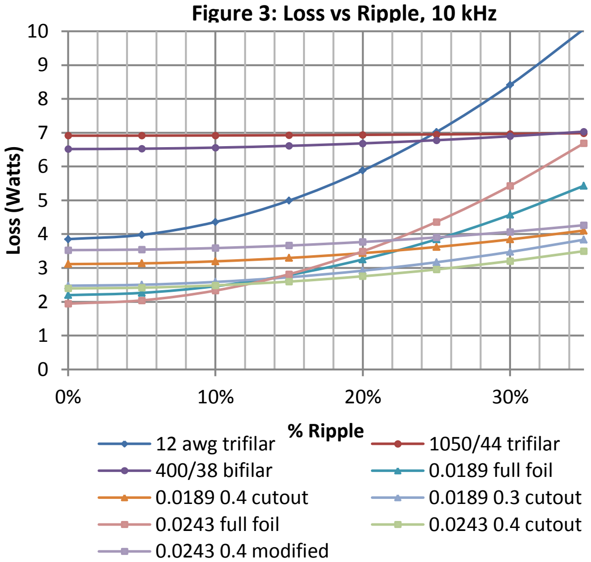


Figure 4: Loss vs Ripple, 20 kHz

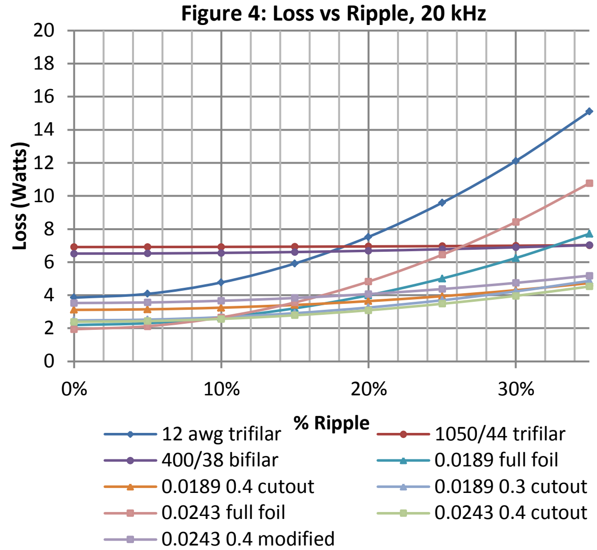


Figure 5: Loss vs Ripple, 40 kHz

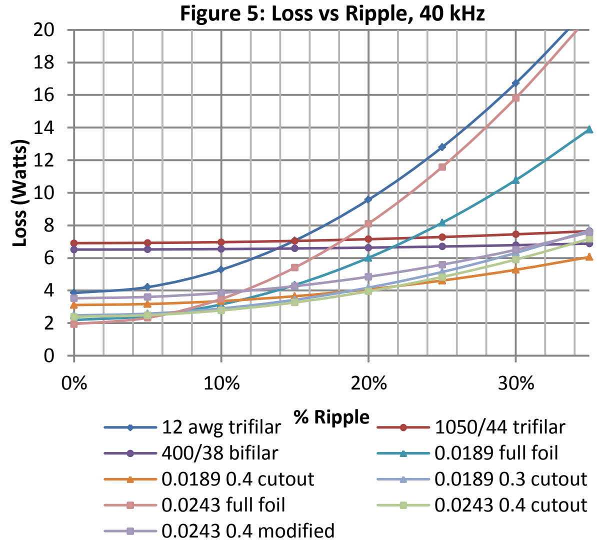
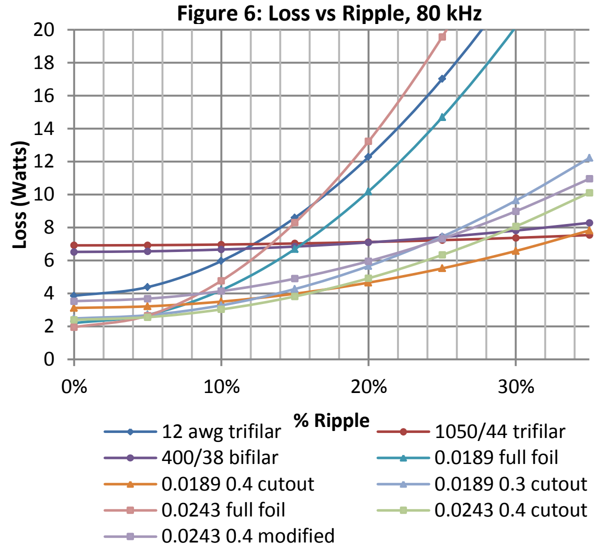
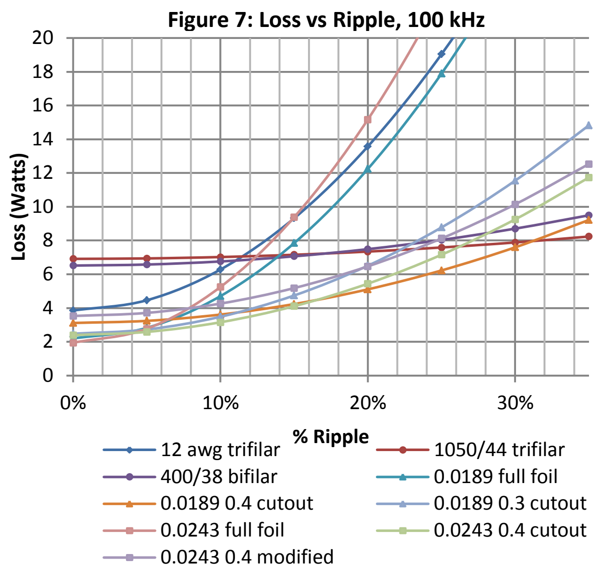


Figure 6: Loss vs Ripple, 80 kHz





The new 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	0.0243" full foil (loss, Watts)	0.0243" 0.4" modified cutout (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 can be recycled close to the original cost minimizing he total cost as seen in Table 3.

Table 3: Cost Breakdown

	$/lb copper	$/lb copper recovered	Copper weight per 1000 parts (lb)	Bobbin	3M56 Tape for 1000 parts	3M Tufquin for 1000 parts	Cost for 1000 parts (copper only)	Recovered copper cost for 1000 parts	Total cost for 1000 parts
12 awg	$5.061	-	488.02	$3.06	$100	-	$2,470	-	$5,630
1050/44 litz	$49.74	-	388.41	$3.06	$100	-	$16,833	-	$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	-	-	$342	$5,918	-	$6,260
0.4" cutout (0.0243")	$5.18	$4.00	1142.48	-	-	$342	$5,918	$1,135	$5,125
0.4" cutout modified (0.0243")	$5.18	$4.00	1142.48	-	-	$342	$5,918	$2,500	$3,760

IV. CONCLUSION

The findings through West Coast Magnetics and Dartmouth College demonstrate that cost savings and energy savings are easily achievable with the new foil cut winding technology. A 70% decrease in power loss compared to the traditional full foil designs can only continue to decrease with further optimizations by decreasing the AC resistance in the winding. West Coast Magnetics has shown that it is possible to create a winding with very low DC and AC resistance at a cost lower than conventional alternatives including litz, solid wire, and full foil. At frequencies of 10 kHz and above, and medium to high ripple current conditions, this new technology outperforms all of the conventional alternatives detailed in this paper with measurably and in some cases dramatically lower overall winding loss.

ACKNOWLEDGMENT

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