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Gapped-Inductor Foil Windings with Low AC and DC Resistance

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Abstract—A new configuration for foil windings in gapped inductors reduces ac resistance while maintaining very low dc resistance. Thus, it is particularly valuable for current waveforms composed of a large dc component with high-frequency ripple. The new technique is applied to an example 50 μH inductor in which several different winding cross sections are compared. Finite-element simulations confirm that losses can be reduced by a factor of five relative to standard foil windings.

I. INTRODUCTION

MANY inductors must carry a large dc current with an ac ripple riding on it. Even if the ripple is small compared to the dc current, large ac resistance can result in large ac losses. Most methods for reducing ac resistance in an inductor winding sacrifice the dc resistance, and with large dc currents, this becomes unacceptable. Foil windings have low dc resistance, but with multilayer windings, ac loss can be proportional to the number of layers squared. This and the effect of the air gap in the core can drastically increase ac resistance. This paper develops a new configuration for foil windings in gapped inductors that can reduce ac resistance substantially with little impact on dc resistance, and thus is particularly useful for current waveforms that contain a large dc component with a high frequency ripple riding on it as in most dc-dc converter circuits. The traditional rectangular winding cross-section, in which the foil spans the entire winding window, is modified by removing copper from the region near the air gap in the core. The resulting designs have much lower loss than conventional foil windings as verified by numerical field simulations.

Previous work done on shape-optimized inductor windings has addressed round-wire or litz-wire windings [1], [2], [3], but little work has addressed shape-optimized foil inductor windings. One exception is [4] in which foil windings are shaped to match the flux lines created by a gapped high-permeability core. Although the method in [4] could be very effective in reducing losses, it is not practical to construct windings in the complex shapes that are proposed. In contrast, the method proposed here is simple and easy to manufacture.

Section II contains a discussion of ac and dc loss in foil windings. Section III discusses how to choose the notch shape for low-loss foil windings. The notch shapes discussed in Section III are evaluated in Section IV using numerical field simulations and the results are discussed. An optimization program to design V-notch foil windings is developed in Section V. The calculations

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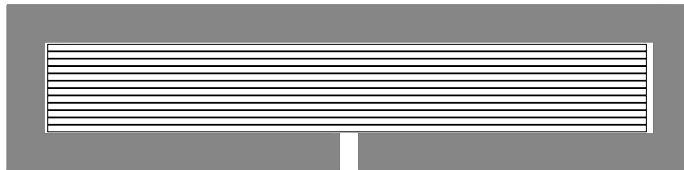


Fig. 1. The cross section of a traditional rectangular foil winding in which each layer occupies the entire width of the winding window. The core is shown in gray.

used to estimate power loss are developed in Section V-A and the optimization method based on them is presented in Section V-B.

II. DC AND AC LOSS IN FOIL WINDINGS

Multilayer windings, such as the traditional rectangular cross-section foil winding shown in Fig. 1, can have high losses at high frequencies partly because currents in the top layers induce eddy current in each of the intervening layers between the current where the MMF is produced and the gap or opposing winding where the MMF is dropped. The ac resistance can be several orders of magnitude larger than the dc resistance, and even in an inductor that carries a large dc current with a small ac ripple current (a dc choke), the ac loss can be large. To get lower ac resistance in a multilayer winding, one can use thinner layers, but this increases the dc resistance, and so is not viable in an application with high dc current.

In single-layer windings, the ac resistance is increased, because the current only flows in a layer one skin-depth thick, but the increase is not as severe in a multilayer winding. And a crucial advantage of single-layer windings in applications with large dc current is that the layers may be made very thick with no penalty in ac loss. The current flows in a layer one skin-depth thick, regardless of the total thickness, so the thickness can be increased for low dc resistance without degrading ac resistance.

In a foil winding, a single layer corresponds to a single turn, which is rarely practical. In order to achieve the advantages of a single layer in allowing thick foil, without the excessive ac resistance that normally occurs in multilayer windings, we propose to cut the foil before winding, such that each turn has an area that directly faces the gap with no intervening layers of copper. The high-frequency current can flow on this surface. Fig. 2 shows a foil winding with a V-notch section of copper removed from the region of the air gap in the core. The foil can now be as thick as space permits, since thick foil no longer degrades ac resistance. Removing some of the copper increases

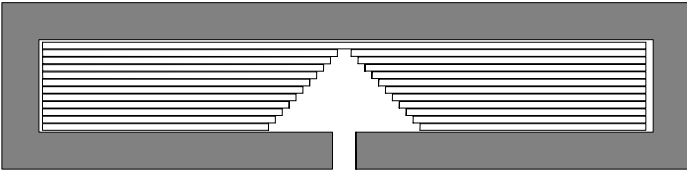


Fig. 2. The cross section of a V-notch foil winding. The gapped core is shown in gray.

dc resistance somewhat, but by properly selecting the amount of copper removed, we can, as shown below, improve overall performance dramatically. In this paper, we compare the ac and dc resistance of various shaped notches to determine the lowest resistance winding designs.

Foil windings are relatively easy to manufacture compared to solid-wire or litz-wire windings. The new foil winding configuration proposed in this paper does not impose difficult or expensive manufacturing challenges. Since the foil is cut before winding, the only additional step is to cut out a shaped piece of copper of the appropriate dimensions from the center of the foil.

III. CHOOSING SHAPES

A V-shaped notch in a foil winding can reduce the high-frequency ac resistance greatly. However, other shapes may offer greater benefits. The influence of shape has been studied extensively through finite-element simulations, some of which are presented in Section IV. However, it is not practical to simulate all possible shapes to find those that perform best. Thus, we sought to develop a qualitative understanding of how shape influences current distribution, in order to guide the search for the best shapes. The discussion below is not a rigorous proof of what shapes are best, but rather is a general explanation of the thought process that guided our search for good shapes. The finite-element analysis (FEA) in Section IV was necessary to confirm the intuitive ideas discussed here.

At frequencies where the skin depth is small compared to the winding dimensions, a total current of NI must flow on the inside surface of the notch in a notched winding, where N is the number of turns (assumed to be equal to the number of layers of foil) and I is the terminal current. Ideally, the total surface current NI would be implemented by a current I in each layer, flowing at the edges of the notch. However, if there is current flowing elsewhere—typically along the top and/or bottom of the foil—the total current can match the terminal current with a different current at the edge. For example, Fig. 3 shows a winding with the edges of the lower foil layer next to the gap carrying half of the terminal current I , and the top layer carrying $1.5I$ near the gap. However, there are equal and opposite currents in the top and bottom of each foil making the total current equal to I in each layer. The currents on the tops and bottoms of foil layers typically have a much larger area to flow in than the currents at the edge facing the gap, and so the associated losses are relatively small.

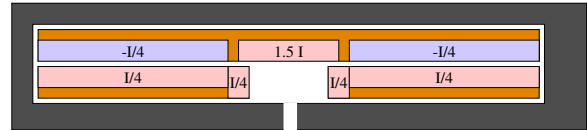


Fig. 3. Hypothetical current distribution in a winding with two layers of foil.

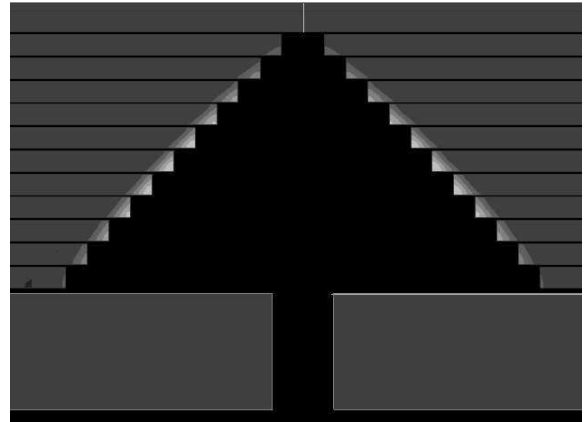


Fig. 4. Current density in a V-notch winding. Lighter areas correspond to higher current density. We see that the highest current density is in the center of the side, where the distance to the gap is smallest.

Considering the possibilities suggested by the above discussion and Fig. 3, to minimize ac resistance, we wish to shape the notch based on three objectives: First, we wish to maximize the area of edges of the notch facing the gap, so that the total current NI flowing there is carried by a wide cross sectional area. Second, we wish to achieve uniform current density around the circumference of the notch to minimize losses. Third, we ideally would like the edge current in each layer to be equal to the terminal current, so as to minimize the top and bottom currents that must flow as in Fig 3. However, because of the wide area typically available for this "redistribution current", the losses associated with this are small, the first two criteria (large area at the edge of the notch and uniform current density around its circumference) are the most important.

The relative current density around the circumference of the notch is determined primarily by distance to the gap—shorter distances lead to higher current density. This is because current will flow in the lowest-inductance path. The fringing field between the gap and the winding is smaller if the current flows closer to the gap, and so the paths closest to the gap are associated with the smallest field and lowest inductance. This effect is illustrated in Fig. 4. The layers whose edges have the highest current density are the middle layers. This can be explained by the fact that they are the closest to the gap.

In order to keep the current density uniform, it is best to keep the distance to the gap the same everywhere on the edge of the notch. Thus, a semicircle is a desirable shape for a notch. The radius of the semicircle should be equal to the height of the winding, in order to maximize the area of the edge of the notch, and to expose all layers to face the gap.

The ac resistance is not, however, the only factor to consider—

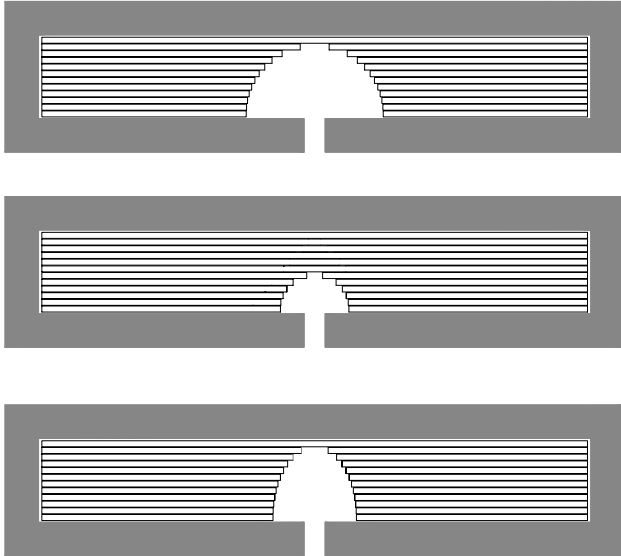


Fig. 5. Three possible notch shapes to consider: a) Full semicircle that is expected to minimize ac resistance. b) Smaller semicircle as a way to decrease dc resistance, and c) ellipse as a way to decrease dc resistance.

one must also consider the dc resistance. Thus, we must consider how to modify the ideal notch shape that gives minimum ac resistance to get lower dc resistance when that is more important. For a semicircle notch, two possible compromises are to use a smaller radius semicircle, such that only the lower layers are notched, or to use an ellipse with height equal to the height of the winding, but with decreased width compared to the full semicircle. The smaller semicircle maintains equal distance to the gap, but reduces the circumference greatly and does not expose all layers to the gap, thus necessitating the redistribution of currents via current flow on the tops and bottoms of layers as in Fig 3. The ellipse does not decrease the circumference as much, and it maintains the exposure of each layer to the gap, but it sacrifices the equal distance to the gap.

After considering and simulating many other possibilities, we believed that the best possibilities were the straight-sided V-notch for its simplicity and easy of manufacturing, the full-size semicircle for its potential to provide the lowest ac resistance, and two candidates for situations in which lower dc resistance is desired: smaller semicircles and ellipses. To select between these options required quantitative analysis, as discussed in the next section.

IV. EVALUATING SHAPES

The performance of the new foil winding shapes was evaluated using a commercial finite-element package (Ansoft Maxwell). The validity of finite element analysis (FEA) for determining losses in power magnetics is not examined here, because its accuracy has been well established in published literature (e.g.,[5]–[8]), as discussed in [9].

The winding cross-sections shown in Fig. 1, Fig. 2 and Fig. 5 were simulated using FEA for the example 50 μ H inductor

TABLE I
INDUCTOR SPECIFICATIONS

Specification	Value	Units
Inductance	50	[μ H]
Number of Turns, N	12	NA
DC current, I_{dc}	170	[A]
Peak-to-Peak Ripple Amplitude	8.5	[A]
Ripple Frequency	30	[kHz]
Core	Metglas AMCC-125	NA

described in Table I. The results of these simulations are shown in Fig. 6 where the ac resistance is plotted versus the dc resistance at 30 kHz for the V-, semi-circle- and ellipse-shaped notches. Each point represents a design with a different size notch.

In the cases of the V-notch and elliptical-notch designs, the widths of the notches are varied as the height is kept equal to the height of the winding. For the semi-circular notch design, the radius of the semicircle can vary from zero to the height of the winding.

In Fig. 6, it can be seen that there is a minimum point on each curve, where a specific notch size yields a minimum ac resistance. The semi-circle-notch appears to be the optimal shape since it has the lowest ac resistance for any given dc resistance. The semi-circle notch is unique because the entire surface of the notch is an equal distance from the gap in the core. This results in a relatively uniform current distribution along the surface of the notch. The elliptical-notch design has higher ac and dc resistance compared to the semi-circle design until the width of the ellipse approaches the height of the winding and becomes a semicircle. At this point, the ac and dc resistance become essentially the same for these two designs. The resistance of the V-notch winding is slightly higher than the semi-circle-notch winding, but the ease of manufacturing a V-notch winding may make it the most practical winding notch shape.

The ac and dc resistance of the full rectangular winding cross-section, shown in Fig. 1, is a point plotted as a star in Fig. 6, and can be used to compare the improvements in resistance made by the notched winding designs. The full rectangular cross-section has the lowest dc resistance compared to any notched winding design and is the best design when the inductor current is almost purely dc with only a negligible ac component. However, even small ripple currents can create significant loss with the high ac resistance of this design, and, as shown in Fig. 6, a notch can rapidly decrease ac resistance with very little increase in dc resistance, providing an improvement even for small ripple ratios. We define ripple ratio, r_r , which is important in determining ac losses, as:

$$r_r = \left(\frac{I_{ac_{pp}}}{I_{dc}} \right) \quad (1)$$

where $I_{ac_{pp}}$ is the peak-to-peak ripple current. The optimum notch size depends on ripple ratio.

Fig. 7 shows the same curve of dc resistance versus ac resistance for the semi-circle notch design as shown in Fig. 6, but with contour lines of constant total power loss added, calculated based on 5% ripple. The contour lines are spaced logarithmically,

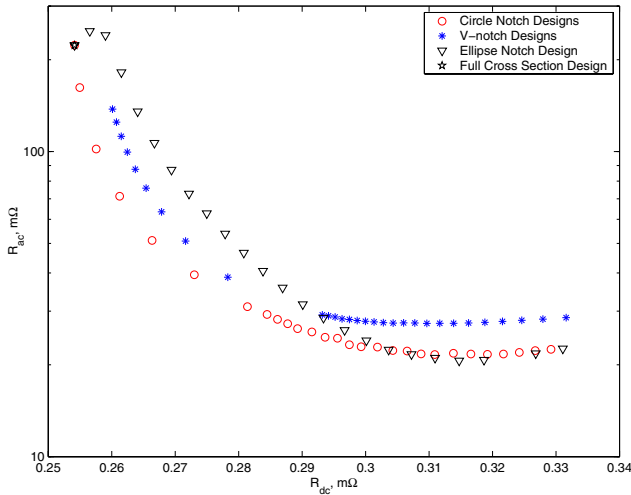


Fig. 6. The ac resistance plotted versus the dc resistance at 30 kHz for three possible notch shapes over a range of notch sizes to evaluate performance.

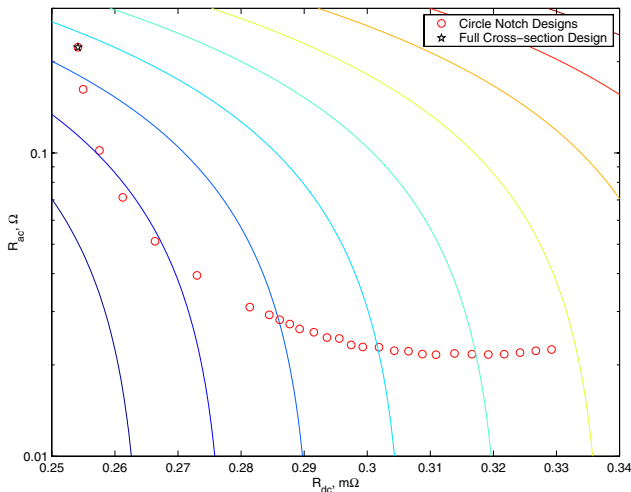


Fig. 7. AC resistance plotted versus dc resistance for semi-circle-notch winding and the full cross-section winding, as in Fig. 6, with contour lines of constant total power loss for a ripple ratio of 5%. The contour lines are spaced 5% change in total loss apart; the lowest loss is found at the lower-left hand corner and the highest loss is found at the upper-right hand corner of the plot. The lowest loss design has about 8% lower loss than the full cross-section design.

with the spacing between lines corresponding to a 5% increase in loss. In Fig. 7 the lowest-loss semi-circle-notch design is approximately 1.5 contours below the full cross-section design (marked with a star). This corresponds to an 8% reduction in loss. Fig. 8 shows the same data as Fig. 7 except at a ripple ratio of 20% instead of 5%. At 20% ripple, there are approximately 20.5 contour lines between the full cross-section design and the lowest loss semi-circle-notch designs which indicates about a 63% reduction in loss. These figures show that even at small ripple, such as 5%, the proposed method provides significant reduction in loss (8% in this example). With moderate ripple, the improvement is much greater. In this example, with 20% ripple, the losses are reduced by better than a factor of two. Here the optimal notched

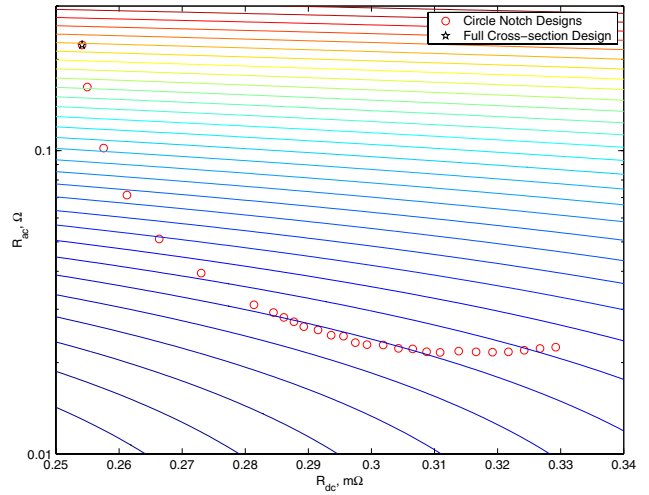


Fig. 8. AC resistance plotted versus dc resistance for semi-circle-notch winding and the full cross-section winding, as in Fig. 7, but with contour lines of constant total power loss for a ripple ratio of 20% instead of 5%. With a higher ripple ratio, the lowest loss semi-circle design has about 63% lower loss than the full cross-section design.

winding designs were determined graphically using the data from many FEA simulations for one example inductor. To facilitate designing notched-winding inductors without the need to run many FEA simulations for each design, we would like to have a simpler method to approximately calculate losses. A simple approximate loss calculation can then be used to automatically optimize winding designs. The preliminary development of such a loss calculation and optimization program is outlined in the next section.

V. DESIGN

A preliminary version of an optimization program to design notched foil windings was developed in MATLAB [11]. The optimization attempts to determine the size of the notch that minimizes total power losses, which are calculated based on the simplified estimates described below. Improvements to the predicted loss calculation are needed in order to adequately capture the behavior observed in the finite-element simulations and accurately predict losses.

A. Power Loss Estimation

The total power loss is calculated by summing the ac and dc loss components. The dc component of loss is calculated by $P_{dc} = I_{dc}^2 R_{dc}$, where the dc resistance, R_{dc} , is equal to $R_{dc, total} = \sum_{i=1}^N \frac{\rho l_i}{A_{dc, i}}$ and $A_{dc, i}$ is the cross-sectional area of the i^{th} layer, l_i is its length, and ρ is the resistivity of copper.

The ac power loss is computed for each harmonic of the ripple frequency and then summed to give the total ac power loss,

$$P_{ac, total} = \sum I_j^2 R_{ac_j} \quad (2)$$

where I_j is the amplitude of the current for the j^{th} harmonic and R_{ac_j} is the resistance for the j^{th} harmonic. The resistance

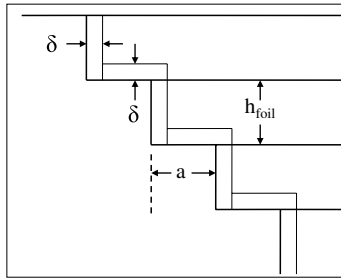


Fig. 9. The area used to approximate where the ac current flows in the winding. The area is calculated for each harmonic.

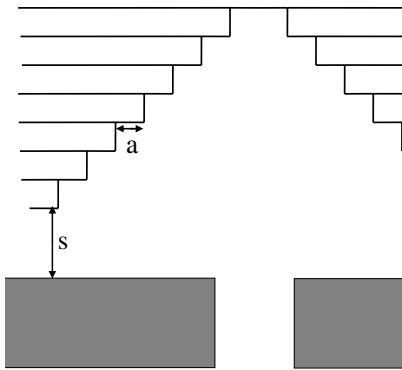


Fig. 10. This figure shows the parameters a and s which are optimized to determine the lowest loss cross section. The core is shown in gray.

for each harmonic is calculated based on an estimate of the cross sectional area where the current will flow. As shown in Fig. 9, the area of current flow for the j th harmonic, A_{acj} , is approximated by rectangles that are a skin depth, δ , thick by the height of the foil, h_{foil} or the length of the foil gap increment, a . The resistance of the bottom layer is estimated based on [9]. There are two important effects described in Section III and observed in finite-element simulations that are not modelled by this method. The power loss estimation neglects the current redistribution effects shown in Fig. 3 and the non-uniform current distribution shown for the V-notch design in Fig. 4.

B. Optimization Method

Given the method for the calculation of power loss in Section V-A, standard numerical optimization algorithms can be used to find the optimum values of the geometrical parameters a and s for the V-notched designs as defined in Fig. 10 to minimize total estimated loss. We used the Nelder-Mead simplex algorithm as implemented in the MATLAB function `fminsearch` [12].

This approximate method has been applied to the same example design discussed in Section IV and detailed in Table I; results are shown in Fig. 11. For comparison, we also include optimized litz-wire windings, designed using the technique in [13]. Above about 5% ripple, the V-notch winding shows significantly smaller losses than the full-width winding in both the approximate loss estimate and the FEA results. For example, the FEA results show

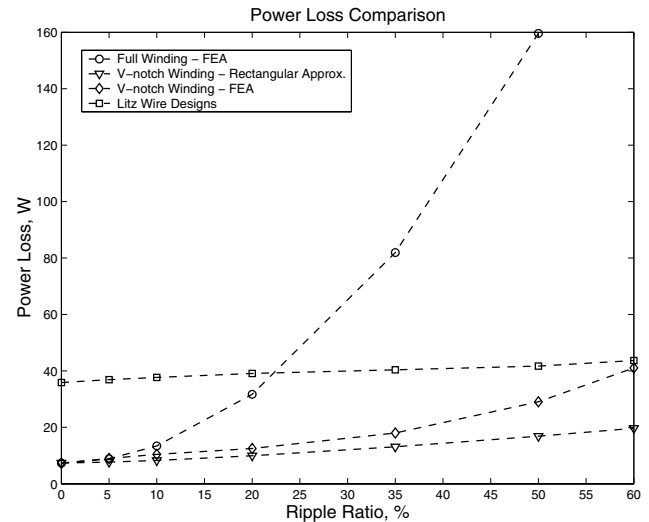


Fig. 11. This plot shows the winding loss for a full width cross-section given by FEA simulation and the winding loss for the rectangular approximation and FEA simulation for a V-notch cross-section.

that at 10% ripple, the losses in the full-width winding are 22% higher than the losses in the V-notch winding. This improvement is seen even though the V-notch was designed based on the simple method described in Section V-A; a more accurate loss calculation would facilitate a better choice of V-notch size, which would further reduce losses. When the ripple ratio is 35%, the V-notch design reduces losses by 78% compared to the full-width design, based on the FEA simulations for each. When the ripple ratio is greater than 60%, the design with litz wire gives lower losses than the V-notch winding shape found by the rough optimization method. The V-notch provides the lowest loss for ripple magnitudes between 5% and about 60%, a range that includes most dc-dc converters. Semi-circle notches and better optimization of notch size will improve on this performance.

VI. CONCLUSION

Significant reductions in winding losses can be achieved by modifying the shape of the cross section of a foil winding. Numerical field simulations show that notched windings can have much lower losses than full-width designs. V-notches are simple to cut and work well. Semi-circular notches can provide even better performance. The size of the notch should be chosen based on the current waveform—larger notches should be used with higher ripple ratios. Optimization using a simple approximation of the winding losses that has limited accuracy is nonetheless successful at producing designs with better performance than the full-width windings, as confirmed by the finite-element simulations. The new foil winding configuration presented here provides a substantial reduction in power loss and is easy to manufacture.

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TABLE II

COMPARISON OF WINDING LOSSES. THE SIZE OF THE V-NOTCH IN DESIGNS INCLUDED HERE WAS CHOSEN USING THE APPROXIMATE OPTIMIZATION METHOD DISCUSSED IN SECTION V.

Ripple Ratio	Length of Foil Gap in Bottom Layer	Full Width FEA AC Loss	V-notch FEA AC Loss	V-notch Rectangular Approx. AC Loss	Full Width FEA Total Loss	V-notch FEA Total Loss	V-notch Rectangular Approx. Total Loss	Litz Wire Total Loss
%	mm	W	W	W	W	W	W	W
0	0	0	0	0	7.345	8.455	7.347	35.9
5	2.30	1.523	1.563	0.2404	8.867	9.012	7.699	36.9
10	5.12	6.090	2.850	0.6840	13.43	10.44	8.287	37.7
20	13.15	24.36	4.499	1.870	31.71	12.51	9.929	39.1
35	25.73	74.61	9.189	4.070	81.95	18.02	13.11	40.4
50	35.54	152.3	19.41	6.712	159.6	29.08	16.87	41.7
60	40.72	219.3	30.85	8.775	226.6	41.08	19.67	43.7

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