Aluminum Windings and Other Strategies for High-Frequency Magnetics Design in an Era of High Copper and Energy Costs

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Aluminum Windings and Other Strategies for High-Frequency Magnetics Design in an Era of High Copper and Energy Costs

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***Abstract*—Recent Cu price increases motivate careful examination of approaches to minimize Cu use in high-frequency transformers and inductors. Approaches that can reduce Cu use without increasing losses include careful winding design, trading winding volume for core volume, replacing Cu with Al, and using Cu-clad Al (CCA) windings. Al wire is particularly attractive. The cost of Al is lower than it might appear from the cost per unit mass when the much lower density of Al is also considered, and the disadvantage of higher resistivity becomes less important when high-frequency effects are considered.**

***Index Terms*—Cu-clad Al (CCA).**

I. Introduction

FROM May 2005 to May 2006, Cu prices nearly tripled, as shown in Fig. 1. This is after nearly doubling the year before. In 2006 and 2007, prices fluctuated rather than monotonically rose, but prices remained four times higher than typical prices five to ten years earlier. It is reasonable to expect future prices to be both high and volatile. This calls for reconsideration of the Cu content in any cost-sensitive product; in power electronics, transformers and inductors typically have the largest amount of Cu.

At the same time that Cu prices are rising, energy prices are also rising, and global warming is generating serious concern. Thus, sacrificing efficiency to save money on Cu is not an attractive or responsible option. Fortunately, there are ways to decrease Cu usage without decreasing efficiency. For the high-frequency windings used in transformers and inductors in power electronics applications, skin-depth effects mean that much of the Cu in a high-frequency winding often carries little or no current, and careful design can eliminate this excess without increasing losses. In addition, reducing the amount of Cu can reduce proximity-effect losses, and can, in some cases, lead to an overall decrease in losses. A core geometry for a given power-handling capability can be adjusted to use a larger volume of core material and a smaller volume of Cu. And, of course, there is the possibility of using higher switching frequencies to reduce the overall size of magnetic components in high-frequency power converters (which are already much smaller than their line-frequency equivalents).

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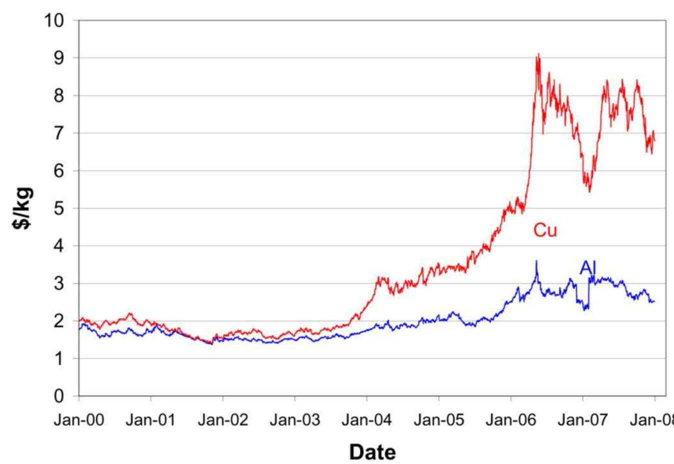

Fig. 1. Cu and Al commodity prices in U.S. dollars per kg, based on New York prices from [2].

It is also possible to completely eliminate the Cu content by substituting Al windings. Although the price of Al spiked in May 2006 along with Cu, the price per kg averaged 40% of the price of Cu in 2007 (Fig. 1) Because the resistivity is normally expressed in $\Omega \cdot \mathrm{m}$ (or $\mu\Omega \cdot \mathrm{cm}$), rather than on a basis related to mass, the cost per unit volume, shown in Fig. 2, is more relevant. On this basis, Cu cost 8.4 times as much as Al, on average, in 2007. Considering this order-of-magnitude cost difference, the 64% higher resistivity of Al compared to Cu is quite tolerable. For the same conductor length and resistance, the cross-sectional area, and thus also volume, of Al must be 1.64 times that of Cu. The cost of an Al conductor is then $1.64/8.4 = 0.195$ times the cost of a Cu conductor with the same length and resistance. Although the cost difference decreases after the cost of drawing and insulating magnet wire is added, Al can still provide dramatic savings. Additionally, because the drawing and insulating costs are not subject to the volatility of metal prices, switching to Al can reduce exposure to price volatility by better than a factor of five, even if the overall cost reduction is somewhat more moderate.

It is impossible to predict future Cu and Al prices, but some insight can be gained by comparing reserves and production rates for Cu and Al. World Cu reserves are given by [1] as 480×10^6 metric tons, which, dividing by 2006 consumption of 15.3×10^6 tons [1] gives 31 years. This should not be taken as a prediction that we will run out of Cu in 31 years: The rate of production is rapidly increasing which could result in depletion much sooner, but continued price increases could drive reductions in consumption and increases in recycling, postponing

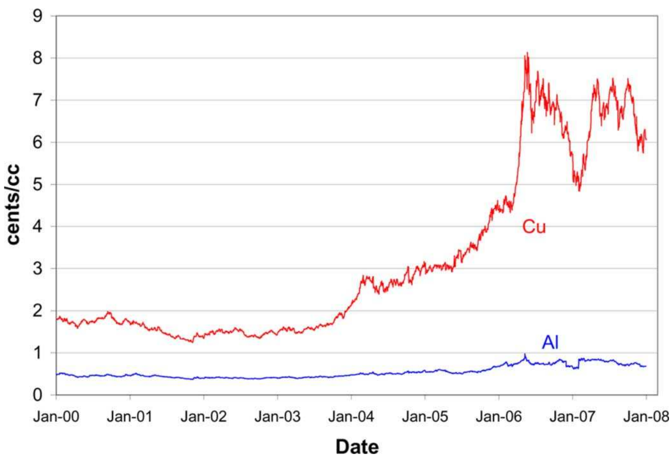

Fig. 2. Cu and Al commodity prices in U.S. cents per cubic centimeter, based on New York prices from [2].

depletion. Furthermore, the figure for reserves is based on resources that are economically recoverable at present prices; additional deposits would become economically recoverable with an increase in prices. However, the 31-year ratio for Cu can be compared to the ratio for the bauxite ore which is used for producing Al, in order to get a qualitative impression of likely future price trajectories. World bauxite reserves of 25×10^9 tons divided by annual production of 177×10^6 tons [1] yields 141 years, 4.5 times the ratio for Cu. The volume of Al that could be produced from the world bauxite reserves is about 3 $(\mathrm{km})^3$, 55 times the 54×10^6 m^3 volume of the world Cu reserves. From these comparisons, one can expect that the cost advantage of Al will persist or increase in the long term.

Though already widely used in large line-frequency transformers and lamp ballasts, Al wire is rarely used in high-frequency windings. Presumably this is because the quantities of Cu involved are smaller in typical high-frequency windings, and the cost savings possible by switching to Al have not been considered necessary or worth the extra difficulty of terminating Al windings. With present high Cu prices, it is no longer possible to ignore the cost savings possible with Al. Furthermore, as we show both theoretically and experimentally in Section III, the advantage of Al can be even greater at high frequency than it is at line frequency. We also discuss methods for terminating Al windings.

II. Efficient Use of Copper in Windings

Whether driven by thermal or efficiency considerations, power loss in windings is always a critical constraint. In high-frequency windings, the loss comprises simple ohmic losses due to the dc resistance and rms current $P_r = I_{rms}^2 R_{dc}$ and eddy-current losses due to circulating currents induced by changing magnetic fields. Eddy-current losses include skin-effect losses, due to fields in a conductor generated from the current within that same conductor, and proximity-effect losses, due to fields generated by other conductors, and influenced by the core and gapping configuration.

In multiturn components, proximity effect is dominant over skin effect. Two strategies that can effectively control proximity-effect losses are the use of a single-layer winding, or the use of multiple layers that are each thinner than a skin depth [3]–[6].

In a single-layer winding, high-frequency current flows on the surface, effectively in a layer one skin-depth deep. The skin depth is given by $\delta = \sqrt{\rho/(\pi f \mu_0)}$ where ρ is the resistivity, f is the frequency of the current waveform, and μ_0 is the permeability of the conductor, equal to the permeability of free space in most conductors. In a thick conductor, the current density actually decays exponentially with distance into the conductor, but the loss is the same as if it were uniformly distributed in a layer one skin depth deep. Based on this simple conceptual model, we see that making the layer thicker than a skin depth is a waste of Cu, unless the current contains a dc component that can utilize the additional thickness. A more accurate calculation, based on [7], [8], shows that the loss is actually minimized with a layer thickness $h = \pi\delta/2$, at which point the loss is 15% lower than in a layer one skin-depth deep.

In multilayer windings, loss calculations become more complex, and are different for planar layers such as foil or printed-circuit windings [9], single-strand round wire [5], [10], [11], or litz wire [12], [13]. In many cases, the optimum design does not fill the bobbin [6], [14]–[16]: filling the bobbin both uses more Cu and causes more loss. This underlines the importance of careful design according to the approaches described in, for example, [5], [6], [14]–[16], and also indicates that many existing designs that have full bobbins have the potential for reduction of both loss and Cu usage.

A. Configurations for Reducing Fields in the Winding

The conductor size is not the only factor that influences the proximity-effect loss. The proximity effect is a result of the field in the winding. Because the geometry of the winding, core, and particularly, any gaps in the core can have a strong effect on the field configuration, they can also strongly affect the proximity-effect loss. Geometry changes that reduce proximity-effect loss can allow reductions in the amount of Cu used without an overall increase in loss.

In transformers, the most common and effective way to improve the field intensity in the winding region is to interleave primary and secondary winding sections [5], [6], [17]. Another approach is to stretch the aspect ratio of the winding window. A large breadth, extending the border(s) between the windings, increases the reluctance of the leakage flux path and thus decreases the field and the proximity-effect losses. One approach to optimizing aspect ratio is addressed in [17]. Both interleaving and large winding breadth also are advantageous in reducing leakage inductance, although they increase interwinding capacitance. One can opt to use these strategies either to reduce loss, or to reduce the amount of copper needed to achieve a given level of loss. Part of the savings in copper cost could in some cases cover the added manufacturing cost incurred by interleaving.

In inductors, the field configuration is dominated by the gap placement [5], [18]–[22]. For wire or litz-wire windings, turns that are close to the gap incur the highest loss. If the portion of the winding window nearest the gap is left empty, the proximity-effect loss is reduced, although the dc resistance is increased compared to a design that uses the full window [5]. As with any winding design, there is a tradeoff between eddy-current effects and ac resistance, but it is possible to effect large reductions in eddy-current losses with only a small increase in dc resistance by removing Cu only from the region of highest eddy-current loss. Thus, there is an opportunity to reduce both total loss and the amount of Cu used. Optimization of the shape and size of the region left open is discussed in [19]–[22]; software to perform such an optimization is available for free download or use online at [23].

Another way to reduce eddy-current loss in gapped inductors is the use of multiple, small gaps to approximate a lower permeability material which would act as a distributed gap. Although this "quasi-distributed" gap approach does not directly reduce the Cu usage, the loss reduction it provides can allow reducing the amount of Cu used without incurring extra loss. Formulas and guidelines for calculating the loss in foil or planar windings with quasi-distributed gaps are given in [5], [18].

B. Core Volume versus Winding Volume

A given transformer or inductor's power-handling capability and efficiency can be achieved either with a small core cross section and a large winding area, or vice versa. If Cu prices are high relative to ferrite prices, it makes economic sense to use a larger core cross section and a smaller winding area. In 2007, Cu commodity prices averaged 6.5 US cents per cubic centimeter (6.5 $\mathrm{cent/cm^3}$). The volume of a winding also includes air and insulation which decreases the cost per volume. However, the cost of drawing and insulating the wire increases the cost, such that the overall cost per unit volume may be on the same order as the commodity price of Cu, 6.5 $\mathrm{cent/cm^3}$. Ferrite prices are more variable, depending on factors such as the material grade and the core shape and size. However, they are typically much lower than the present cost of Cu windings, and can be under 1 $\mathrm{cent/cm^3}$. Thus, minimum cost is likely to be found with a large core cross-sectional area and a small winding area. Careful optimization of shapes including this ratio as well as the window aspect ratio [17] is recommended for high-volume applications. Unfortunately, the designer is typically limited to standard core geometries, and cannot specify the optimum geometry for each design.

A survey of standard core geometries, such as ETD, EC and EE, shows that ratios of window area to core area are usually in the range of one to two, with about 1.3 being typical. However, the range of PQ and RM cores includes some with much lower ratios as is preferred with high Cu costs. The aspect ratios of the winding windows in PQ and RM cores also tend to be relatively square, which is more favorable for gapped-inductor windings [22], but is less favorable for leakage and eddy-current considerations in transformers.

To reduce winding area and cost, one can also use a larger core and leave the winding window largely empty. Although this is wasteful in the sense that the window could in principle be shrunk to fit the winding, saving both core cost and core loss, it can be a cost-effective solution in some situations where small production quantities do not merit custom core design and tooling.

III. Aluminum in High-Frequency Windings

As described in the introduction, the cost of an Al conductor is dramatically lower than the cost of a Cu conductor for the same resistance and length. In this section, we first examine that comparison more carefully, and in particular, consider the implications of resistivity at high frequency. Next, we consider the practical issues of termination and insulation, and finally we briefly compare the environmental impacts of Cu and Al. The use of Al in low-frequency transformer windings is well established; reference [24] has extensive information on practical aspects. However, little has been written about the use of Al for high-frequency windings.

TABLE I
Physical Properties of Copper and Aluminum

	Cu	Al	units
Resistivity, pure	1.67	2.65	$\mu\Omega$cm
Resistivity, conductor grade	1.72	2.83	$\mu\Omega$cm
Temperature coefficient of resistivity	4027	4308	ppm/K
Density	8920	2700	kg/m^3

A. Performance and Cost

Relevant physical properties of Cu and Al are summarized in Table I. The resistivity of practical conductor grade Al, designated 1350 or EC, is 2.83 $\mu\Omega\mathrm{cm}$ at room temperature[1]. This is 64% higher than the resistivity of standard conductor grade Cu, as defined by the International Annealed Copper Standard (IACS) [25]. Comparison at room temperature is adequate, since the temperature coefficients of resistivity are very similar. As described in the introduction, the combination of slightly higher resistivity and much lower price makes Al a very attractive alternative to Cu. Based on average prices for 2007 of US$7.24/kg for Cu and US$2.84/kg for Al, the cost per volume of Al is 12% the cost of Cu. On this basis, for the same dc resistance and length, Al is 19.5% the cost of Cu.

However, at present, it is not easy to obtain ready-to-wind Al magnet wire for 12% of the cost of Cu magnet wire. Commercial availability is now poor, and prices per kg (or pound) can be similar to those for Cu magnet wire, though this may be a temporarily inflated price as a result of many low-frequency designs being changed over to Al following the recent rise of Cu prices. But even at similar finished-wire prices, the cost per unit volume of Al is only 30% that of Cu. The cost for equal resistance and length is still half of that for Cu wire.

Although Al is clearly cheaper than Cu for simple conductor applications, two additional factors must be weighed in considering it for high-frequency windings: the extra space required for equal resistance and the effect of resistivity on eddy-current loss.

The requirement of extra space is a disadvantage: sometimes a larger core must be used. However, as discussed in Section II, it is often advantageous to design high-frequency Cu windings to use less than the full space available in the winding window; this can mean that the necessary space for an Al winding is already available. If it is not, a larger core may be needed, but the cost increase from a larger core is likely to be offset by the savings from using Al.

The increased resistivity of Al, while normally a disadvantage, actually confers an advantage when it comes to eddy currents, which are reduced by the higher resistivity. The extent to which this offers an advantage depends on the magnitude of the

[1]Resistivity of 2.79 $\mu\Omega\mathrm{cm}$, slightly better than 1350 specifications, is guaranteed by many manufacturers.

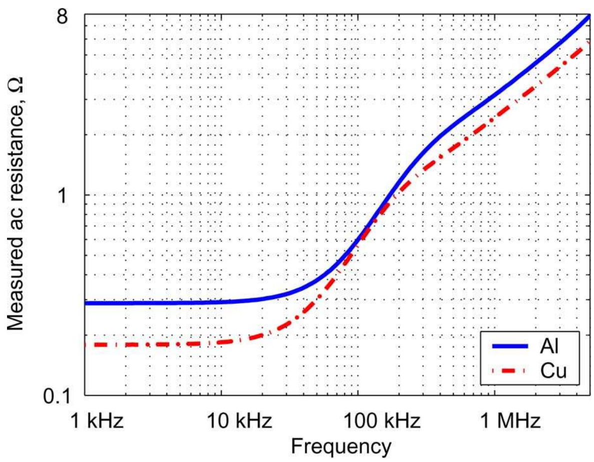

Fig. 3. Experimentally measured ac resistance of two transformers, one wound with Al and the other with Cu. Both transformers use 29 turns of 0.5 mm (AWG 24) wire, wound in two layers, for both primary and secondary, on EE-19 size ferrite (TDK PC-40) cores. The self-resonance frequency of this configuration was over 40 MHz, and thus did not introduce significant error into the measurement.

eddy currents compared to the magnitude of the ohmic losses, and the frequency of the current waveform for a given wire size. Fig. 3 shows experimental measurements of the ac resistance of two transformer windings, one wound with Al and the other wound with Cu, using the same size wire in the same configuration. At low frequency and at high frequency, the Cu winding has lower resistance, but at intermediate frequencies, the performance of the two is nearly identical.

The measured performance can be explained as follows: At low frequencies, only the dc resistance matters (eddy currents are negligible), and Al should have about 1.64 times the resistance of Cu. Thus, the measured 1.61 low-frequency ratio is as expected. At intermediate frequencies, the eddy-current losses become significant, especially in a winding with many layers. Although these windings only have two layers, the eddy-current losses are still large enough to offset the dc resistance difference and make the resistances of the two windings approximately equal. At high frequencies, the proximity-effect losses become proportional to the square root of resistivity, and the advantage of Cu reappears, but the advantage is only half of what it was at low frequency: the Al winding has about 30% higher resistance than the Cu winding.

At low frequency, Al windings can provide a cost savings despite Al's higher resistance for the same size winding. Furthermore, at high frequency, Al's disadvantage in resistance is decreased or may even be eliminated. Thus, Al can be even more advantageous at high frequency than at low frequency.

B. *Effect of Resistivity on Optimized Designs*

Our experimental measurements (Fig. 3) compared the performance of one winding design, constructed using either Al or Cu. A more important comparison is between windings that are optimized for the best performance possible with each material. The constraints of the optimization are subtly different for single-strand-wire windings, litz-wire windings, and planar or foil windings, so we consider them separately.

1) Wire Windings: Although more accurate and sophisticated models exist [5], [11], [26], [27], we use a simple model of proximity-effect loss in a wire winding [12] in order to facilitate a simple optimization that more clearly shows the effect of conductor resistivity on the final performance[2]. We describe the loss in terms of an ac resistance factor $F_r = R_{ac}/R_{dc}$, such that $P_{winding} = I_{rms}^2 F_r R_{dc}$. For a winding with a large number of layers, a wire diameter that is not too large compared to skin depth (as is the case for optimal designs), and a one-dimensional field configuration, the ac resistance factor can be approximated by

$$F_r = 1 + \frac{\pi^3 \omega^2 \mu_0^2 n^2 N^2 d^6}{3 \cdot 768 \rho^2 b_w^2} \tag{1}$$

where n is the number of strands in parallel (values higher than one are used for bifilar windings, litz wire, etc.), N is the number of turns in the winding, d is the diameter of the conductor, ρ is its resistivity, b_w is the breadth of the winding window, μ_0 is the permeability of free space, and ω is the radian frequency of a sinusoidal waveform, or the effective frequency [12], [14] of a nonsinusoidal waveform. The optimum wire diameter can be found by setting the derivative of power loss with respect to d equal to zero. This results in an optimum ac resistance factor $F_{r,opt} = 1.5$ [6], [29]–[31], and

$$R_{ac} = \frac{6}{1152^{1/3}} N^{5/3} \ell_t \left(\frac{\omega \mu_0}{b_w}\right)^{2/3} \frac{\rho^{1/3}}{n^{1/3}} \tag{2}$$

where ℓ_t is the average length of a turn.

We see from (2) that, for an optimized wire-winding design, the ac resistance is proportional to the third root of the resistivity. The 64% higher resistivity of Al compared to Cu translates into only a 18% increase in resistance for an optimized wire winding. The optimum diameter is higher with Al (proportional to $\rho^{1/3}$), and thus the volume of conductor used goes up (proportional to $\rho^{2/3}$, or 39% for Al relative to Cu). This is a smaller increase in volume than is needed for equal dc resistance, and so the cost savings from using Al is even greater than we estimated previously based on equal dc resistance: for example, the cost of the optimized Al winding is one third that of the optimized Cu winding based on a typical 1:4 ratio of cost per volume for finished Al and Cu magnet wire. A summary of these results is provided in Table II.

A factor-of-three cost savings is not bad for an 18% increase in loss. However, in some applications, any increase in loss may be unacceptable. In these cases, it may be necessary to make other changes to reduce the loss, such as increasing the core size, increasing the degree of interleaving, or increasing the number of parallel strands. The cost savings from switching to Al can typically pay for any of these modifications. For example, changing from a single strand to bifilar can bring the loss of an optimized Al winding below the loss of an optimized Cu design. It is also important to note that many Cu windings in production have not been carefully optimized; switching to Al and optimizing the design will typically reduce cost and loss.

2) Foil Windings: In a multilayer foil winding, the foil thickness that minimizes ac resistance is that which gives an ac resistance factor (ratio of ac resistance to dc resistance) equal

[2]Careful comparisons with optimization based on a more accurate model in [28] show that the designs chosen by either optimization are usually the same, though in some cases the better model provides appreciably better accuracy in predicting the loss of the optimum design.

TABLE II
COMPARISON OF OPTIMIZED AL AND CU HIGH-FREQUENCY WINDINGS

Winding Type	Relative Performance of Al Winding (vs. Cu): Loss	Raw Material Price	Wire Cost
Wire Winding (or litz, bifilar with fixed number of strands)	118%	16.5%	35%
Foil	128%	15%	
Litz with fixed strand diameter	100%	19.5%	

Based on average raw material prices for 2007 of US$7.24/kg for Cu and US$2.84/kg for Al, and an approximate finished magnet wire cost-per-volume ratio of 4:1

to 4/3 [14], based on similar approximations to those used for wire windings. The ac resistance factor is a function of the ratio of thickness to skin depth, $\delta = \sqrt{\rho/\pi\omega f \mu_0}$, Since δ is proportional to the square root of resistivity, the thickness of an optimized Al winding will be greater than the thickness of an optimized Cu winding, by a factor of $\sqrt{\rho_{\rm Al}/\rho_{\rm Cu}} \approx 1.28$. Since the dc resistance of the Al winding is then higher than that of the Cu winding by a factor $\sqrt{\rho_{\rm Al}/\rho_{\rm Cu}} \approx 1.28$, and the ac resistance factor is the same for both windings (by design), the Al winding's ac resistance is higher by the same factor $\sqrt{\rho_{\rm Al}/\rho_{\rm Cu}} \approx 1.28$. The cost ratio can be calculated from the ratio of cost per volume for the two materials, and the 28% larger volume used in the case of Al: the net result is that the Cu winding costs 6.6 times as much as the Al winding, based on metal commodity prices. These results are also summarized in Table II. The Al winding offers a dramatic cost savings with only a modest increase in loss.

3) Litz Wire: Choosing a litz-wire design entails the choice of both number and diameter of strands. A true optimum design [12] is rarely practical because it typically entails a large number of extremely fine and expensive strands. Thus, consideration of cost and loss is necessary in order to find a true optimum solution for a practical design [15]. However, Al litz wire is not widely available commercially, and thus obtaining data to construct a cost model, as done in [15], is not yet feasible. Instead, we consider cases in which the number of strands or the diameter of strands are fixed: the sub-optimal scenarios considered in [12]. The use of anodization for insulating Al litz strands may lead to further cost advantages for Al litz which are not considered in this analysis [32].

A constraint on the number of strands can be a reasonable approximation to a cost constraint for a typical litz strand diameter because the manufacturing cost of finer strands offsets the reduced material cost, making the cost proportional to the number of strands and roughly independent of their diameter. The analysis of this case is very similar to that for single-strand wire, discussed above, and the conclusions are identical; the first line of Table II applies to litz-wire windings with a fixed number of strands as well as to single-strand wire.

In the near future, Al litz wire may become commercially available. However, it may initially be available in only a limited number of strand diameters. Thus, optimization with a fixed strand diameter may be important. As shown in [12], the optimum value of ac resistance factor is, in this case, $F_{r,opt} = 2$. From (1), we then have

$$\frac{\pi^3\omega^2\mu_0^2 n^2 N^2 d^6}{3\cdot 768\rho^2 b_w^2} = 1 \qquad (3)$$

which shows that the number of strands, n, is proportional to the resistivity ρ. This leads to the surprising result that the dc resistance of the optimum design is independent of the conductor resistivity, and, given the fixed value of $F_{r,opt} = 2$, the ac resistance of the optimum design is also independent of the conductor resistivity. The commodity price of the raw materials used then show the same trend as in a dc application: for the same resistance, the cost of Al is 19.5% that of copper. However, the cost advantage may be substantially less when the full cost of producing and bundling a larger number of strands is included. These results are also included in Table II.

C. Practical Issues in Using Aluminum

1) Termination: The difficulties in terminating Al wires are well known, due to well publicized problems with overheating of connections in Al building wiring installed in the US in the late 1960s and early 1970s [33], [34]. The problems are usually attributed to a combination of Al's high thermal expansion, which loosens connections, and its tendency to rapidly oxidize in air, which degrades the loosened connections. Electromigration can also be a factor [35].

However, reliable connections to Al wires are not only possible but are widely used [34]. For example, they are used extensively in line-frequency transformers and power transmission and distribution systems [24], and are also used in virtually every semiconductor device, in which Al bond wires make the connection from the Al metalization on the die to the Cu leadframe, and are connected by ultrasonic welding. Five options for terminating Al wire are crimp connectors, screw connectors, soldering, welding, and electroplating (to prepare the wire for other termination methods). Crimp and screw connection systems specifically designed for Al wire, strip, or foil can provide reliable connections if used according to manufacturers' recommendations [34]. Some techniques include the use of anti-corrosion compounds; connectors may be pre-loaded with such a compound, or it may be applied to the conductor prior to crimping or tightening. However, crimp and screw connection systems for Al are presently available primarily for larger wire than is used in many high-frequency transformers.

Soldering Al normally requires mechanical removal of the oxide on the surface, followed by Zn-based solders with strong flux. Where mechanical abrasion is used to remove magnet wire insulation, it may be possible to also remove the oxide in the same step.

Welding of Al for electrical connections is presently used for terminations in some large transformers, and in ultrasonic wire bonding in semiconductor packaging. It is also used for some large Cu terminations, and has been proposed and successfully tested for small Cu magnet wire termination [36]. Although welding requires specialized equipment, it is reliable and simple.

Plating Cu on the ends of the lead wires allows easy soldering with standard solders and fluxes, or termination by other standard methods designed for Cu. Although Cu can be plated on Al, the process is somewhat complex, again because of the oxide. The process usually entails coating the Al with Zn to provide an oxide-free surface on which to plate Cu. Traditionally the Zn coating was added using a highly toxic cyanide-based "zincate" solution. However, cyanide-free zincate solutions are now commercially available, and zincate-free plating processes are also possible [37]. Although the process is still more complex than welding it is attractive for backwards compatibility with terminations designed for Cu wire.

2) Insulation: Conventional magnet-wire film insulations have been shown to be more stable on Al than on Cu. Cu may catalyze the thermal degradation process, whereas Al forms an inert oxide film that does not interact with the insulation [38]. Data in [24] shows life at high temperature increases by factors of about two to nine when Al is used in place of Cu with various insulation films at various temperatures. Anecdotal evidence indicates that difficulties can arise in using a Cu magnet-wire insulation process on Al without modification, and this has contributed to the present poor availability of Al magnet wire, but this situation should be resolved quickly as more manufacturers produce Al magnet wire.

Al can also be anodized to form an Al_2O_3 coating thick enough to serve as insulation. This has not been widely used on magnet wire because the brittle Al_2O_3 can crack, at least on thick magnet wire [24]. However, it is used on thinner foil or strip windings, and it may also be viable for small-diameter magnet wire or for strand insulation on individual strands of litz wire [32].

3) Mechanical Properties: Al has lower tensile strength than Cu, by about a factor of three for basic conductor grade (1350) Al. Although the lower tensile strength makes drawing fine Al wire more difficult than fine Cu wire [32], and it is easily available only in diameters larger than 100 to 300 μm, Al bond wire is commercially available down to 18-μm diameter [39]. The lower tensile strength also requires lower winding tension; fortunately, because Al is softer, less tension is necessary. The lower "springback" of Al windings [24] is particularly advantageous for winding on rectangular bobbins or forms. Some winding equipment may not be able to work consistently with the lower tension required for Al, but the necessary equipment is readily available. For example, equipment for automatically winding copper wire down to 20-μm diameter (AWG 52) should be suitable for Al wire down to 35 μm (AWG 47). Higher-strength alloys of Al [40] can also be used if breakage becomes a problem in winding or in drawing fine wire.

D. Environmental Impact

In addition to cost, environmental impact should also be considered in evaluating a possible material change. A comprehensive life-cycle analysis of environmental impacts is beyond the scope of this paper, and similarly outside the scope of what can reasonably be expected in most power electronics design work. However, a rough analysis is much better than no analysis. The European-Union "Eco-Indicator" project [41] developed a simplified method and dataset for this reason. The approach has been adopted, and adapted for the US, by the Industrial Designers Association of America for their "Okala" design approach [42]. The "Eco-Indicator" method quantifies environmental impact in terms of "points", where 1000 points roughly corresponds to the annual impact of an average European. Millipoints (mpt) are often the appropriate units for evaluating practical decisions in design work. The values given in [41] for primary Cu and Al are 1400 mpt/kg and 780 mpt/kg, respectively. As with cost, comparisons based on volume are more useful than comparisons on mass: per volume, the values can be expressed as 12.5 $\mathrm{mpt/cm^3}$ for Cu and 2.1 $\mathrm{mpt/cm^3}$ for Al. Even considering the 64% additional Al needed for equal dc resistance, Al has under 30% of the environmental impact of the Cu needed for the same winding by this measure.

TABLE III
CURRENT DENSITIES CHOSEN TO MINIMIZE ENVIRONMENTAL IMPACT OR COST FOR FIVE YEARS OF CONTINUOUS OPERATION

	Cu	Al	
EI environmental impact	1400	780	mpt/kg
Cost	9	6	\$/kg
Current density for min. EI points	79.6	25.6	A/cm^2
Minimum EI points per amp per meter	31.4	16.5	mpt/(Am)
Current density for min. cost	112	27.9	A/cm^2
Minimum cost per amp per meter	0.143	0.058	\$/(Am)

Note that costs and environmental impacts are high variable—this table is not definitive and is intended only as an illustration of trends. Values used for electric power cost and environmental impact are \$0.1/kWh, and 26 mpt/kWh, representing typical numbers for North America [42]. Costs reported are present value assuming 6% annual discount rate for future payments; no discounting is used for EI points.

Although Cu and Al are both widely recycled, and in both cases the Eco-Indicator point values are much lower for recycled metal, conductors are usually made using primary metal, because of the importance of high purity in conductors. The designer could nonetheless assume some credit for recycling at the end of life, if the product and component are designed for disassembly and the manufacturer implements a takeback program.

The lower environmental impact of Al production and the lower resistivity of Cu might seem to imply a tradeoff between the impact associated with material production and the impact associated with energy production, but this is not the case. Even when enough Al is used such that the losses are the same, materials impact is more than a factor of three lower for Al. However, for any given conductor, there is a tradeoff between the energy and materials impact. One can choose the amount of conductor used to optimize this tradeoff, or to optimize the tradeoff between materials cost and energy cost.

The results of one such optimization are shown in Table III. It is interesting to note that the optimum current density chosen based on total cost is very similar to the optimum current density chosen based on environmental impact. Cu, Al, and electricity all have high environmental impact per dollar.

IV. COPPER-CLAD ALUMINUM WIRE

An interesting compromise between Cu and Al is Cu-clad Al wire (CCA). An Al rod is surrounded by a thick layer of Cu, such that 5 to 15% of the cross section is Cu. This ratio is maintained as the wire is drawn to its final diameter. Traditionally, CCA has been used in specialized applications for its weight advantages over Cu. However, as the price of Cu increases, CCA is becoming attractive for a wider variety of applications because of its cost advantage over Cu. Compared to Al, CCA has the

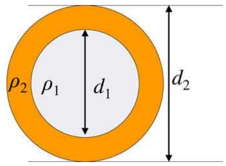

Fig. 4. Conductor comprising two concentric cylinders of different metals. In the case of CCA (copper-clad aluminum), the outer cylinder, with resistivity ρ_2, is copper and the inner cylinder, with resistivity ρ_1, is aluminum.

advantages of allowing termination and insulation processes to remain the same as for Cu.

In the case of frequency sufficiently high that the skin depth is smaller than the Cu layer thickness, the current flows almost entirely in the Cu, and the electrical performance of CCA is nearly identical to that of Cu. In many cases, a good winding design for a power application would use a wire diameter small compared to a skin depth, and current would flow in both the Al and the Cu. However, wire large compared to a skin depth can be a good choice in some applications, such as single-layer windings or windings that carry significant dc current [4]. The minimum frequency for which the Cu layer is equal to or thicker than a skin depth can be calculated from the skin-depth formula to be

$$f_{min} = \frac{\rho}{\pi \mu_0 t_c^2} \tag{4}$$

where t_c is the thickness of the Cu cladding, which means that

$$f_{min} = \frac{\rho}{\pi \mu_0 r_c^2 (1 - \sqrt{1 - k_c})} \tag{5}$$

where r_c is the overall radius of the conductor, from the center to the Cu surface, and k_c is the fraction of Cu area in the wire, typically 5 to 15%. For example, the minimum frequency for a 10%-Cu CCA conductor to behave the same as solid Cu is around 200 kHz for AWG 16 (1.3 mm diameter), ranging up to 20 MHz for AWG 36 (0.13 mm diameter).

If the wire is small compared to a skin depth, the proximity-effect losses can be calculated with the assumption of uniform flux throughout the wire cross-section, similar to the analysis of solid single-material conductors in [5], [6], [43]. Fig. 4 shows a wire comprising concentric cylinders of different conductivity such as CCA. For such a conductor, the proximity-effect eddy-current loss can be shown to be

$$P_e = \frac{\pi}{128} \omega^2 \hat{B}^2 \ell \left[\frac{1}{\rho_2} \left(d_2^4 - d_1^4 \right) + \frac{1}{\rho_1} d_1^4 \right] \tag{6}$$

where ℓ is the total length of the wire, $\hat{B}$ is the peak value of the sinusoidally varying flux density, perpendicular to the wire axis, and ρ_1 and ρ_2 and d_1 and d_2 are the resistivity and diameter of the two conductor layers, as shown in Fig. 4. Equation (6) can be derived by direct integration, or by calculating the loss in each section from the formula for the loss in a solid cylinder [5], [6], [43]: the loss in the inner cylinder can be obtained from direct application of the formula, and loss in outer cylinder is the difference in loss between a solid cylinder of diameter d_2 and a solid cylinder of diameter d_1, both with resistivity ρ_2. The contributions in the two sections are summed to obtain (6).

Unfortunately, (6) shows that the position of the Cu on the outside, while favorable for skin-effect considerations, is actually unfavorable for proximity-effect losses. For 10% Cu CCA, this effect increases proximity effect losses about 10.5% compared to the proximity-effect losses that would be incurred in a hypothetical conductor of the same diameter made from a uniform material with a resistivity chosen to match the dc resistance of the CCA.

Because of this small performance disadvantage in the intermediate-frequency range, CCA is most useful in the high-frequency range, i.e., where the wire is large compared to a skin-depth, such as in single-layer windings or windings with large dc current. It can also be useful in winding operations in which terminating Al windings would be difficult.

V. Conclusion

Many effective options exist for reducing Cu content in high-frequency magnetics without increasing power loss. Often all that is needed is a more careful design considering high-frequency effects. Because core material often costs less than copper, it can also be advantageous to use larger core volume with smaller Cu volume.

One may also eliminate Cu by switching to Al windings. Although Al has 64% higher resistivity, it is dramatically less expensive, especially in terms of the cost per unit volume, which is more relevant for winding design than the cost per unit mass. The higher resistivity need not mean higher losses: the cost savings from using Al enables other improvements that can easily make up for the resistivity increase. Although Al is presently popular only at low frequency, we have shown, both theoretically and experimentally, that its advantages are actually greater at high frequency.

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