Bundle Compression Overcomes Aspect Ratio Constraints On Transformer Design

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In a prior work,* the impact of winding-window aspect ratio on transformer design was analyzed. This ratio is important because it imposes limits on the current density and hence the transfer power that can be achieved when using round or square wires in bundles as discussed previously. For bundles that are large relative to the window dimensions, window aspect ratio imposes a *boundary effect* that can reduce packing factor.

Apart from resorting to foil, there is seemingly no solution to this problem—except for compressing the round bundles. In this article, we take the analysis of winding-window aspect ratio's effect on transformer design a step further, by answering this question: how much can the bundles be compressed?

In transformer design, bundles with five or fewer strands are desirable because they tend to minimize proximity effect. Compressing such bundles also tends to be more difficult than for bundles with higher numbers of strands. For both of these reasons, we'll focus on the low strand count bundles in this discussion. We'll determine the extent to which these low-strand-count bundles can be deformed in different configurations, leading to new freedom in winding optimization.

Factors Determining Bundle Design

In a previous article on this topic, "Transformer Design (Part 2): Aspect Ratio,"* the calculation for allowable bundle size was based on the allotted winding area, taking into account the winding fill factor of the bundles. Round bundles pack in linear layers in a hexagonal configuration (nestled into the grooves of layers beneath) with packing fill factor $k_{pf} = \pi/4 \approx 0.7854$. Then for a loosely-twisted bundle of N_b bundle turns, the maximum allowable bundle area is

$$A_{bw} = \frac{k_{pf} \cdot A_{ww}}{N_b} = \pi \cdot r_{bw}^{\ 2}$$

where $A_{ww} = k_{ww} \cdot A_w$ = the allotted winding area as a fraction, k_{ww} of the window area, A_w. The round bundle radius is

$$r_{bw} = \sqrt{\frac{A_{bw}}{\pi}}$$

The bundle can then be designed based on strand count, N_s, strand insulated-wire radius, r_{cw}, and bundle packing factor, k_{pb}, where the twisted bundle radius to untwisted strand radius is

$$\frac{r_{bw}}{r_{cw}} = \sqrt{\frac{N_s}{k_{pb}}} \Rightarrow r_{cw} = r_{bw} \cdot \sqrt{\frac{k_{pb}}{N_s}}$$

Twist factor, k_{tw}, is an additional packing factor for bundles with appreciable twist. Twisting causes expansion of the bundle in both radius and length, and the *twist factor*, k_{tw}, will be explained in an upcoming article. This design scheme of choosing strand size, however, assumes that window boundary effects are negligible. It gives a maximum r_{bw} which can be used as an upper bound on subsequent calculations that include boundary effects.

To include boundary effects, we resort to a different scheme that is based explicitly on winding area dimensions, not on winding area alone. For winding width, w_{ww} and height, h_{ww}, then winding area, $A_{ww} = w_{ww} \cdot h_{ww}$. N_b turns of bundle radius r_{bw} fitted into a layer of width w_{ww} has a bundle radius of

$$r_{bw} = \frac{w_{ww}/2}{N_b}$$

A round bundle of this radius has a height of $2 \cdot r_{bw}$ and fills the height dimension only if $h_{ww}/2 \cdot r_{bw}$ is an integer, but usually it is not. The fractional part is lost boundary-effect area.

Compression And Packing Factor

There is no solution to this geometric quandary apart from abandoning round or square wire for foil or else considering squashed bundles. Bundles can be compressed to change their aspect ratios. How much depends on the number of strands, N_s in the bundle. By compressing a bundle, its shape changes from round to an oval shape, assumed here to be elliptical. With vertical compression, an ellipse has a major horizontal semi-axis width, w and a minor vertical semi-axis height, h. Its area is

$$A = \pi \cdot w \cdot h$$

For $w = h = r$, the ellipse reduces to a circle. Because the number of strands in the bundle does not change under compression, the bundle area changes only by a change in bundle packing factor, k_{pb}. But if k_{pb} remains constant, then the bundle area remains constant. This can be visualized from Fig. 1.

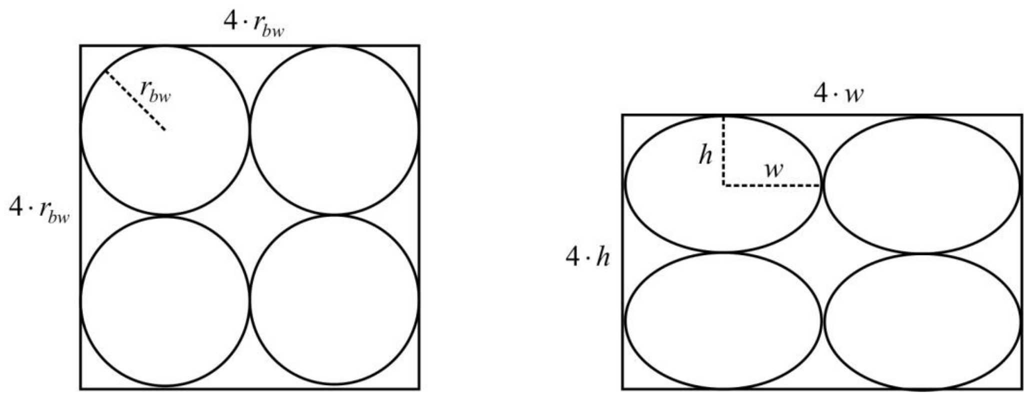

Fig. 1. A winding area with aspect ratio, a = 1 fits four round bundles (left). When the bundles are compressed to a bundle aspect ratio of a_{bw} = w/h, they fit a winding area with the same aspect ratio as the compressed bundles.

The circular bundles in a square window have a packing fill factor of

$$k_{pf} = \frac{4 \cdot (\pi \cdot r_{bw}^2)}{(4 \cdot r_{bw})^2} = \frac{\pi}{4} \approx 0.7854$$

If the round bundles are packed in a hexagonal configuration, the top layer shifts to the right or left by r_{bw} and two half-circles appear at each boundary resulting in the same bundle area. Of course, half-bundles are impermissible geometrically, but the derivation of fill factor within the window remains the same.

Now the window and bundles in it are compressed vertically. Compression tends to compact the bundles, and increase their packing factor. Thus to assume that the bundle area remains constant under compression is a worst-case (conservative) design assumption. Then the result is the compressed window with a packing fill factor of

$$k_{pf} = \frac{4 \cdot (\pi \cdot w \cdot h)}{(4 \cdot w) \cdot (4 \cdot h)} = \frac{\pi}{4} = 0.7854$$

Ellipses pack with the same fill factor as circles.

Compression Of Low-N_s Twisted Circular Bundles

From eddy-current considerations for bundles, the proximity effect within bundles is minimized for $N_s \le 5$ because the strands in such a low-strand-count bundle twist through the full bundle area of the other strands in one twist cycle. Bundles with $N_s >> 1$ are easier to compress and their analysis is not included here. Because low-N_s bundles are most attractive for magnetics design, the three of interest are examined here.

Bifilar bundles ($N_s = 2$) are another possibility. Their packing factor is low ($k_p = 0.5$), yet compensated for somewhat by having the greatest adjacent bundle interpenetration that increases packing. Bifilar bundles compress at most (as do all other bundles) into a planar bundle under maximum compression with a maximum aspect ratio of N_s.

As shown in Fig. 2, the trifilar bundle ($N_s = 3$) is a compact and thus attractive bundle, with untwisted $r_{bw}/r_{cw} \approx 1.866$. The trifilar bundle can compress as the base angles of the inscribed triangle shown in Fig. 2 decrease and the upper vertex angle increases. In the limit of compression, the bundle becomes planar. Its uncompressed aspect ratio is $a_{b3} = 1$ because of its symmetry about its center. Its aspect ratio under compression has an ultimate range of

$$a_{b3} \in [1, 3]$$

This compression range is wider than that of low-N_s bundles with more strands, though a three-strand bundle, having so few strands, is also not easy to compress.

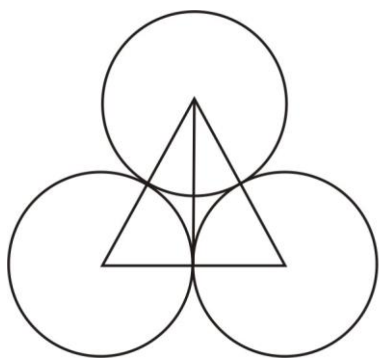

Fig. 2. The untwisted trifilar bundle is compact and not easy to compress, though it can compress vertically as the base angles of the inscribed triangle decrease.

Quadrafilar (untwisted) bundles can take multiple configurations, as shown in Fig. 3, where square and diamond configurations are congruent (meaning geometrically the same in shape and size), rotated 45° from each other.

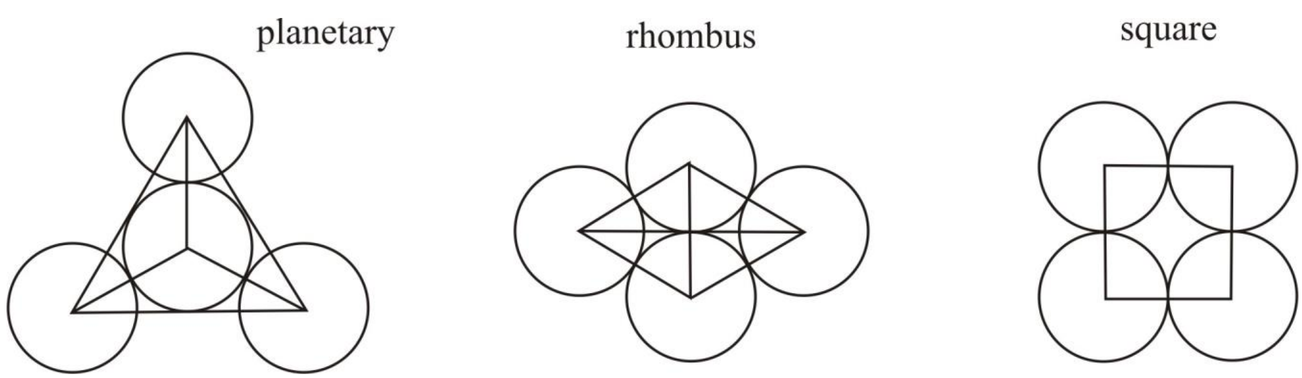

Fig. 3. Quadrafilar bundle configurations. The rhombus is the most compact—a flattened diamond.

The planetary configuration is "loose" and can, when compressed, collapse into either a rhombus or square configuration. The square configuration is symmetric and has $a_{b4s} = 1$ as does the 45°-rotated square that is the diamond configuration. When a diamond is vertically compressed, it becomes a rhombus for which

$$a_{b4r} = \frac{4 \cdot \sqrt{3} \cdot r}{4 \cdot r} = \sqrt{3} \approx 1.732$$

If the rhombus is the most compact configuration, then the aspect-ratio range for vertically-compressed quadrafilar bundles is

$$a_{b4} \in [1,\ \sqrt{3}\,] \approx [1,\ 1.732]$$

Ultimately, any bundle can be flattened to where it is planar. The compression ranges considered here end with more compact yet useful configurations. (Excessive compression will, of course, damage strands.)

The square configuration is actually the most compact of quadrafilar configurations, having k_{pb} = 1/1.458. Rhombus k_{pb} = 1/1.866. As a diamond compressed into a fully compact rhombus, the average is k_{pb} = 1/1.66. None of these configurations is as well-packed as the trifilar bundle, with k_{pb} = 1/1.16, nor does it have as large a compaction range, as expressed in aspect ratio.

For N_s = 5, the uncompressed bundle configurations are shown in Fig. 4. Both planetary and pentagon configurations compress into a hexagonally-configured, two-layer shape of 3 and 2 strands. The pentafilar bundle has a slight advantage over the quadrafilar bundle in that it has an extra strand though its packing is comparable: for planetary, k_{pb} = 1/2.25—not good; pentagon k_{pb} = 1/1.46, comparable with quadrafilar square; and the fully-compressed hex configuration, k_{pb} = 1/1.27 ≈ 0.7854. As it is compressed, the average between pentagon and hex is k_{pb} = 1/1.37 ≈ 0.730. The aspect ratios begin with a_{b5p} = 1 for the symmetric planetary and pentagon shapes, and decrease for the hexagonal configuration to

$$a_{b5h} = \frac{6 \cdot r}{2 \cdot \sqrt{3} \cdot r} = \frac{3}{\sqrt{3}} = \sqrt{3} \approx 1.732$$

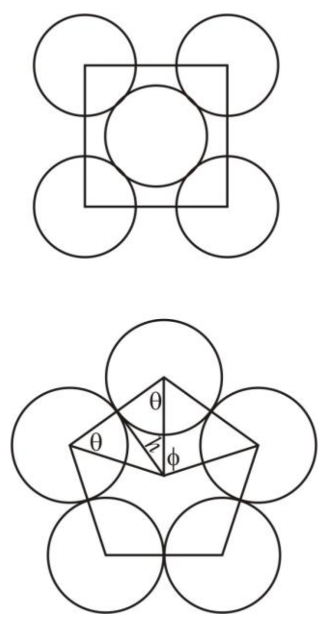

Fig. 4. Uncompressed and untwisted pentafilar bundles.

There is another possible configuration, of a square of four strands with a fifth off to the side, in the groove between two strands. This configuration has an aspect ratio of

$$a_{b5s} = \frac{4 \cdot r + 2 \cdot \sqrt{3} \cdot r}{4 \cdot r} = 1 + \frac{\sqrt{3}}{2} \approx 1.866$$

Therefore, the range of the pentafilar bundle aspect ratio under vertical compression is

$$a_{b5} = \left[1, 1 + \frac{\sqrt{3}}{2}\right] \approx [1, 1.866]$$

The pentafilar bundle has slightly more compression range than the quadrafilar bundle.

For both the quadrafilar and pentafilar bundles, increased compression results in an increasing aspect ratio and increased k_{pb} from which it can be concluded that the area of the bundle is decreasing. Thus, the constant-area assumption applies to the least compressed configuration and is the most conservative in area margin for fitting the winding to the allotted window area.

Bundles can also be compressed horizontally, though this is not of much practical consequence. The horizontal compression range is $1/a_b$, and to include it in the overall range,

$$a_{b4} \in [0.5774, 1.732] \;\; ; \;\; a_{b5} \in [0.5359, 1.866]$$

Dimensions Of A Compressed Bundle

Assuming again that the bundle area remains constant under compression, and given a winding window of w_w wide by h_w in height, having a window area of $A_w = w_w \cdot h_w$ and a bundle layer count of M_b with N_{lb} bundles per layer, find r_{bw} of the circular bundle that can be compressed into an ellipse that maximizes window area utility, $U_w = A_{ww}/A_w$.

The elliptical semi-axis dimensions that fill A_w are

$$2 \cdot w = \frac{w_w}{N_{lb}} \Rightarrow w = \frac{1}{2} \cdot \frac{w_w}{N_{lb}}$$

$$2 \cdot h = \frac{h_w}{M_b} \Rightarrow h = \frac{1}{2} \cdot \frac{h_w}{M_b}$$

With constant bundle area under deformation, the round (uncompressed) bundle radius is derived;

$$\pi \cdot w \cdot h = \pi \cdot r_{bw}^2 \Rightarrow r_{bw} = \sqrt{w \cdot h} = \sqrt{\left(\frac{1}{2} \cdot \frac{w_w}{N_{lb}}\right) \cdot \left(\frac{1}{2} \cdot \frac{h_w}{M}\right)}$$

Noting that

total number of bundles = $N_b = N_{lb} \cdot M_b$,

window area = $A_w = w_w \cdot h_w$

then substituting into r_{bw} and solving for bundle diameter, $d_{bw} = 2 \cdot r_{bw}$,

$$d_{bw} = \sqrt{\frac{A_w}{N_b}}$$

The window aspect ratio remains $a_w = w_w/h_w$ and the bundle aspect ratio is $a_{bw} = w/h = a_w \cdot (M_b/N_{lb})$. For bundle aspect ratios less than one, horizontal compression is required but is usually impractical. Instead, some margin is left in the height dimension of unused area while spanning the width dimension.

With these derivations and bundle compression, the aspect ratio quandary can sometimes be overcome.

Reference

*"Transformer Design (Part 2): Aspect Ratio" by Dennis Feucht, How2Power Today, Feb. 2018 issue.

About The Author

Dennis Feucht has been involved in power electronics for 30 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

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