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Can Foil Folding Improve Winding Performance In Transformers?

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Foil as a conductor shape can have advantages over wire. This article explores methods for winding with it. The concept is somewhat reminiscent of origami or Japanese paper folding, though the constraints on winding performance are an additional consideration.

Here I'll explore various ideas about how to wind with foil. The methods are illustrated with yellow strips of paper, including explanatory drawings and notes.

Although optimal-thickness foil reduces eddy-current constant-frequency resistance ratio F_r to valley values between the low-ξ and medium-ξ regions on Dowell graphs (where penetration ratio ξ is the wire conductive radius in units of skin depth), it lacks the F_r minimization achieved by twisting wire into bundles. Twisting conductors reverses their magnetic fields each half-twist, and when up to four or five strands of wire are twisted into a bundle, proximity effects become largely cancelled by twisting and bundling.

Foil lacks these cancellation benefits that reduce F_r unless methods are devised for twisting or folding foil in some way. In general, this has not been a major impediment for foil because its application has largely been limited to windings with high currents, few turns and few layers that result in limited eddy-current effects.

However, foil has only 1D eddy-current effects—not 2D as does wire. Its width dimension greatly exceeds its height (or thickness) which increases packing factor and reduces static resistance. So, if the eddy-current benefits of twisted conductors could be combined with the advantages of foil, winding design might be advanced.

Consequently, this article is more of a presentation of ideas or a "brainstorm" than an ordinary didactic discourse in the hope that readers might go beyond my limited thinking to the discovery of new folding methods that enhance the use of foil in winding design.

Creating A Two-Foil Twisted Winding

The top layer of Fig. 1 shows a way to translate a foil "strand" by one foil width. It moves over to the next "track" through two 90° bends and does not invert except in the transition. The thickness at the bends of the transitional segment is two foil heights, and this affects use of the allotted winding area.

Another foil strand placed below-right of the drawn foil could also be bent, to trade tracks with the foil, so that it would continue above the foil to the left, after the bends. In effect, this alternation of foil conductors is the beginning of twisted foil, and if the bends are displaced to not coincide, the height remains that of two foils, or $2{\cdot}h$ for the layer. Constructing a "twisted" foil winding in this way might be more easily accomplished as a linear construct before winding it on the bobbin.

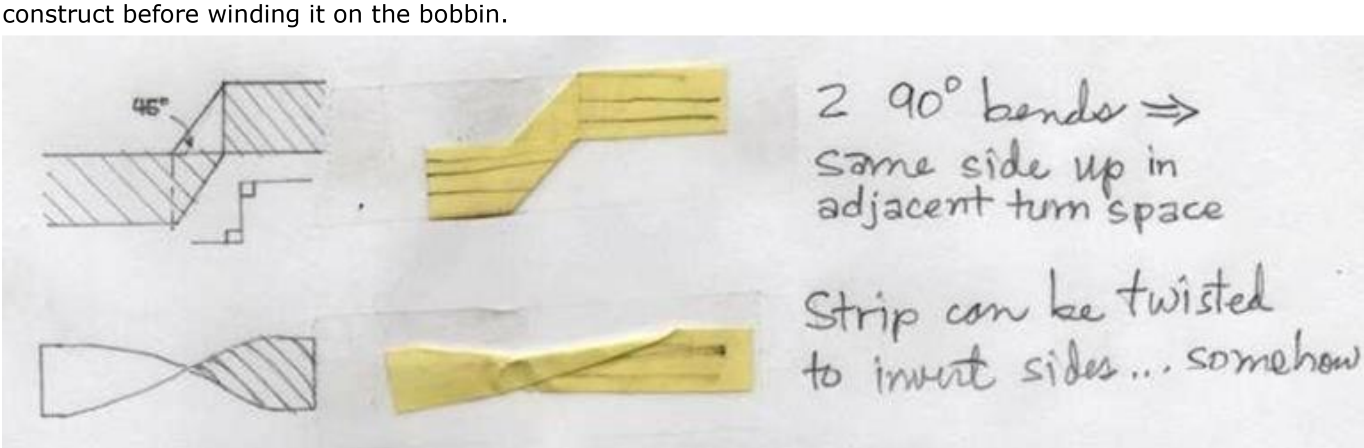

Fig. 1 top layer. Folded inverted foil strip within turn.

The second layer of Fig. 1 shows the inversion of a foil strand merely by twisting it 180°, then flattening it. Although this seems somewhat crude, the height along the twist remains $2{\cdot}h$. The length of the twist can vary. This foil transformation does not introduce a translation but keeps the strand in the same track as before. If adjacent strands are also twisted and phased spatially from each other, the same effect as twisting wire might be achieved, though the foil traces are not wound around each other but remain planar.

An alternative to wire twisting that maintains the foil strand on its own track yet inverted is shown in the three folding steps in Fig. 2. Three consecutive 45° folds alternating in direction place the inverted foil on its own track. The disadvantage of this triple folding is that within the transition the foil height is $3{\cdot}h$, though next to this height is a larger region lacking any foil—a region that an adjacent foil strip could occupy with its own $3{\cdot}h$ bend.

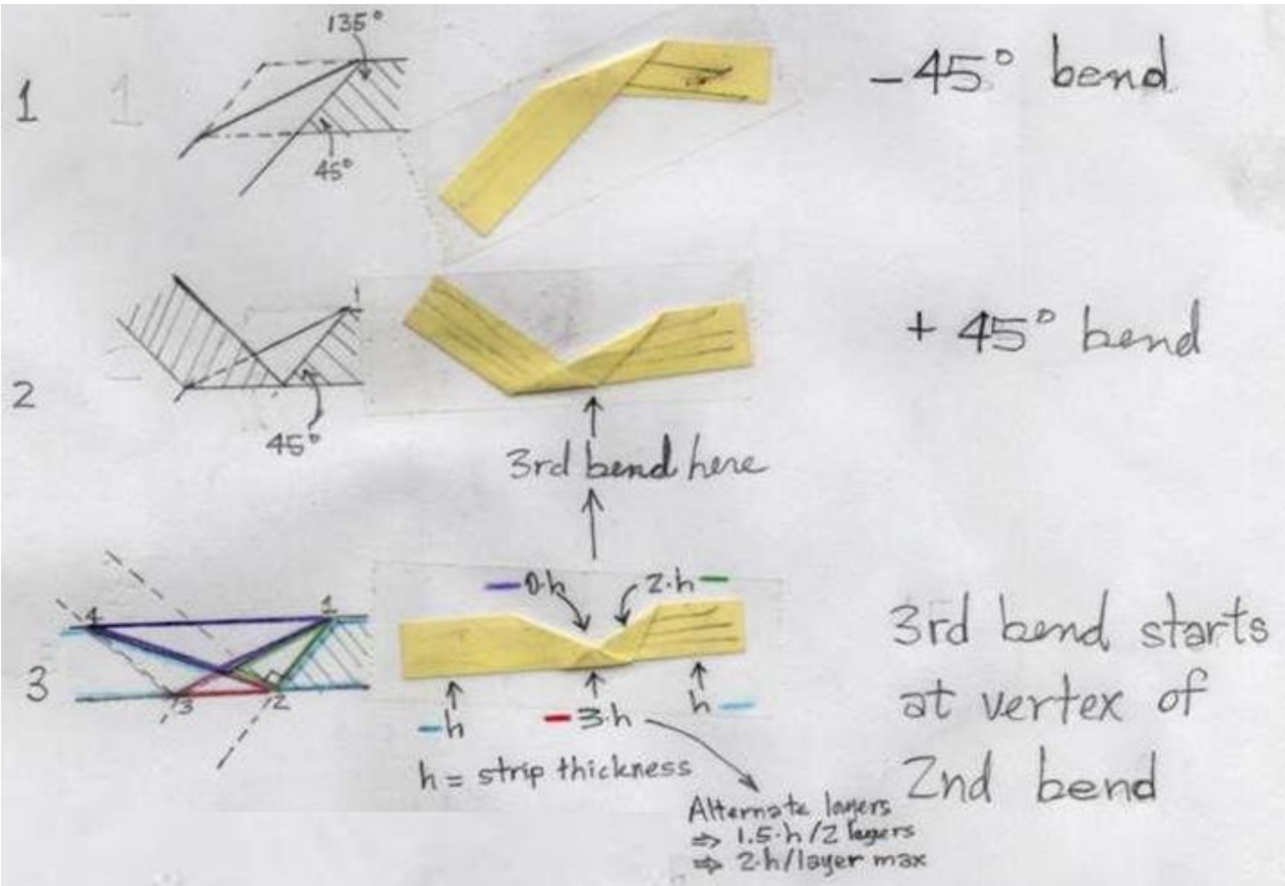

Fig. 2. Three bends invert strip on same turn track.

Details of the bend geometry and trigonometric equations for the angles are shown sketched in Fig. 3; w = foil width, $\alpha = 45°$ = the fold angles, and β = the angle formed by the upper edge of the strip at the left end of the fold. Point 3 is w to the left of point 2, causing $\beta < \alpha$. Thus, $\beta = \tan^{-1}(½) \approx 26.57°$.

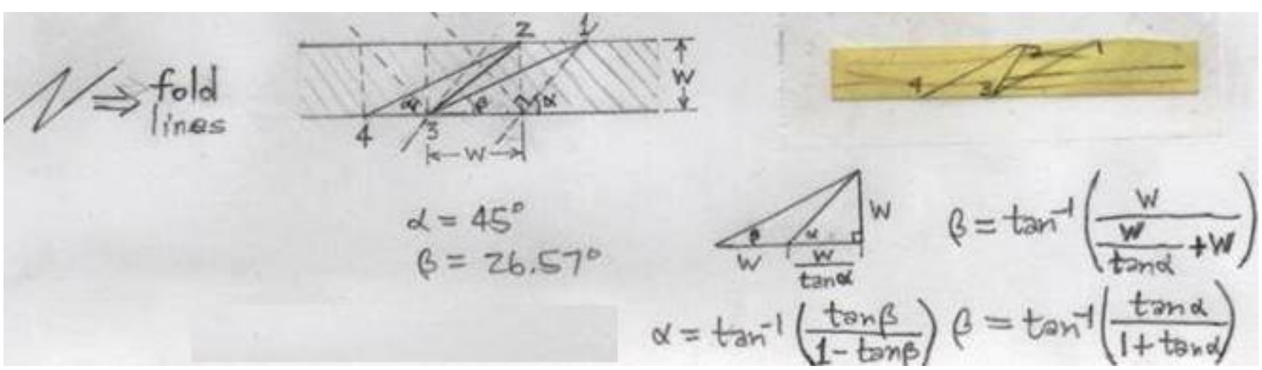

Fig. 3. Developed (unfolded) view.

A foil winding that terminates at both ends near its bobbin pin reduces the problem of end connections to the windings. If the ends are at the width ends of the bobbin and near the connector pins, they could be soldered to the pins directly to avoid soldering an end wire or braid across the end of the foil for external attachment.

Other possibilities must exist for expansion of foil winding development. Foil lends itself to helical winding that traverses the width of bobbins. The foil turns overlap as they progress along the bobbin width. Foil-like windings are found in a related form in planar transductors as metal stampings that require custom manufacture. These helical windings can also be formed from foil, though are not optimum as are stampings.

Multiple helical layers running in opposite directions have not (to my knowledge) been analyzed to any extent for their cancellation effects, nor have other foil-configuration possibilities. Foil folding has probably not been explored much because it is an odd combination of art, science, and engineering. Foil winding design or winding of any new geometric conductor shape is in its infancy and future refinement from idea to concept will show the physical and design limitations of it. As foil folding is just now in its early exploratory phase, this is an area that offers research opportunities for graduate students and inventive engineers alike.

Note: the drawings in Figs. 1 through 3 above were taken from the author's engineering notebook entries shown in their original form in Fig. 4.

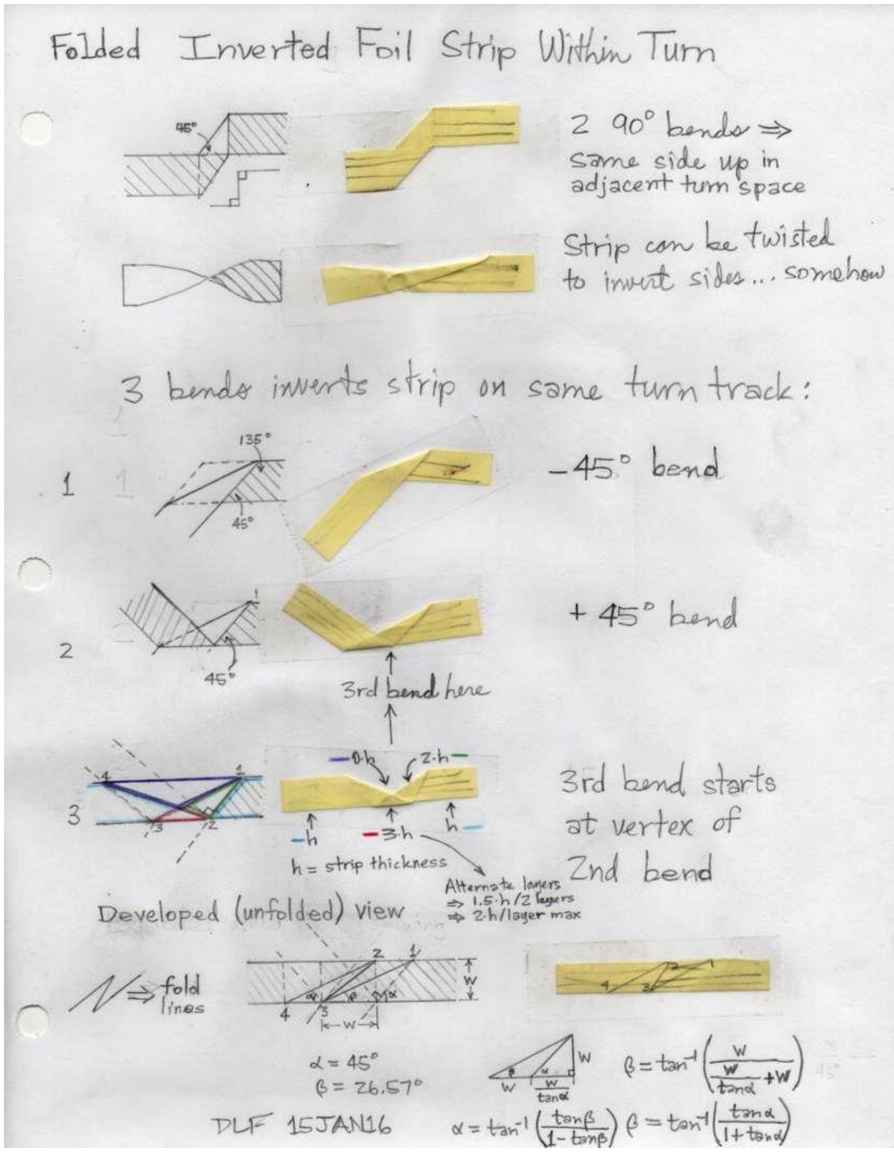

Fig. 4. Various notebook entries for methods of winding with foil.

About The Author

Dennis Feucht has been involved in power electronics for 40 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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