ISSUE: April 2021

Bunched Vs. Cabled: Litz Wire Bundle Twist Geometry Influences Proximity Effects

by Dennis Feucht, Innovatia Laboratories, Cayo, Belize

Litz wire is a name for strands of individual wire conductors twisted or braided into a bundle that can then be wound on a core bobbin to form a winding. Each turn of the bundle is a winding turn, and within it are strands of wire. A winding bundle can simply be N_s strands twisted together, or can consist of sub-bundles of twisted wire which are twisted together to form the overall bundle.

Commercial Litz wire usually consists of sub-bundles and is more elaborate to construct, especially if it is braided. This article describes some of the geometric features of Litz wire consisting of multiple twisted bundles and their magnetic effects, mainly with respect to proximity effects.

Single-Bundle Construction

Bundles can be constructed as ribbon cable, by laying down strands in a planar, linear shape. This is usually not the form used in magnetic components because with each strand conducting current of the same turns, foil is advantageous; it has more conductive area in the same cross-sectional area as the ribbon cable. More commonly, strands are combined by either *twisting* or *braiding* them.

Braiding is more difficult, and usually requires automated machinery to direct the trajectories of the strands through the bundle. Twisting, in contrast, is easy and applies to in-house winding construction. A variable-speed drill and a wire hook at the far end are all it takes to twist strands into bundles. (Some skill in handling wire is also involved, to keep it from knotting and kinking. Skill is quickly acquired after terrifying experiences with “Gordian knots”.)

A single twisted bundle of strands is often quite adequate for bundle design; the eddy-current effects can be kept low if the strand count is not high or if many strands are very small as explained in reference [1]. A few larger strands are easier to work with as a preferred design alternative for winding optimization.

The two fundamental limits on N_s for a wiring bundle are the number of strands for the required ampacity, N_{si} and the number of strands in the given number of turns that keep the bundle within the allotted cross-sectional area of the winding, N_{sw}.

Sometimes, with high switching frequencies and large currents, many strands are unavoidable, and N_{si} is large. With a single bundle configuration this could be problematic as the high number of strands could lead to higher eddy-current effects.

However, even in this case it is possible to minimize the proximity effect by applying just a few strands, though in a *nested* way. That is, we can twist *sub-bundles* of twisted strands together to form one larger bundle. We now examine the twisting of multiple bundles of wire as sub-bundles to form an overall bundle.

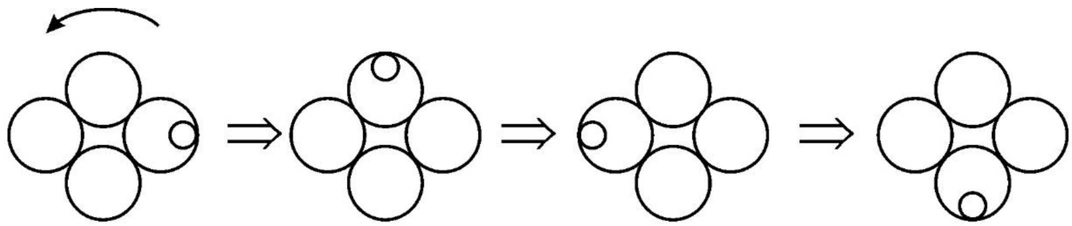
Twisting Sub-bundles Into A Larger Singe Bundle

To keep the analysis simple yet realistic, consider each sub-bundle to be round. With $N_s >> 1$, bundles tend toward a round shape with round wire strands. Then for a given strand within a sub-bundle, as the sub-bundle advances its way along through the bundle, the strand will change its position relative to other strands within the bundle. The *pitch* is the bundle distance of one revolution of strands in the bundle. This leads to two methods for combining sub-bundles:

- *Bunched*: sub-bundles twisted in the same direction as the strands in the sub-bundles themselves; $f > 0$
- *Cabled*: sub-bundles twisted in opposite direction from the strands in the sub-bundles themselves; $f < 0$

where f is the *spatial frequency*; one pitch is a cycle, and $f > 0$ for CCW rotation where the bundle rotates out of the page, advancing toward us.

To describe the motion of strands in sub-bundles as viewed in a cross-section of the bundle, a concrete example of four sub-bundles illustrates the concept. Suppose the strands in the sub-bundles are not twisted and remain in the same place in their sub-bundle. Shown in Fig. 1 is the bundle of four untwisted sub-bundles. This is not a practical case, since (short of gluing the strands together) some type of twisting or braiding would normally be required to hold a sub-bundle together, but this helps to define some key terms and illustrate twisting concepts. In the leftmost bundle position, a single strand on the right side of the rightmost sub-bundle is singled out for observation.



$$f_{st} = f_{sb} + f_b = f_b$$

Fig. 1. Cross section of a bundle of four sub-bundles with the rightmost sub-bundle strand on the right identified for tracking its motion within the bundle, as the bundle twists along its length in successive 90° CCW rotations. The four 90° rotations are cyclic and the next one after the rightmost is the leftmost again.

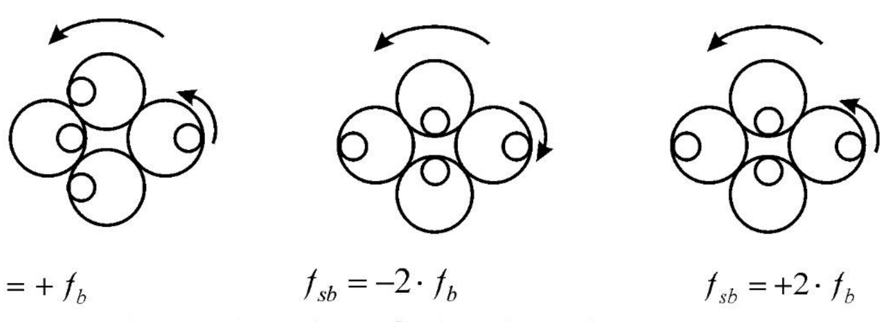
The whole bundle rotates CCW by 90° steps as shown. The strand rotates with it, being part of the bundle, and at the same rate, *f* as the bundle. For successive 90 degree rotations, Fig. 1 shows the progression of the strand. The strand frequency,

$$f_{st} = f_{sb} + f_b = 0 + f_b = f_b$$

where f_{sb} is the frequency of rotation of strands within sub-bundles, and f_b is the rotational frequency of the bundle itself relative to the stationary page. A *pitch* is the length of one cycle of a spatial frequency, and is a measure of how tightly twisted a bundle is, as its twist cycles per length. Instead of 1/time, spatial frequency has units of 1/length. In Fig. 1, with no twisting within the sub-bundle, $f_{sb} = 0$ and the given strand rotates at $f_{st} = f_b$.

Now to the more practical case where twisted sub-bundles are twisted together. On the left side of Fig. 2, the strands in the sub-bundle rotate within the sub-bundle at the same frequency and same direction as the bundle, or $f_{sb} = f_b$ and $f_{st} = 2 \cdot f_b$. Four 90° rotations in Fig. 2 are compressed into one figure, with each successive CCW sub-bundle being the same sub-bundle rotated 90° CCW.

In the leftmost bundle, the strand rotates at twice the rate and advances 180° for each 90° bundle rotation, or a half-cycle for every quarter-cycle rotation of the bundle. This bundle is *bunched* because both bundle and sub-bundles rotate in the same direction. The strand rotates through all positions in the bundle in one cycle, asymmetrically.



$$f_{sb} = +f_b \quad f_{st} = f_{sb} + f_b = 2 \cdot f_b \quad \Rightarrow \Delta 180°$$

$$f_{sb} = -2 \cdot f_b \quad f_{st} = -2 \cdot f_b + f_b = -f_b \quad \Rightarrow \Delta -90°$$

$$f_{sb} = +2 \cdot f_b \quad f_{st} = 3 \cdot f_b \quad \Rightarrow \Delta 270°$$

Fig. 2. Sub-bundle strands in left bundle rotate or twist at the same spatial frequency as the bundle; sub-bundles of the bundle in the center counter-rotate at twice the speed of the bundle and counter-rotate relative to the stationary page at the bundle speed; the bundle on the right has sub-bundles rotating at twice the bundle speed in the same direction and is the alias of the center bundle.

In twisted bundles with fewer than 5 strands, all the strands go through all the cross-sectional strand positions in one cycle. This effectively eliminates intrabundle proximity effects. Consider the usefulness of that idea. If we were to twist 16 strands together in a single bundle, bundle proximity-effects would occur in about 4 layers of strands. However, if the strands instead were organized as four 4-strand sub-bundles, then neither the sub-bundles nor the overall bundle would have more than 4 strands (where a bundle strand is a sub-bundle), and proximity effects within the bundle would be minimized.

Moving on, the next Litz-wire configuration, shown in the center of Fig. 2, is cabled instead of bunched, and the sub-bundle twists CW at twice the bundle frequency, or $f_{sb} = -2 \cdot f_b$. The strand frequency is

$$f_{st} = -2 \cdot f_b + f_b = -f_b$$

The strand rotates in the opposite direction (CW).

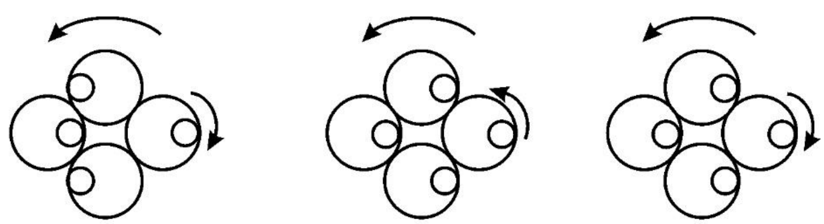
In the bunched bundle on the right, the sub-bundles are rotating CCW at twice the frequency as the bundle, being more tightly twisted and with half the pitch of the bundle; $f_{sb} = +2 \cdot f_b$. The strand frequency is thus

$$f_{st} = +2 \cdot f_b + f_b = +3 \cdot f_b$$

and the observed strand is rotating relative to the page at Δ270° each 90° rotation of the bundle. Note that the positions of the observed strand are the same as for the center bundle. The right bundle is twisting at the *alias frequency* of the bunched configuration; $f_{sb} = -2 \cdot f_b$, and *the strand positions are the same each 90° of bundle twist*.

Now, let's consider the case where the sub-bundles are twisted tighter, to three times the bundle twist rate. Three configurations are shown in Fig. 3. On the left, the Litz-wire bundle is cabled and the sub-bundles rotate CW at three times the CCW frequency of the bundle, resulting in $f_{st} = -3 \cdot f_b + f_b = -2 \cdot f_b$. Strands in this bundle rotate at the opposite frequency of the bundle on the left of Fig. 2, which turns at Δ180° each increment. Thus, $f_{sb} = +f_b$ is the alias of f_{sb} $-3 \cdot f_b$.

The center bundle in Fig. 3 is bunched, with $f_{sb} = +2 \cdot f_b$ and $f_{st} = 3 \cdot f_b$, and is the alias of the center bundle of Fig. 2 which has $f_{sb} = -2 \cdot f_b$. Finally, the right bundle of Fig. 3, which is cabled, is the alias of the center bundle. The center bundle $f_{sb} = +3 \cdot f_b$ and for the right bundle, $f_{sb} = -f_b$. The difference in sub-bundle frequency between aliases is always $4 \cdot f_b$.



$f_{sb} = -3 \cdot f_b$ $f_{st} = -3 \cdot f_b + f_b = -2 \cdot f_b$ $\Rightarrow \Delta -180°$

$f_{sb} = +3 \cdot f_b$ $f_{st} = 4 \cdot f_b$ $\Rightarrow \Delta 360°$

$f_{sb} = -f_b$ $f_{st} = 0$ $\Rightarrow \Delta 0°$

Fig. 3. The left bundle is cabled and is the alias of the left bundle of Fig. 2; the bunched center bundle and cabled right bundle are also aliases.

The Fig. 3 left and center bundles, with $f_{sb} = \pm 3 \cdot f_b$ are more loosely twisted (× 3 longer pitch) than that of the sub-bundles. The strand in the bunched center bundle rotates at $f_{st} = 4 \cdot f_b$ and strand position changes by Δ360° per step, an entire twist cycle each quarter-turn of the bundle. Consequently, the strand stays at the same page location in the sub-bundle.

In the case of the cabled left bundle, the observed strand is counter-rotating in its sub-bundle at $f_{sb} = -3 \cdot f_b$ and is opposed to the bundle motion, resulting in a net strand motion of $f_{st} = -3 \cdot f_{sb} + f_b = -2 \cdot f_b$. It is rotating each bundle quarter-turn by a half-cycle and is the alias of $f_{sb} = +f_b$ of the left bundle of Fig. 2.

In the Fig. 3 center and right bundles, although the sub-bundles are twisting, the strands in the sub-bundles are remaining stationary relative to the bundle, as though they are not twisting with the bundle. Twisting is required for canceling fields and minimizing the proximity effect. Do these configurations defeat that goal?

More research is needed to answer the question to determine the optimal sub-bundle frequencies. Nevertheless, because the relative twisting motion has ceased, these frequency combinations are best avoided despite the twisting of the bundle relative to a stationary observer, and the twisting of strands in the sub-bundles relative to the sub-bundle. External fields are not cancelled by strands remaining stationary relative to those fields.

Additional questions about sub-bundle versus bundle pitches remain. For instance, sub-harmonics are also possible when the sub-bundles are twisted less tightly than they are on the bundle. For $f_{sb} = \pm½ \cdot f_b$, a given strand goes through its own cycle in two bundle cycles. Another question is what effect N_s has, if any.

Charles R. Sullivan and Richard Zhang (now at MIT) of the Thayer School of Engineering at Dartmouth College have studied the effect of pitch relative to winding length.[2] Although it is difficult to include these aspects of winding design quantitatively, especially for calculator-oriented magnetics design optimization, knowing the major features of the results in reference [2] can guide design choices away from highly suboptimal design decisions.

References

1. "How Wire Bundle Configurations Influence Eddy-Current Proximity Effects" by Dennis Feucht, How2Power Today, February 2019.

2. "Analytical Model for Effects of Twisting on Litz-Wire Losses" by Charles R. Sullivan, and Richard Y. Zhang, www.power.engineering.dartmouth.edu.

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.

For more on magnetics design, see these How2Power Design Guide search results.