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# Foil Vs. Wire Windings—How Do They Differ?

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The two most common conductor shapes for windings are round wire and flat foil. Square wire is a distant third option. Its packing fill factor is nearly ideal ($k_{pf} = 1$) yet in winding construction, square wires rotate and skew, and it is not easy to make them pack side-by-side as squares.

This article assesses the merits of round wire and foil in winding magnetic components. Four comparisons are made to describe the impact of conductor shape on winding loss, with three involving eddy-current resistance.

We begin by comparing foil windings with round and square windings in terms of their effect on packing factor. Next we see how wire geometry affects the penetration ratio and winding resistance ratios used in Dowell's equations, and then go further to explore 1D and 2D skin resistance effects. Finally, we'll generate Dowell's curves to show how winding resistance due to eddy current effects varies with wire thickness and number of layers.

## Porosity: Conductor Separation

The simplest comparison of round wire and foil is of the geometric cross-sections of each. Foil has the advantage of continuous and constant height of conductor over a layer whereas wire has gaps that reduce its packing factor because of its round shape.

If the round wires are reshaped into squares of the same cross-sectional conductive area, as shown in Fig. 1, they would be separated from each other by gaps of length $p - h$, as shown in the middle column of square conductors. On the right, the cross-sectional area equivalence is shown for circle and square. Then the gap length is also expressed as $d_c - 2 \cdot h \approx (1 - 0.886) \cdot d_c = 0.114 \cdot d_c$. This separation of conductors, or *porosity*, reduces the packing factor by the porosity factor, $k_{pw}$. For foil, shown in the left column of Fig. 1, no separation exists and for foil, $k_{pw} = 1$ within a single layer.

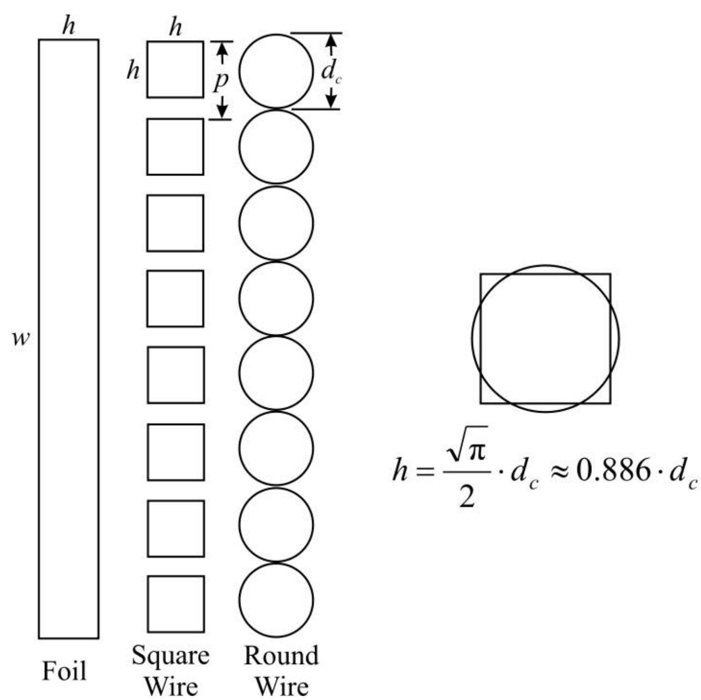


*Fig. 1. Conductor cross sections for single-layer columns of foil (left) and round wire (right). Separated squares, shown in the middle column, have the equivalent cross-sectional area of the round wire column. Area equivalence geometry is shown to the right. These views equate to a winding window being cut such that the single conductor layer is coming out of the page and then bending to form a turn. In the foil case, w is the width of the foil and h is the thickness.*

The packing-factor advantage of foil diminishes when multiple layers are considered. To keep foil layers from shorting, insulating tape is laid down between them, and this separation introduces inter-layer foil porosity. For round wire, the same separation of conductors within a layer applies to adjacent layers, and the resulting packing factor has a *fill factor*, $k_{pf}$ for wire centered in the grooves of adjacent layers. This results in hexagon vertices as centers of clusters of wires, and the fill factor for this hex configuration is $k_{pf} = \pi/4 \approx 0.7854$. Additionally, the wire insulation adds separation between the conductive centers of the wires and porosity, $k_{pw} < 1$.

For high-turns-count foil, $k_{pw}$ is low because of the tape separation between turns layers. Tape can be as thick as the foil thickness, though derivations of optimal foil thickness usually result in thicker foil, but not by a large amount. The optimal foil thickness also varies with layer number,[1] though it is usually not feasible in construction to change foil thickness every layer. Consequently, foil is better applied in designs where few layers are required.

What further reduces packing factor for foil is the need for end terminations, which are often round wires soldered across the width of the foil for a lower-resistance connection. The wire diameter causes a bump in the cross-sectional height of the winding and reduces the fraction of conductor in it—that is, it reduces the packing factor.

A reduced packing factor means that a smaller fraction of the winding window is conductor and this results in higher-resistance windings. Ideally, all of the winding window would be conductor (though that would result in shorted turns).

For a given window geometry and number of turns of a winding, the foil or wire length is largely determined. The packing factor then places a limit on conductor cross-section. Resistance is minimized with a maximum wire or foil cross-section (size) and a higher packing factor makes more conductive cross-section available.

## *Eddy-Current Resistance*

Eddy-current analysis of the skin effect in round wire and foil involves conductor dimensions that affect eddy-current resistance. Conductor size is best expressed in normalized units of *skin depth*, $\delta$ as the *penetration ratio*,

$$\xi = \frac{l_c}{\delta}$$

where $l_c$ is the applicable geometric length that applies to eddy-current loss. For foil,

$$\text{Foil: } \xi_f = \frac{h}{\delta} \approx \xi \text{ , } h = \text{foil height (thickness)}$$

$\xi$ is the penetration ratio of Dowell's equation from which the resistance factor, $F_R(\xi, M)$ results for a given conductor size, $M$ is the number of winding layers and $g_r$ is a geometric shape factor. Dowell's equation is based on parallel plates which are approximately equivalent to foil having a large radius of curvature. Other conductive shapes are adapted by a geometric equivalence to $\xi$ of Dowell's parallel plates.

Square wire has a different penetration ratio, $\xi_h$ and a geometric factor, $g_h$ for adaptation to $\xi$;

$$\text{Square wire: } \xi_h = \frac{h}{\delta} \text{ , } \xi = g_h \cdot \xi_h \text{, } h = \text{square wire conductive side length}$$

Foil penetration ratio, $\xi \approx \xi_f$ is related to round-wire $\xi_r$ by a geometric constant,

$$g_r = \sqrt{\frac{r_c}{r_{cw}}} \cdot 2 \cdot \left(\frac{\pi}{4}\right)^{3/4} \approx \sqrt{\frac{r_c}{r_{cw}}} \cdot 1.669 \approx 1.547$$

 

The value of $g_r$ is derived from the geometry shown in Fig. 1 and derived in references 2 and 3. For round wire,

$$\text{Round wire: } \xi_r = \frac{r_c}{\delta},\ \xi = g_r \cdot \xi_r \approx 1.547 \cdot \xi_r$$

where $r_c$ is the round-wire conductive radius. Because the $l_c$ of $\xi_x$ is different for the different conductor geometries—foil, and round and square wire—the geometric constants, $g_x$ relating them also differ. This causes differences in conductive shapes to affect $\xi$ and hence $F_R$.

As an interesting side note, there is no generally agreed way in the field of magnetics to derive $g_r$, though the rationale of Kazimierczuk,[1] as followed here and derived in reference 2, is the more comprehensive. The inclusion of $g_r$ makes $\xi$ larger than $\xi_r$ and shifts the $F_R$ curves as plotted on a graph to the left. This tends to move $\xi$ into the region of higher $F_R$ values. Consequently, the lower values of $\xi$ for foil ($g_f = 1 < g_h < g_r$) result in lower eddy-current resistance and lower winding loss. Further examination of why takes us to the 1D versus 2D skin effect of different conductor shapes.

### *1D And 2D Skin Effects*

Foil has an advantage over round wire with eddy-current effects because it shows a geometric length limit in only the height dimension for wide foil. Square and round wire have the same dimensional limitations in both height and width dimensions. For foil, the constant-frequency resistance factor is

$$\text{Foil: } F_r(\xi_f) = \frac{F_R(\xi)}{\xi} \quad \text{1D skin effect}$$

where $F_R$ is the constant-size resistance ratio of foil thickness or height. Constant-frequency $F_R$ and constant-wire-size $F_r$ are related to winding resistance as follows:

$$F_R(f) = \frac{R_w(f)}{R_{w0}},\ R_{w0} = R_w(0\text{ Hz}) = \text{static } R_w$$

$$F_r(\xi_r) = \frac{R_w(\xi_r)}{R_\delta},\ R_\delta = R_w(f_\delta) = R_w \text{ at } f(\xi_r = 1),\ r_c = \delta$$

$R_\delta$ is the resistance of the conductor at $f_\delta$, the frequency at which $r_c = \delta$. At a constant frequency, $R_\delta$ is a constant and $F_r$ varies only with conductor size, expressed as $\xi$. $F_R$ at a fixed wire size has a static resistance of $R_{w0}$ and varies only with $f$. Of the two resistance ratios—constant-size, $F_R$ or constant-frequency, $F_r$—the most useful in design is usually $F_r$ because the converter switching frequency is fixed and is a circuit-dependent magnetics parameter while wire size is optimized in winding design.

The two resistance ratios are related. For wire,

$$\text{Round or square wire: } F_x(\xi_x) = \frac{F_R(\xi)}{\xi_x^2},\ x = r \text{ or } h \quad \text{2D skin effect}$$

The denominator is, for foil, $\xi$ but for wire (both square and round), $\xi^2$. This difference is a result of the 1D limitation of foil height on skin effect whereas for wire, both dimensions are constraining, and the effect of $\xi$ is $\xi^2$. For $\xi < 1$, foil $F_r$ increases less with foil height than $\xi$ does for wire. For $\xi > 1$, wire has the advantage.

The $F_r$ reference resistance of $R_\delta$ also shows this difference:

$$R_{\delta f} = \frac{\rho \cdot l_w}{w \cdot \delta} \; , \; R_{\delta h} = \frac{\rho \cdot l_w}{\delta^2} \; , \; R_{\delta r} = \frac{\rho \cdot l_w}{\pi \cdot \delta^2}$$

where $\rho$ = conductor resistivity, $l_w$ = conductor length, and $w$ = foil width. $R_{\delta f} = R_{\delta r}$ at $\delta = w/\pi$, and $R_{\delta f} < R_{\delta r}$ for $\delta < w/\pi$. Whenever foil $w > \pi \cdot \delta$, foil has lower resistance than wire for the same length of conductor, and that is usually true.

## *Winding-Loss Minimization*

As $\xi$ increases from a low value, the $F_r$ curves decrease with a log-log asymptotic slope of −1 in the low-$\xi$ region, then increase where the proximity effect dominates. The value of $\xi = \xi_v$ is where $F_r$ is a minimum or at a valley point, as observed in Fig. 2. $\xi_v$ varies somewhat with $M$. For foil and round wire, it is

$$\text{Foil: } F_{rv} \approx 1.013 \cdot \sqrt{M}$$

$$\text{Round wire: } F_{rv} \approx 1.595 \cdot M$$

The minimum resistance increases linearly for wire layers, but foil resistance is less affected by layers, and increases by the square-root of $M$ instead. This shows foil to be superior to wire when adding layers.

The value of $\xi$ at $F_{rv}$ is not the same for foil and wire. For both, it varies inversely by the square-root of $M$. For several layers of foil,

$$\text{Foil: } \xi_{fv} \approx \frac{1.316}{\sqrt{M}} \, , \, \xi_v \le 1.5, \, M >> 1$$

This formula is valid for $\xi_{fv} < 1$, which is typical for foil. For round wire,

$$\text{Round wire: } \xi_{rv} \approx \frac{1.120}{\sqrt{M}} \, , \, M >> 1$$

The minimum-$F_r$ size formulas for foil and round wire are not much different, though the minimum $F_r$ for wire is somewhat less than that for foil. Foil thickness is thus slightly greater than wire conductive radius for minimum $F_r$ with the same number of layers but less than the wire diameter.

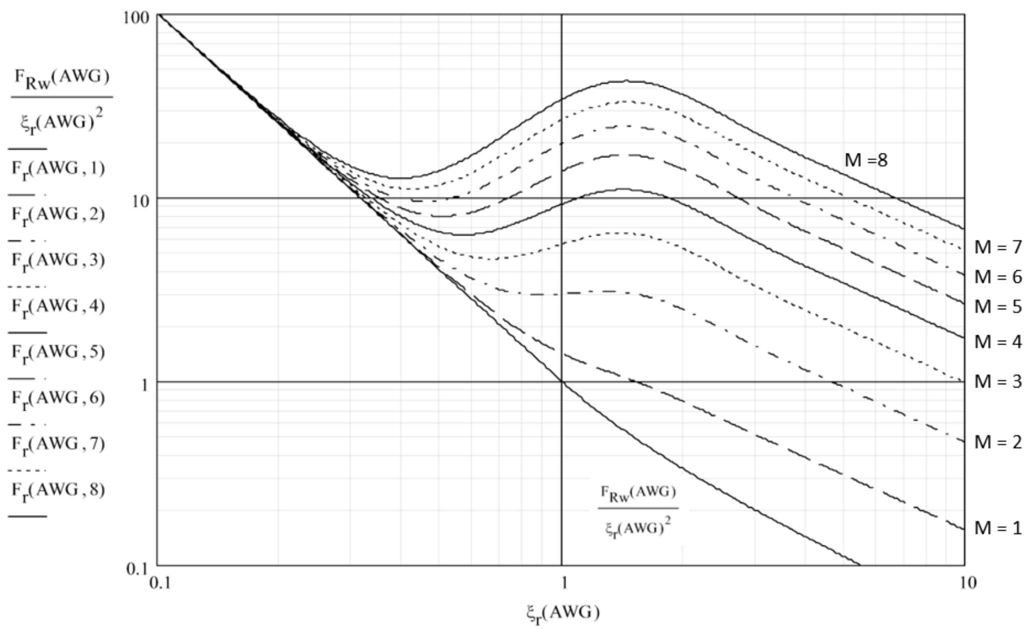


*Fig. 2. $F_r(\xi_r, M)$ Dowell plots with M as parameter, plotted against $\xi_r$. The two regions of low-$\xi$ and high-$\xi$ have decreasing curves and are skin-effect dominated while the middle-$\xi$ region is dominated by the proximity effect. The minimum value of $\xi_r$ at the lower $\xi_r$ limit of the middle-$\xi_r$ region (on the left) is at $\xi_{rv}$, the valley points on the M plots, shown for M = 1 through 8. The lowest plot is the isolated single-wire eddy-current resistance plot.*

## *Closure*

In conclusion, foil is superior to wire in minimizing eddy-current effects on resistance, though for many layers, wire can have a higher packing factor and lower resistance. Wire is also more versatile in how strands of it can be combined into bundles to minimize eddy-current effects. It is also easier to connect to bobbin terminals.

Consequently, foil more frequently appears in designs of low-turns, high-current windings, where ends are brought out of the winding window as flat braided wire. Development of twisted or folded foil has yet to appear, though Japanese paper folding (origami) supplies to the creative mind ideas yet to be explored.

### References

1. *High-Frequency Magnetic Components*, *Second Edition* by Marian K. Kazimierczuk, Wiley, 2014, pp. 300 to 306.
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3. *Power Magnetics Design Optimization* by D. L. Feucht, Innovatia, 2016, pp. 134 - 138. PDF available at www.innovatia.com.

### About The Author

*Dennis Feucht has been involved in power electronics for 35 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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