# Multi-Layer Folded High-Frequency Toroidal Inductor Windings

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*Abstract*—**Multi-layer windings can effectively decrease losses in inductors and transformers in many applications. We introduce a simple way to achieve lower losses in both air-core and magnetic-core inductors or transformers by incorporating multiple layers, with proper interchange of layer positions to ensure the same flux and current in each layer. We have applied this technique to toroidal inductors, but it can be applied to other winding geometries like windings on E cores or U-U cores. Experimental measurement of an inductor constructed using this approach match predicted performance.**

## I. Introduction

Advances in both semiconductor devices and circuit designs are enabling some experimental power conversion circuits to operate efficiently with switching frequencies in the range of 10s of MHz [1], [2]. Most such circuits use resonant circuits for soft switching, impedance matching, and absorbing parasitics. This requires low-loss high-frequency inductors; often several are required for a single power stage. Toroidal inductors, either air-core [3] or using low-loss high-frequency materials [4], can be a good choice, with very low external field which reduces electromagnetic interference (EMI) problems. However, conventional wire windings do not take full advantage of the winding area available on the surface of a toroid, and are limited by skin effect, proximity effect or both.

Improved toroidal inductors have been constructed by microfabrication [5], by wire winding with specially shaped wire [6], or by combinations of methods [3], [4]. For high-frequency applications, the windings in [3], [4] offer high performance, albeit with somewhat difficult fabrication, involving vacuum deposition of a conductive seed layer on the surface of a toroid, electroplating, and various processes for separating the metal on the surface into individual turns. The curvature of the winding then follows the shape of the field, as suggested for other geometries in [7], resulting in uniform current flow on the surface of the winding, in a layer one skin-depth deep.

In this paper, we introduce an approach that is simpler to produce and can achieve lower losses, through the use of multiple layers of conductor thin compared to a skin depth, with the layer positions interchanged to balance flux and current. The winding is not curved to ideally follow the flux as in [3], [4], [7], but finite-element analysis (FEA) shows that the resulting degradation in performance is much smaller than the gain provided by using multiple layers. The layer interchange method used can also be applied to other winding geometries, such as windings on E cores or U-U cores.

In order to verify the concept, first a prototype was built which is relatively low-frequency, low-$Q$, and large in size for ease of construction. After it performed as predicted, another inductor for high-frequency application, with high $Q$ and smaller size is being built for tests.

## II. Winding Configuration

The winding is constructed by folding copper foil or laminate, cut out in a shape such as that shown in Fig. 2, into a polygonal toroid as shown in Fig. 1. Multiple layers of conductor, each thin compared to an electromagnetic skin depth, can be used to provide lower high-frequency ac resistance than a single-layer conductor [8]. However, in order for this strategy to be effective, the positions of the layers need to be interchanged regularly, such that each layer occupies each position in the stack for an equal portion of the winding, or, more precisely, each layer must link the same amount of flux through the whole length of the winding. In litz wire, this interchanging is performed by twisting; in planar windings, other strategies are needed. Both the use of vias in PCB technology [9] or folding [10] have been used in the literature. For the polygonal toroid shown in Fig. 1, the wide portions of the winding around the outside provide an opportunity to introduce vias with a minimal impact on total resistance, because that portion of the winding is wide enough to provide room for a large number of vias; the total resistance may still be dominated by the resistance of the thin vertical strips going through the center hole.

Performing the interchange with vias in flex printed-circuit-board (PCB) technology would be a viable way to fabricate a winding; however, the best strategies that
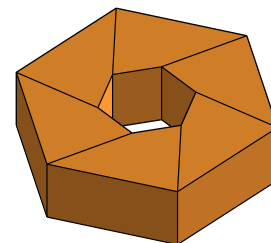


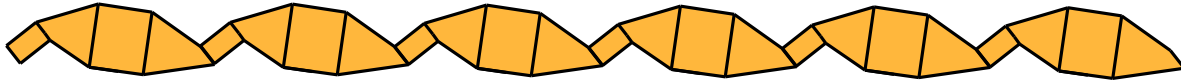Fig. 1.   Six-turn folded-foil toroidal winding.

Fig. 2.    Six-turn folded-foil toroidal winding layout.

minimize the extra resistance require blind vias (vias that go between two layers without contacting traces in other layers) if more than a few layers are used. This can rapidly become very expensive to produce or prototype.

A less expensive alternative is illustrated in Fig. 3. Notches are cut into the foil, going half-way across the width, and the layers are fitted together to swap positions. Although Fig. 3 shows only one layer going up (in the front) and one layer going down (in the back), any number of layers can be grouped together and can go up or down together.
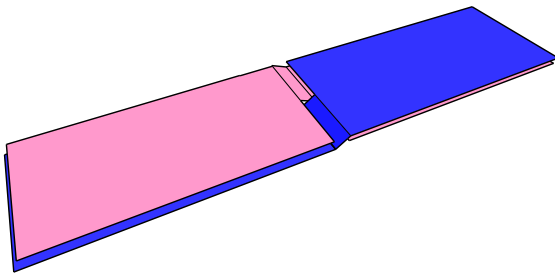


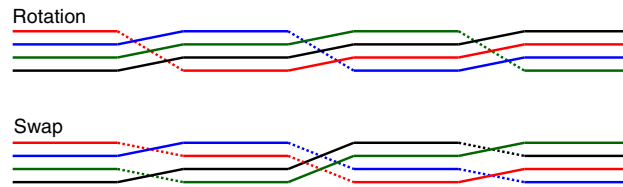Fig. 3.    Interchanging the position of two coil layers



Fig. 4.    Organization of layer interchanges for a four-layer winding. The layers which transition in one area are shown as solid lines; in the other, dashed.

For a four-layer winding, three interchanges are needed, each one-quarter of the way through the length of the winding. Two ways to organize this with the type of interchange shown in Fig. 3 are shown in Fig. 4. The "swap" strategy is preferred to the "rotation" strategy because two of the interchanges involve only pairs of layers, which makes it easy to keep flat and does not require wide notches in the windings. In addition, the interchange that involves all four layers has two layers in front and two in the back, unlike the "rotation" strategy which has three in front and one in the back; this distributes the current more uniformly. However, the "swap" strategy is only applicable to numbers of layers that are powers of two, whereas the "rotation" strategy can be applied to any number of layers. Note that in

order to have the interchange locations spaced at integer numbers of turns, the number of turns must be a integer multiple of the number of layers.

Producing such a winding requires special shapes cut from copper foil. Depending on the size and thickness of the layers, and the volume of production, they may be cut by hand (as was done for the first prototype reported here), by photochemical etching, by die-cutting, or by laser cutting. If the foil is sufficiently thick to handle easily, the foil may be first cut, and then insulated, for example with tape, with powder coating or with spray or dip varnish. For thinner foil, a laminate of the foil and plastic film, such as polyimide used in flex PCBs, can be used both to support the thin foil and to provide insulation between layers.

### III. ANALYSIS OF FACTORS AFFECTING PERFORMANCE

Compared to a single-layer conformal winding on a round toroid, the new winding design has higher ac resistance due to the polygonal shape and the extra resistance of the interchanges; but lower ac resistance because of the multiple layers.

The effect of the polygonal shape was studied by two-dimensional finite element analysis of a hexagonal winding, in comparison to a perfectly circular winding. The simulations were performed for an inductor with an outer diameter of 10 mm and inner diameter of 4 mm. Only the inside and the outer faces of the winding were considered for the simulation where the effect of the polygonal shape is most significant. The loss was only 13% higher for the polygonal winding as compared to the circular winding. Furthermore, the effect on the overall component is lower than 13% even for six turns since the top and bottom portions of the winding are not affected as significantly. We note that the effect is smaller for larger numbers of turns, where the polygon better approximates a circle; analysis of a 12 turn winding of larger dimensions same as the first prototype we built shows only a 3% deterioration.

The effect of narrowing the conductor at the interchanges was estimated by performing dc conduction finite-element simulations of conductors with slits in them. For a narrow slit, the extra resistance was 0.44 squares (0.44 times the sheet resistivity of the foil). Wider slits increase the effect; for example 0.52 squares for a slit 1/20 the width of the foil, or 0.58 squares for a slit 1/10 the width of the foil. The effect of this on a particular design depends on the ratio of inner and outer diameters and on the height of the toroid. As an example, we calculated the effect on an eight-turn design

with inner diameter 1/3 the outer diameter (which is typically near the optimum [3]), with a height equal to half the outer diameter, and assumed an extra 0.6 squares of resistance from each of the three interchanges needed for four layers. The effect is only a 2.7% increase in overall resistance—an almost negligible effect.

The benefits available from multi-layer windings have been quantified [8]. If the number of layers is constrained to $p$, the power loss in a multi-layer winding $P_{ml,opt}$, using the optimal layer thickness, is lower than the loss in a thick single-layer winding by the ratio

$$\frac{P_{ml,opt}}{P_{sl}} \approx \frac{1.013}{\sqrt{p}}. \tag{1}$$

The required thickness (relative to a skin depth) is given by

$$\Delta_{opt} \approx \frac{1.3}{\sqrt{p}}. \tag{2}$$

Thus, for a four-layer winding, one can expect nearly a factor-of-two improvement, which is only mildly hindered by the effects of the polygonal winding and the interchange resistance, for a net effect of about a factor of 1.7 improvement. Even a two-layer polygonal winding should generally have lower resistance than a single-layer round winding, if not by very much. Examples of the required layer thickness are shown in Table I.

TABLE I
EXAMPLES OF OPTIMUM LAYER THICKNESS

| Layers | 20 kHz | 200 kHz | 2 MHz | 20 MHz | 200 MHz |
|---|---|---|---|---|---|
| 4 | 304 $\mu$m | 96 $\mu$m | 30 $\mu$m | 10 $\mu$m | 3 $\mu$m |
| 16 | 152 $\mu$m | 48 $\mu$m | 15 $\mu$m | 5 $\mu$m | 1.5 $\mu$m |

## IV. EXPERIMENTAL RESULTS

### A. Large Prototype

An air-core twelve-turn inductor prototype was constructed with four layers of copper winding to operate at a frequency of 170 kHz. The optimal thickness of each layer for this frequency is calculated using (2) to be 0.105 mm. The shape of the inductor is a solid, which has regular polygons of twelve sides as the inner and outer boundaries. The average inner diameter is 2.7 cm, average outer diameter is 9.16 cm and height is 2 cm. The prototype used an air core in order to make it easier to separate the small winding resistance from inductive impedance to avoid any issues in separating core losses and winding losses in the measurement. The low frequency and large size of the inductor were chosen for ease of handling and accurate measurements. Copper foil was cut out in the proper shape and notches cut out after each quarter length for the interchanges. Each layer was insulated using thin polypropylene tape. The four layers were wound around a plastic form and their ends joined by soldering.

For these dimensions and frequency and a single layer winding thicker than a skin depth at this frequency,

using the equations from Appendix A, the ac resistance is calculated to be 11.9 milliohms, inductance to be 703 nH and $Q$ to be 63. Using a four-layer winding of optimal thickness instead of the single-layer should ideally decrease the ac resistance by a factor of two or 50 % at 170 kHz. But taking into account the increase in ac resistance due to the polygonal windings and interchange resistance we expect the improvement factor to be less than two. This expectation is conformed in Fig. 5, which shows the measured values for single-layer and four-layer inductors. Impedance was measured using an Agilent 4294A impedance analyzer.

We have been able to achieve a decrease in ac resistance by 32% for the four-layer inductor as compared to single-layer inductor. The inductance is 934 nH and $Q$ is 100.3. It should be noted that the length of the outermost layer of each turn is longer than the inner one due to the thickness of the insulation and the other layers. The calculated values as shown by the green curve in
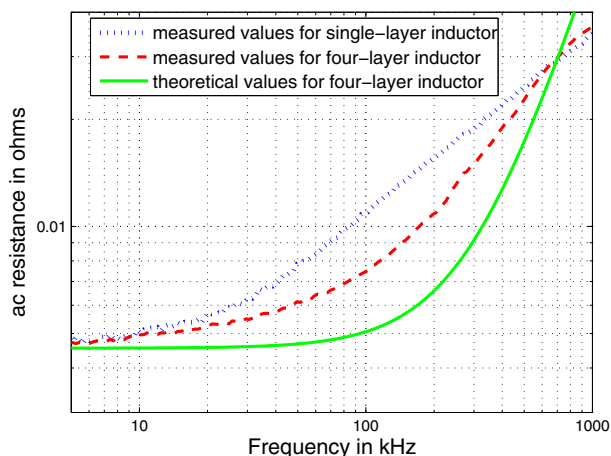


Fig. 5. Ac resistances for single-layer and four-layer inductors and theoretical value for the four-layer inductor ignoring the effects of polygonal winding and interchange resistance.



Fig. 6. Photograph of prototype.

Fig. 5 are based only on the ideal length of the innermost turn. Also, the actual thickness of the copper coil when measured was found to be 0.13 mm instead of the nominal thickness of 0.105 mm. The actual loss is higher than calculated even after taking into account the above effects. One possible reason for this discrepancy would be partial shorts between turns or layers, for example if the thin insulating tape was cut through by sharp edges of the hand-cut copper. Improved construction may lead to an even larger performance improvement.

### B. 50 MHz design

After the larger prototype had been tested and shown to have improved performance as compared to a similarly sized single-layer inductor, a smaller inductor for application at a higher frequency of 50 MHz has been designed and is being constructed for measurement.

*1) Design:* The optimal thickness of each layer for 50 MHz is calculated using (2) to be 6.07 $\mu$m. We decided to use single-sided copper-polyimide laminate in which the copper side will be the winding layer and the polyimide side will be a support for the very thin copper and will also act as the insulation between each of the copper layers. The nearest thickness of copper in a copper-polyimide laminate available in the market and hence the one we used is 5 $\mu$m. To compare the losses in case of each thickness we calculate

$$\frac{F_r}{\Delta} = \left[ 1 + \left( \frac{5p^2 - 1}{45} \right) \Delta^4 \right] \left( \frac{1}{\Delta} \right) \qquad (3)$$

where $F_r = \frac{R_{ac}}{R_{dc}}$ is the ac resistance factor, $\Delta$ is the ratio of thickness of each layer to the skin depth and $p$ is the number of layers [8]. The ratio given by (3) is proportional to the loss because the dc resistance is inversely proportional to $\Delta$. The difference in thickness would affect the performance by increasing the loss only by 5.8% at 50 MHz. We decided to build the new inductor with inner diameter, $d_i$ of 4 mm, outer diameter, $d_o$ of 12 mm, height, $h$ of 4 mm and 8 turns.

Using the calculations in Appendix A for the new dimensions of an air-core inductor with a single layer winding thicker than a skin depth at the frequency of operation, the ac resistance, $R_{ac}$, is calculated to be 97.8 milliohms, inductance, $L$, to be 56.2 nH and $Q$ to be 182.5 for a single-layer inductor at 50 MHz.

The corresponding four-layer inductor should have half the ac resistance and double the $Q$ as above. But taking into account deterioration in performance due to polygonal windings, notches and non-exact thickness, the expected ac resistance should be reduced to a little over half and $Q$ increased to a little less than double as compared to the corresponding single-layer values.

*2) Fabrication:* A program was developed in MAT-LAB for drawing out the necessary layouts including the notches for the four layers. This program takes the layer number, dimensions of the inductor, number of turns, thickness of each layer including the insulation, space between each turn, dimensions of the notch, a notch orientation matrix and a winding factor as its inputs and draws out the corresponding layout of the specified layer. The calculations are shown in Appendix B. We used the swap interchange method as shown in Fig. 4. The position of each layer changes after every quarter length according to Table II, where 1 is the innermost position

TABLE II
POSITION OF EACH LAYER AFTER EVERY QUARTER LENGTH

| Layer | Quarter 1 | Quarter 2 | Quarter 3 | Quarter 4 |
|-------|-----------|-----------|-----------|-----------|
| 1 | 1 | 2 | 4 | 3 |
| 2 | 2 | 1 | 3 | 4 |
| 3 | 3 | 4 | 2 | 1 |
| 4 | 4 | 3 | 1 | 2 |

and 4 is the outermost position. Since the outer layers in each turn will have to be longer than the inner layers, extra length is added to the corresponding parts of the layouts. A winding factor has been defined to account for flaws in the winding process of the coil. Its value is higher for lose windings and near to one for a tightly wound coil. The extra length calculated using Table II is multiplied by this winding factor to make allowance for imperfection in the winding process.

The notches in the layout are present after each quarter length, and will be facing either upward or downward depending upon their position and which layers are involved in the interchange. Their orientation is decided by an orientation matrix specified as an input, which is selected according to the interchange pattern desired by the user. There are four flat areas in each turn where notches can be placed. We decided to place the notches in the broad rectangular area, as shown in Fig. 8 in Appendix B, since it would conveniently be on the outer side of the inductor and also easier to lay out and cut out. For four layers, there are three interchanges, as shown in Fig. 4, hence each layer includes three notches and the orientation matrix is a $3 \times 1$ matrix. The notches go half-way into the width of the winding at that part to allow convenient interchange of the layer positions. Extra area was added to either ends of the eight-turn layout for circuit connections.

The copper-polyimide laminate was laser cut according to the drawn layouts. The laser cutting is advantageous for cutting small parts precisely. When the copper-polyimide layers are stacked on top of each other we need to ensure that the copper part of one layer does not come in contact with the copper part of the layer above or below it. The polyimide part of the laminate would take care of the insulation between the copper layers. We also need to have insulation between copper in adjacent turns. To achieve this we will etch out some copper back from the edges of the layout so that when they are laid side by side there will be a non-copper margin in between. To do this we will apply some tape on the copper side of the cut-out foil and dip it in etchant solution for some time. This would etch out the outer
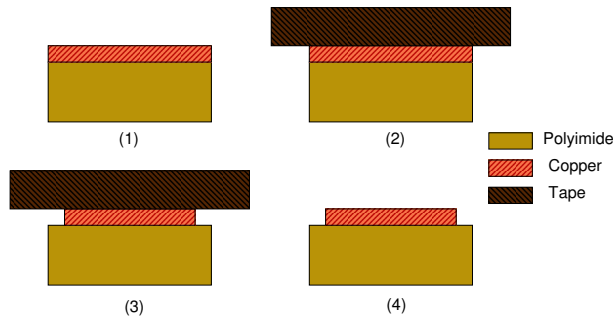
Fig. 7. Steps in the etching process

edges of the copper which is sandwiched between the polyimide and the tape. The result of each step of this process is shown in Fig. 7. The new inductor design will be tried out on both an air-core and a magnetic-core. The magnetic core to be used will be made up of stacks of Co-Zr-O nano-composite magnetic material sputtered on a polyimide substrate [4].

## V. OTHER APPLICATIONS

Interchanged multi-layer foil windings can be applied more broadly than just to polygonal toroids, and polygonal toroid windings can be used over a broad range of frequencies, with and without cores.

To illustrate the range of applicability and to know what our experimental results mean for higher frequency applications, we calculate how performance scales with frequency and size, for a fixed geometry. For a single-layer winding, the resistance is proportional to the square root of frequency because of skin effect. The same is true of a multi-layer winding, if the layer thickness is chosen according to (2). Since the inductive impedance is proportional to frequency, the $Q$ of an air-core inductor is also proportional to the square root of frequency.

For a given geometry (meaning fixed ratios between dimensions of the toroid, and a fixed number of turns), the inductance scales proportional to the linear dimensions. For a fixed foil thickness, with the other dimensions scaled together, resistance is constant independent of scaling, and $Q$ is proportional to linear dimensions.

Thus, for a given $Q$, geometry, and number of layers, the required linear dimensions are inversely proportional to the square root of frequency. (The volume is proportional to $f^{-\frac{3}{2}}$.) Thus, for example, our prototype at 170 kHz is 17 times larger diameter than an inductor with equivalent performance at 50 MHz would be—a 5.2 mm diameter inductor, 1.3 mm high, could have the same $Q$ of 100.

The method of interchanging winding layers shown in Figs. 3 and 4 can be used to make multi-layer foil windings effective in other types of foil windings, such as barrel-wound foil on E-E cores, pot cores, or U-U cores. A complication in this case is that the proper positions for the interchanges are no longer equally spaced along the length of the foil, since the flux is different for each turn (whereas it is the same for each turn of the folded toroid). Since the interchange locations are no longer positioned at the same point in each turn, there is no restriction on the relationship between the number of turns and the number of layers.

## VI. CONCLUSION

Single-layer folded-foil windings in polygonal approximations to toroids have low ac resistances approaching those of conformal windings on round toroids. Multi-layer windings can further reduce the ac resistance if the layers are interchanged, theoretically by a factor of the square root of the number of layers. Our first prototype achieved a 32% reduction in ac resistance compared to a single-layer folded-foil prototype, and a factor-of-two reduction in ac resistance compared to a wire-wound toroid. Our motivation was applications in the 10s of MHz; an inductor using our design for operation at 50 MHz is under construction and is expected to show reduction in winding losses even at high frequencies. Our prototype was a 170 kHz air-core; folded-foil multi-layer toroidal windings are beneficial over at least this range of frequencies, with and without magnetic cores. Interchanged multi-layer foil windings, using the approach introduced here can also be applied to more conventional winding configurations on E-E cores or U-U cores.

## APPENDIX

### A. Impedance Calculations

The inductance of a toroidal inductor with inner diameter $d_i$, outer diameter $d_o$, height $h$ and number of turns $N$ may be calculated as

$$L = \frac{N^2 h \mu_0}{2\pi} \ln\left(\frac{d_o}{d_i}\right) \qquad (4)$$

where $\mu_0$ is the permeability of free space [3]. The ac resistance of the inductor may be calculated as a sum of the ac resistance of the cylindrical parts at the outer and inner sides of the inductor, $R_{ac,side}$, and the ac resistance of the flat top and bottom parts of the inductor, $R_{ac,ends}$, which are calculated as

$$R_{ac,sides} = N^2 h \sqrt{\rho_c \mu f \pi} \left(\frac{1}{\pi d_o - N w_C} + \frac{1}{\pi d_i - N w_C}\right) \qquad (5)$$

and

$$R_{ac,ends} = \frac{N^2 \rho_c}{\pi \delta} log\left(\frac{\pi d_o - N w_C}{\pi d_i - N w_C}\right) \qquad (6)$$

where, $\rho_c$ is resistivity of copper, $\mu$ is permeability of copper, $w_c$ is the space between the foil in each turn, $\delta$ is the skin depth and $f$ is the frequency of operation. The quality factor may be calculated as

$$Q = \frac{2\pi f L}{R_{ac}} \qquad (7)$$

## B. Layout Calculations

The MATLAB function used for finding the dimensions of the layouts of the foil takes input arguments described in Table III. Fig. 8 shows the layout and

| Input | Description |
|---|---|
| $n_{layer}$ | layer number |
| $d_i$ | diameter of inner polygon |
| $d_o$ | diameter of outer polygon |
| h | height of the inductor |
| t | thickness of each layer including insulation |
| $w_o$ | width of outer edge of notch |
| $w_i$ | width of inner edge of notch |
| $K_f$ | winding factor |
| $w_c$ | space between turns |
| $M_x$ | row matrix specifying placement of the notches: 1 for up 0 for down |

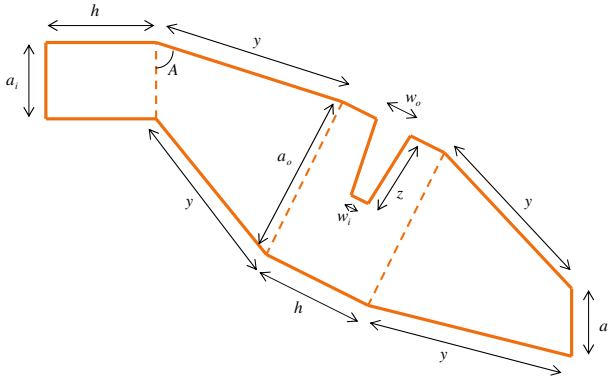dimensions of one turn of the winding, which may be calculated using (8)-(17). The outer polygon is assumed



Fig. 8. Dimensions of one turn of the winding

to be outside a circle of diameter $d_o$ such that the inradius, $R_i$, and the circumradius, $R_o$, of the outer polygon are

$$R_i = d_i/2 \qquad (8)$$

and

$$R_o = \frac{1}{2a_o}\mathrm{cosec}\left(\frac{\pi}{N}\right) \qquad (9)$$

The inner polygon is assumed to be inscribed inside a circle of diameter of $d_i$ such that the inradius, $r_i$, and the circumradius $r_o$, of the inner polygon are

$$r_i = \frac{1}{2}a_i \cot\left(\frac{\pi}{N}\right) \qquad (10)$$

and

$$r_o = d_o/2 \qquad (11)$$

Side length of the outer and the inner polygons may be calculated as

$$a_o = 2r_o \tan\left(\frac{\pi}{N}\right) \qquad (12)$$

and

$$a_i = 2R_i \sin\left(\frac{\pi}{N}\right) \qquad (13)$$

The distance between a corner of the inner polygon and a corner of the outer polygon is

$$y = \sqrt{(R_o - r_i)^2 + (a_i/2)^2} \qquad (14)$$

and the angle that $y$ makes with the edge of the inner polygon is

$$A = \cos^{-1}\left(\frac{y^2 + (\frac{a_i}{2})^2 - x^2}{y_i a_i}\right) \qquad (15)$$

The notch extends half-way into the width of the layout, $a_o$, at that part. The angle inside the notch is

$$J = \tan^{-1}\left(\frac{a_o}{w_o - wi}\right) \qquad (16)$$

and the length of the edge of the notch is

$$z = \sqrt{\frac{w_o - w_i}{2} + \frac{a_o}{2}} \qquad (17)$$

The values from (8)-(17) can be used to find out the dimensions of the layout, when no allowances have to be included to account for imperfections in the winding process and for the variable length of each layer in a turn.

We introduce $l$ and $k_i$ as allowances in our calculations. Within the inner polygon in order to avoid overlapping of foil layers we make the layout thinner by a value

$$l = \cot\left(\frac{\theta}{2}\right)4t + \frac{w_c}{2} \qquad (18)$$

where, $\theta$ is the interior angle of the polygons and is given by

$$\theta = \left(\frac{N - 2}{N}\right)\pi \qquad (19)$$

The second allowance that we make accounts for extra length of the outer turns as compared to the inner turns and may be calculated as

$$k_i = i\frac{\pi}{2}4tK_f \qquad (20)$$

where $k_i$ is the extra length for the $i^{th}$ layer and is added to the corresponding quarter of the winding according to Table II.

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