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Multi-Layer Barrel-Wound Foil Winding Design

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Abstract—Multi-layer windings can effectively decrease losses in high-frequency inductors and transformers in many applications. A simple way to achieve lower losses in barrel-wound foil windings for transformers, by incorporating multiple layers with proper interchange of layer positions to ensure the same flux and current in each layer, is introduced. This method of layer interchange has already been applied to toroidal inductors and in this paper it is shown how to modify it to apply it to barrel-wound foil windings such as windings on E-E cores, pot cores and U-U cores.

Index Terms—Multi-layer, barrel-wound, ac resistance, interleaving, layer interchange.

I. INTRODUCTION

The designers of high-frequency inductors and transformers are faced with the difficulty of eddy-current losses which include proximity effect and skin effect. Employing techniques that force the current in these windings to flow in more than one individually insulated conductor can reduce the winding loss [1]. One such method to reduce the eddy-current losses is the use of litz-wire conductors made up of multiple individually insulated strands twisted or woven together. But litz wire can get very expensive and also have poor packing factor [2] [3].

An approach that can be simpler to produce and can achieve lower losses is the use of multiple layers of foil conductor material. Multiple layers of conductors, each thin compared to an electromagnetic skin depth, can be used to provide lower high-frequency ac resistance than a single-layer conductor [1]. However, introducing multiple layers does not automatically result in lower losses because the current that flows through each of these layers may not be the same. Each of these layers may link a different amount of flux and so the induced voltages are different. These result in extra circulation currents which can increase losses in the conductors. Current sharing between parallel turns of a planar transformer has been analyzed in [4]. In order for the multi-layer strategy to be effective, it has to be ensured that each layer links the same amount of flux through the whole length of the winding. In litz wire, to balance the

flux, interchanging of conductor positions is performed by twisting; in planar windings, other strategies are needed. Both the use of vias in PCB technology [5] or folding [6] have been used in the literature. Another way is to rotate the conductors within the coil, in such a way that continuous close contact between adjacent strips is avoided. These are known as continuously transposed conductors [7] [8] [9].

In [10] a method of interchanging layers to balance flux has been used to achieve lower losses in multi-layer folded toroidal inductor windings. In this paper, the multi-layer foil winding interchange approach of [10] has been modified and applied to barrel-wound foil windings to achieve the reduction in winding losses.

In the case of foil windings, 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 minimize the extra resistance added 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 [10]. A less expensive alternative is illustrated in Fig. 1. Notches are cut into the foil, going halfway across the width, and the layers are fitted together to swap positions [10]. Although Fig. 1 shows only one layer going up (in

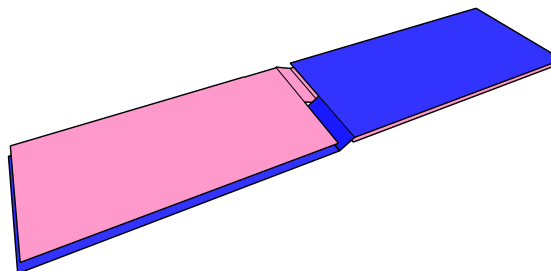


Fig. 1. Interchanging the position of two foil layers

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. The exact placement of the notches

will take into account that the flux changes with each layer and also with each turn.

Producing such interchanges requires notch shapes cut from copper foil, which can be done by cutting by hand, photochemical etching, die cutting or laser cutting and they can be insulated with tape, powder coating, spray or dip varnish.

In [10] the interchanges in the toroidal inductor foil windings take place at equal intervals in each layer to achieve the same flux in each layer. The method in [10] works for the toroidal inductors because same flux is linked by each turn due to the toroidal shape of the core. On the other hand, in barrel-wound windings, if we use conductor foil, the first turn is closest to the core and then the next turn is over the first turn further away from the cylindrical core and so on. Along with being different for each layer, the flux in this case is different for each turn also. Hence, equal interchange spacing cannot advantageously be used for barrel foil windings. In this paper, we introduce a way to achieve the same flux in each layer for barrel-wound foil windings, using a special configuration of windings along with the interchange method. The layer interchange method shown in this paper can be applied to barrel windings on various cores such as E-E cores, pot cores and U-U cores.

II. WINDING CONFIGURATION

The type of winding we propose is a long flat rectangular copper conductor with length according to the number of turns and the core size as required by the design.

Consider an interleaved winding configuration such as shown in Fig. 2, where each turn of primary winding will consist of multiple layers (not shown in Fig. 2). With

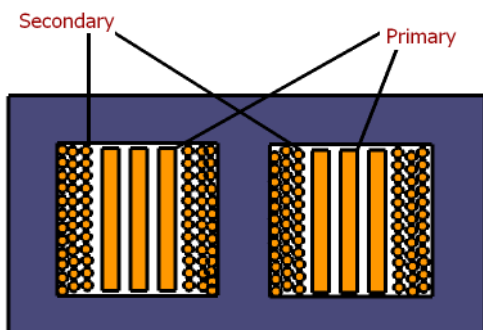


Fig. 2. Interleaved winding configuration of transformer. The primary windings are made up of planar copper foil while the secondary is a wire winding. The core of the transformer is shown in blue.

such an alternating placement of primary and secondary windings in the same window, called interleaving, the primary winding is subjected to a positive field for half the turns and a negative field for the other half of the turns with zero field in the center of the window. Within each turn, the field and flux varies with each layer also.

As an example, the flux distribution is represented by color shading in Fig. 3 for a primary foil winding with four layers and four turns when used in the interleaved configuration of Fig. 2. It can be seen from this figure

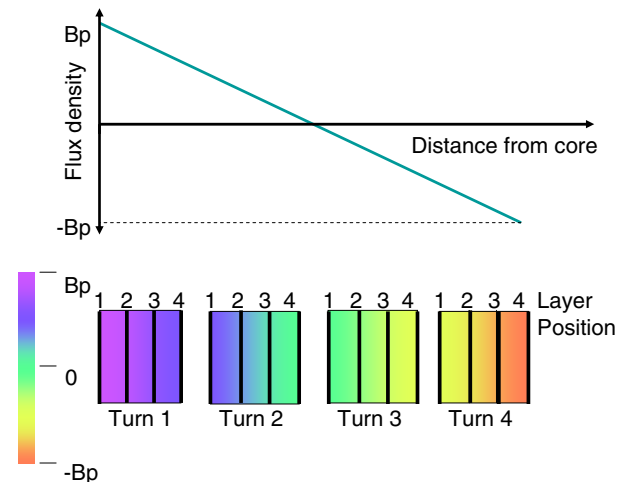


Fig. 3. Variation of flux density with layers and turns for a four-turn four-layer winding. The flux magnitude is maximum at both the ends of the winding but opposite in direction. At the middle portion of the winding the flux is zero. Within each turn the flux varies with each layer also.

that between any pair of adjacent layers the flux density is different for each turn; while it is in one direction for two of the turns it is in the opposite direction for the other two turns. Also, this total flux being different in magnitude in each turn does not add up to the same value when we consider different adjacent layers in the designs. But we need to make this total flux in each of these loops the same in order to gain an advantage out of the multiple layers.

For the purposes of calculation we redraw Fig. 3 as Fig. 4 which shows each continuous layer when the winding has been unwound but with field strength it had when it was still wound. The width of each layer is going into the page and the length is along the page. If we follow a path along any current loop in the design, positive flux is associated with some parts of the loop and negative flux with others. Placing an interchange anywhere in the loop would reverse the flux direction in the part of the loop after the interchange. If we place the interchanges at the proper positions, we can achieve a total flux of zero around the loop. An example of this is shown in Fig. 4. The interchanges can be placed such that all the loops in the design will have a total flux of zero. In that case when current is applied to the ends of the coil it will flow equally through each of the layers. We place the notches in the turns with the maximum flux linkage, as shown on Fig. 4, to make the overall linked flux zero.

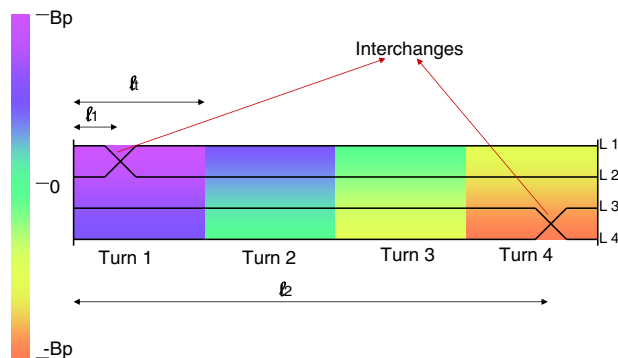


Fig. 4. Variation of field with layers and turns for a four-turn four-layer winding, showing the winding unwound but with the field strength it has when it is wound. Each layer of the winding represented by the solid black lines can be visualized as having a width into the page. When wound around a cylindrical core Layer 1 will be the innermost layer.

III. FLUX BALANCING

For a configuration of primary windings as in Fig. 2, maximum flux is linked between the innermost layer and the second innermost layer in turn 1, and by the outermost layer and the second outermost layer in turn 4 as depicted in Fig. 3 and Fig. 4. The flux linked by each of these parts will be similar in magnitude but opposite in direction if we assume that the length of each turn is equal. When we place an interchange in one of these, the direction of the flux in one of the parts, either before or after the interchange, will reverse. So we place the interchange at a calculated distance that would make the total flux in the loop zero. We express the flux linked between the layers in terms of a peak flux in the winding, ϕ_p , defined as

$$\phi_p = B_p A_t \quad (1)$$

where B_p is the peak flux density as shown in Fig. 3 and A_t is the area between two layers for one turn.

If we say that $\phi_1 + \phi_2$ is the total flux between the first and second layer in turn 1, where ϕ_1 is the flux in the part before the interchange and ϕ_2 is the flux in the part after the interchange, then without interchanging layer positions,

$$\phi_1 + \phi_2 = \left(N - \frac{1}{2}\right) \frac{1}{N} \phi_p \quad (2)$$

where N is the number of turns in the winding using four layers for each turn. Now when the interchange is placed in this part, ϕ_2 changes direction and then the flux in the first turn between the first and second layer has to be equal and opposite to the flux in the rest of the loop (between layers 1 and 2) through turns 2, 3 and 4, which gives us

$$\phi_1 - \phi_2 = \frac{-(N-1)}{2N} \phi_p \quad (3)$$

Equations (2) and (3) can be solved to give

$$\phi_1 = \frac{1}{4} \phi_p \quad (4)$$

and

$$\phi_2 = \frac{3N-2}{4N} \phi_p \quad (5)$$

In order to achieve total flux of zero, the first interchange needs to be placed between the first and the second layers at the distance of ℓ_1 , from one of the ends of the winding. This distance is given by

$$\ell_1 = \frac{\phi_1}{\phi_1 + \phi_2} \ell_t = \frac{N}{2(2N-1)} \ell_t \quad (6)$$

where ℓ_t is the length of each turn as shown in Fig. 4 and N is the number of turns in the winding. The second interchange needs to be placed at a distance of ℓ_2 , as given by (7), from the same end that was used to measure ℓ_1 , between the third and fourth layers; or at a distance of ℓ_1 from the other end of the winding.

$$\ell_2 = 4\ell_t - \ell_1 \quad (7)$$

Equations (6) and (7) have been formulated for four layers of winding with N number of turns and assume that the length of each turn is equal.

IV. ANALYSIS OF FACTORS AFFECTING PERFORMANCE

Compared to a single-layer-per-turn foil winding, the design with the four layers should have lower ac resistance. From [1], 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

$$\frac{P_{ml,opt}}{P_{sl}} \approx \frac{1.013}{\sqrt{p}} \quad (8)$$

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

$$\Delta_{ml,opt} \approx \frac{1.3}{\sqrt{p}} \quad (9)$$

Thus, for a four-layer winding, one can expect nearly a factor-of-two improvement compared to a single layer winding, which is only mildly hindered by the effect of the interchange resistance.

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 μm	96 μm	30 μm	10 μm	3 μm
16	152 μm	48 μm	15 μm	5 μm	1.5 μm

The effect of narrowing the conductor at the interchanges was estimated by performing dc conductor

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 width and length of the foil. The effect of the notch on the resistance can be reduced if we narrow the foil width by a factor of two or three and use two or three narrower foils laid side-by-side instead. This would make the overall effect of the notch almost negligible.

V. EXAMPLE DESIGN AND CONSTRUCTION

We use the design procedure as given in [11] to estimate the specifications which are listed in Table II, for a transformer to be used in a dc-dc converter at a 30 kHz switching frequency.

TABLE II
EXAMPLE DESIGN OF TRANSFORMER

Parameter	Value
Power Rating	1 kW
Input Voltage	5.7 V
Output Voltage	98.8 V
Core	ETD 39/20/13
Heat Dissipation	3.9 W
Core Loss	1.95 W
Coil Loss	1.95 W
Primary turns	3
Secondary turns	52

We apply the suggested technique to the three-turn primary winding of this example design, constructed with interleaving as shown in Fig. 2. With four layers in the three-turn primary, the number of layers for loss calculations is 6, counting from the zero-flux point in the center of the transformer to the maximum-field point. As an example in the Fig. 3 with the four layers in the four turn primary the number of layers for calculations is 8.

The optimal thickness of each layer for operation at 30 kHz is calculated using (9) to be 203 μm . The placement of the notches is calculated using (6) and (7).

In case of a single-layer design for the three-turn winding the number of layers for loss calculation would be 1.5, counting from the zero-flux point in the center of the transformer to the maximum-field point. Using the suggested four-layer winding of optimal thickness (for which the number of layers for loss calculation is six) instead of the single layer (for which the number of layers for loss calculation is two) should ideally decrease the ac resistance in the primary winding by a factor of 2 at 30 kHz using (8). But the notches in the winding also

increase the ac resistance of the winding by 5.6%. Hence the improvement factor would theoretically be around 1.89. Imperfections in termination of the winding would also add to the resistance.

The ac resistance of the multi-layer primary winding is too small for accurate measurement with a direct connection to an impedance analyzer. Hence the primary resistance was measured through its reflection on the secondary side with the primary winding shorted.

The windings were constructed by cutting out the copper foil in rectangular shapes to fit in the bobbin for the core. An extra rectangular part, as shown in Fig. 5, was made to extend at right angles from the ends of each of the layers for terminations. The layers were all soldered together at these terminations after the winding had been wound around the bobbin. These

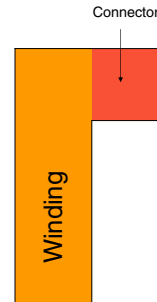


Fig. 5. Foil winding for the transformer needs to have connectors coming out of them for termination. The area shown in darker color from each layer will be soldered together.

rectangular parts should be of width comparable to that of the winding in order that they do not add much to the winding resistance. To make this construction easier we made the winding by dividing the foil width into two and using them side-by-side such that their rectangular connectors also could be of half the width. This could also have been done by making a wide T shape with the winding and the connectors, but making two thinner L shaped conductors also reduces the effect of the notches in the winding. For example if the resistance of the complete undivided winding is R_w and the increase in resistance due to a notch is R_{notch} , the overall resistance of the winding with one notch, $R_{undivided}$, is given by

$$R_{undivided} = R_w + R_{notch} \quad (10)$$

If the foil winding is divided into two parts of the same width each, the resistance of each division will be $2R_w$. Now, with a notch added to each of these divisions and with these two divisions connected in parallel, the overall resistance of the winding will be

$$R_{divided} = \frac{1}{2}(2R_w + R_{notch}) = R_w + \frac{R_{notch}}{2} \quad (11)$$

Hence, using two conductors in parallel reduces the overall effect of the notch in the winding.

For three turns in the primary foil winding ℓ_1 is calculated using (6) to be 5.22 mm. The notches are placed at a distance of ℓ_1 , from the inner end between the first and the second layers, and from the outer end between the third and the fourth layers.

First 26 turns of 18/3/40 litz wire (54 strands, each 80 μm in diameter) were wound around the bobbin, then three turns of the four-layer foil were wound around them and then the litz wire was continued over the foil winding for the next 26 turns forming an interleaved configuration. Each of the foil layers was insulated using polyimide tape and soldered together at the ends to form a shorted winding.

VI. EXPERIMENTS AND RESULTS

The constructed transformer is shown in Fig. 6

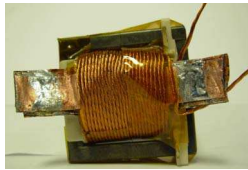


Fig. 6. The E-core transformer prototype.

Before the primary winding was shorted out for measurement through its reflection to the secondary winding, the dc resistance was measured and found to be 0.275 milliohms for the side-by-side foil winding. The dc resistance of the litz-wire secondary winding was found to be 0.290 ohms. These values and their corresponding theoretical values have been tabulated in Table III.

TABLE III

THEORETICAL AND MEASURED VALUES OF DC RESISTANCE.

Value	Theoretical	Measured
Resistance of foil primary	0.17 milliohms	0.27 milliohms
Resistance of litz wire secondary	0.21 ohms	0.29 ohms

After the primary winding is shorted out, at frequencies high enough to induce current in the foil primary winding, the resistance when measured between the litz-wire secondary winding terminals will include the resistance of the litz wire at that frequency and the resistance of the primary reflected onto the secondary.

The resistance of the transformer was measured using an Agilent 4294A impedance analyzer. The theoretical values of the designed prototype and some other windings and the measured values of the constructed prototype are plotted in Fig. 7. The resistance of the litz wire was subtracted from the measured values and then the foil resistance was calculated by dividing it by $\left(\frac{N_2}{N_1}\right)^2$.

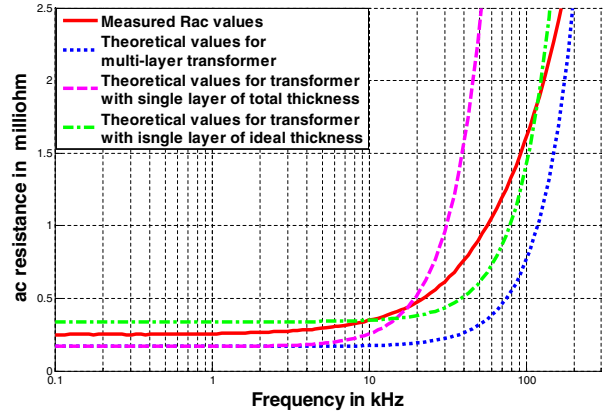


Fig. 7. Measured and theoretical values of the ac resistance of the experimental transformer: The measured values (in red) are being compared to the theoretical values for the same configuration (in blue), the theoretical values of a transformer made with same windings without interchange (in magenta) and the theoretical values for a single-layer transformer with ideal thickness (in green).

The values of ac resistance for the constructed transformer show an improvement in ac resistance values over the theoretical ac resistance values of a transformer without the interchanges between the winding layers. However, when compared to a transformer which has a single-layer winding of ideal thickness for a single layer winding, we don't see an improvement. In fact at some frequencies it is even worse than the single-layer transformer with ideal thickness. A conclusion that the constructed transformer does not perform well based just on this graph, however, may not be correct because we have to keep in mind that there are always some losses that occur due to the construction processes. If actual transformers with these different types of windings were constructed for measurement they would have higher ac resistances than their corresponding theoretical values and we may see that the multi-layer with interchange design does give better performance.

For the sake of better comparison, instead of directly using the theoretical values of ac resistance for other types of windings, we predict what these values would be if we went ahead and actually constructed such a transformer. For each of the three types of windings we need to use different methods to find out these values. For the four-layer winding with notches like in the prototype (design A), we use the the dc resistance value, $R_{dc,measured,A}$, found by direct measurement with a milliohmmeter, to find out the predicted measured ac resistance, $R_{ac,p,A}$ using the theoretical ac resistance factor, $F_{r,th,A}$.

$$R_{ac,p,A} = R_{dc,measured,A} F_{r,th,A} \quad (12)$$

For the other two types of windings (designs B and C), which are a single-layer winding of the total thickness of the four layers and a single-layer winding of

ideal thickness, we need to predict their dc resistance values also. If we subtract the effect of the notches from $R_{dc,measured,A}$ we get the predicted dc resistance, $R_{dc,p,B}$, for a single-layer winding with total thickness of the four layers (design B). Then its ac resistance is calculated by

$$R_{ac,p,B} = R_{dc,p,B} F_{r,th,B} \quad (13)$$

In order to find values for a single-layer winding with ideal thickness (design C), we compare the measured and the theoretical values of dc resistance of the winding design A, $R_{dc,p,A}$ and $R_{dc,th,A}$, to find out the factor of deterioration in performance due to construction, $K_{construction}$. Since the measured values also include the effect of the notches we subtract the notch resistance, R_{notch} , from it for calculations.

$$K_{construction} = \frac{R_{dc,p,A} - R_{notch}}{R_{dc,th,A}} \quad (14)$$

For the single-layer winding of ideal thickness the predicted ac resistance, $R_{ac,p,C}$, is given by

$$R_{ac,p,C} = R_{dc,th,C} K_{construction} F_{r,th,C} \quad (15)$$

These three designs and their parameters have been summarized in Table IV.

TABLE IV

SUMMARY OF THE PARAMETERS IN THE THREE WINDING DESIGNS

Winding design	Number of layers	Layer thickness (mm)	Measured dc resistance (milliohm)	Predicted dc resistance (milliohm)
A	4	0.203	0.275	-
B	1	0.812	-	0.263
C	1	0.405	-	.157

The predicted measurement values of different types of windings and the measured values of the designed prototype transformer have been plotted for comparison in Fig. 8. As can be seen in Fig. 8 the measured values of ac resistance for the constructed prototype show improvement over the values for transformers with no interchange. Hence, the multi-layer method can bring down power loss in windings of transformers.

These values however, are still not very close to the predicted values for the new design. The main reasons for these non-ideal values are limitations in the construction process. Soldering together eight layers of copper conductors can result in terminations with high resistance. Also when these layers come out of the winding area as shown in Fig. 9, they are a hinderance to the flow of flux and result in increased losses. Furthermore, when the distances for interchanges were calculated, it was assumed that each turn was of equal length which

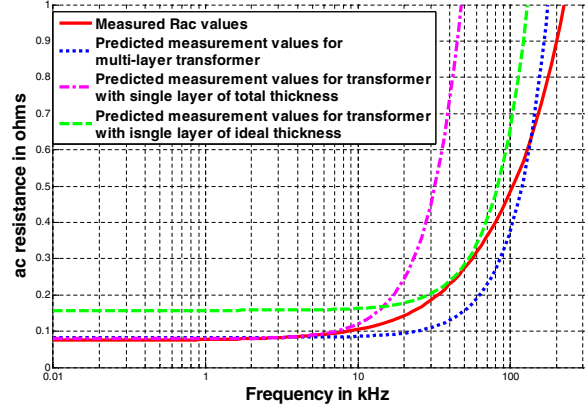


Fig. 8. Measured and theoretical values of the transformer: The measured values (in red) are being compared to the predicted measurement values for the same configuration (in blue), the predicted measurement values of a transformer made with same windings without interchange (in magenta) and to the predicted measurement values for a single-layer transformer with ideal thickness (in green). Predicted values are based on experimental dc resistance multiplied by the theoretical ac resistance factor, as explained in the text.

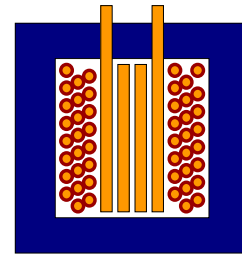


Fig. 9. The connectors at the ends of the foil come out of the winding area and come in the path of the flux flow.

is not true in the actual the transformer. There is also an ambiguity in deciding where should we assume each turn to begin. As in Fig. 5, the turn could be said to begin from the end of the copper part or it could be said to begin just before the rectangular connector ends. For constructing the prototype we have assumed that the turn begins a small distance into the winding from the end of the connector. This placement would not have made a great difference if the length of each turn was long enough or more importantly the distance of the interchange was considerably away from any end of the winding which was not the case in our design.

More accurate calculations taking into account different lengths of each turn can be used for better placement of notches. Also finite-element simulation can be performed with the foil shape at the terminations to find out how much they affect the losses and that factor can be included in calculating the projected values.

VII. OTHER APPLICATIONS

The method of interchanging winding layers shown in Fig. 1 with interleaved windings as shown in Fig. 2 can

be used to make multi-layer barrel-wound foil windings on various transformer cores. Some examples include windings on pot cores, E-E cores or U-U cores. The correct placement of the notches will have to be calculated in each case according to the flux distribution in order to make the total flux around all loops zero. The notch technique can also be applied to toroidal inductors for reducing losses [10], where the interchanges will be equally spaced along the length of the foil.

VIII. CONCLUSION

Multi-layer windings can reduce the ac resistance theoretically by a factor of the square root of the number of layers, when compared to a single-layer winding. This requires the layers to be interchanged such that the flux linked with each layer is the same and the same amount of current flows through each. In this paper, an interchanged multi-layer foil windings approach has been applied to windings on an E-E core. The correct location for the notches have been calculated according to the flux distribution in order to make the total flux around all the loops zero, which result in lowering of the winding losses in the design. The approach used in this paper can be applied to other barrel-wound foil windings such as windings on pot cores and U-U cores.

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