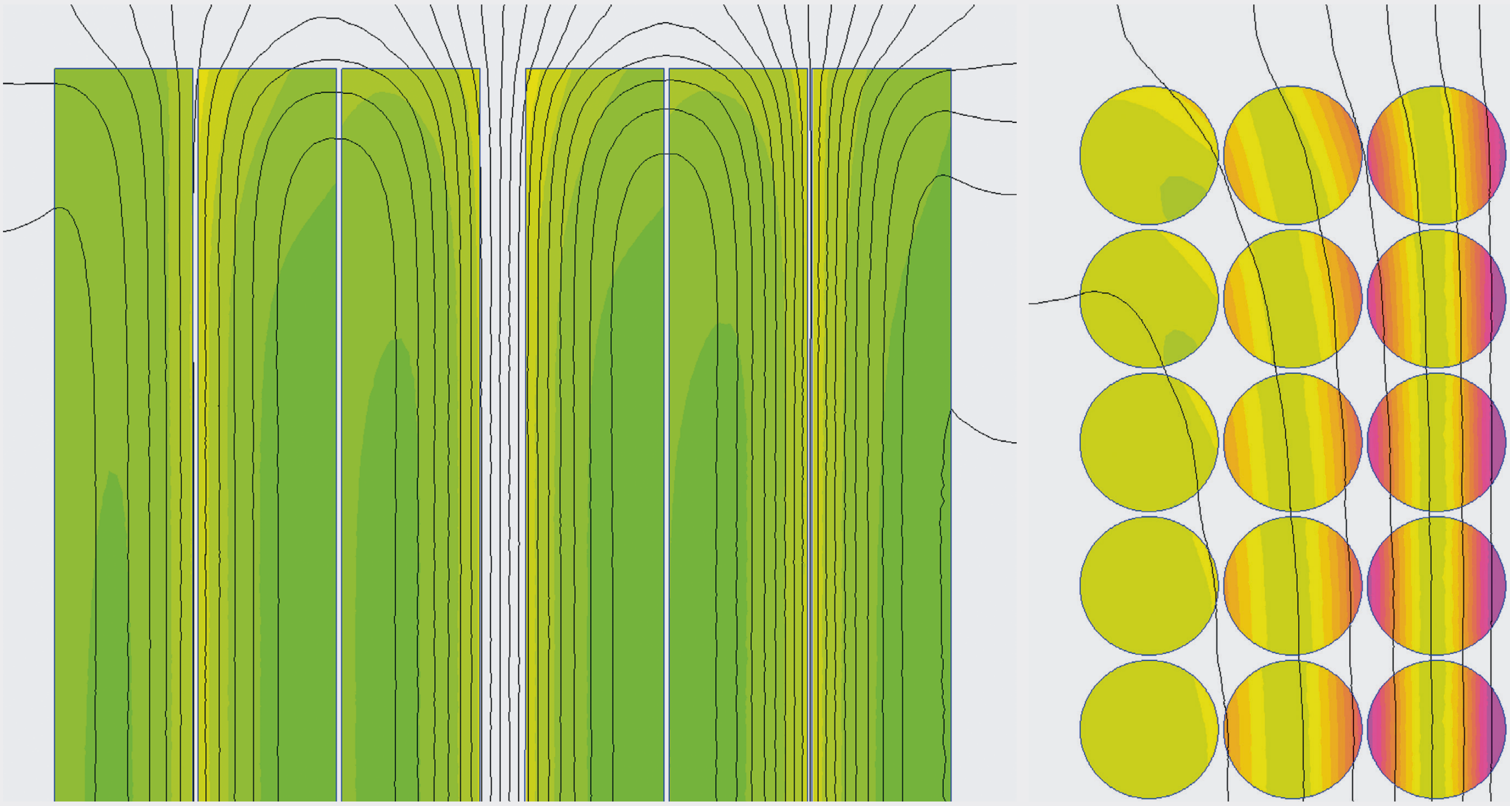


Qualitative FEM study of proximity loss reduction by various winding configurations – Part II

ABSTRACT

Skin depth and proximity effects in transformer windings are important phenomena influencing the design even at power frequencies (50-60 Hz). However, they become critically important at elevated frequencies, especially for high-frequency transformers, operating in switched-mode power supplies for example, at any power level. This article presents a numerical study of optimum winding configurations which can drastically reduce the proximity effects. It is possible to make transformers operating even at 1 MHz without the use of very expensive Litz wire.

KEYWORDS

copper loss, proximity effect, proximity loss, skin effect, eddy currents, windings

How to make a 1 MHz transformer without expensive Litz wire

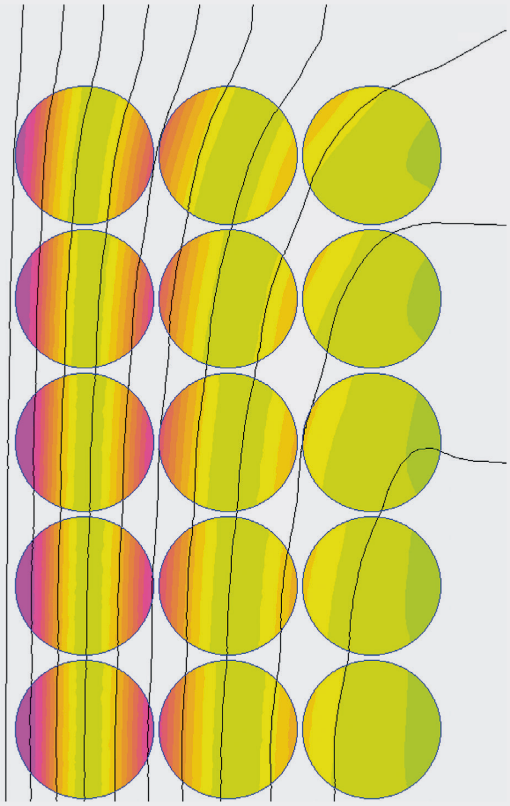
4. Further reduction of proximity loss

Even 1-2 interleaving (1 effective layer) produces some proximity effect, and as suggested by Dowell's curves in Fig. 4 (in Part 1 of this paper), reduction of layers below unity would yield further decrease of proximity loss. Fig. 8a indicates how a value of 0.5 layer can be achieved, but in this particular case the improvement is overshadowed by the skin effect.

Several investigators noticed that a different kind of interleaving is beneficial. Such configurations are, for instance, disclosed in some patents [16, 17]. The concept was partially investigated by Bruce Carsten [12], and Newton Ball [18, 19], and further study and development was made by the author of this paper.

According to the proposed approach, the windings should be limited to at most a single layer each, and wound on the whole

> **The proximity effect is produced by the elevated level of magnetic field between the wires, which also penetrates the volume of the wires**



> **Further reduction of proximity effects is obtained by ensuring that the windings are "coherent" – namely that wires do not cross, adhering to "the same lay, the same pitch" principle**

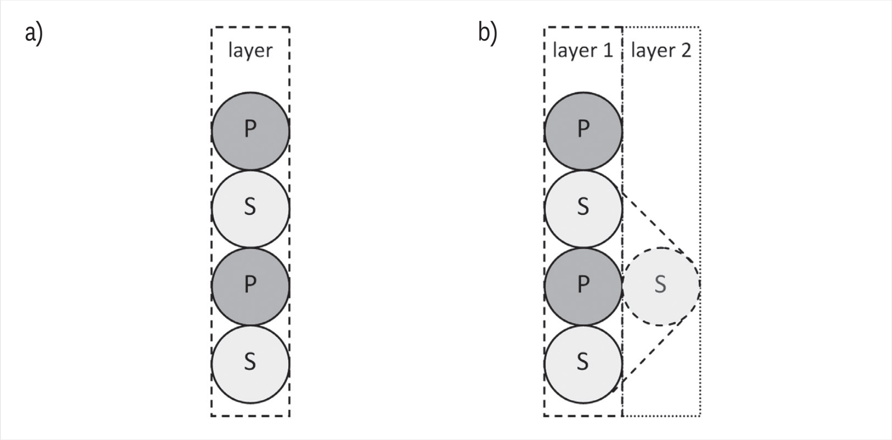


Figure 13. An ideal 1-1 interleave within a single layer (a) and a detrimental wire crossing (b)

length of the core. Further improvement is obtained by ensuring that the windings are "coherent" – namely that wires do not cross, so that "the same lay, the same pitch" principle is always observed (Fig. 12).

Otherwise, the wire crossings produce a localised non-uniformity of the field, and thus some additional proximity losses associated with it. This can be illustrated if the coherent windings are made so that both primary and secondary lie within the same layer, resulting with 0.5 effective layer, as shown in Fig. 12a, and Fig. 13a. Each wire crossing would produce a localised additional layer (Fig. 13b) and as per Dowell's curves this would increase the losses locally. Such local losses summarised over many wire crossings would contribute to a proportional increase of total copper loss.

This is a real problem, because such windings for E-type transformers are usually wound by rotating the bobbin and reversing the pitch so that a right-hand and left-hand screw patterns are produced in alternate layers. For optimum performance this is not allowed. The resulting structure must have only one layer and no wire crossings, so that no local additional layers are produced.

With such configuration (Fig. 12a and Fig. 13a) the proximity effects are driven to much lower values, and the performance of the conductors becomes limited more by the skin effect than the proximity loss.

At 1 MHz the skin depth is 0.065 mm, so a 0.13 mm wire would be sufficient for the skin effect to be negligible. However, because the proximity effect is drastically reduced the conductors can actually be much thicker without detrimental effects. The skin effect produces an increase of AC resistance over the base DC value. But the DC resistance can easily be reduced by using thicker conductor, and therefore AC resistance will be reduced too, *if the proximity effect is absent*. Simply put, a wire with larger diameter has more "perimeter" in which the high frequency current can flow (Fig. 14). As shown in Fig. 14, this is a very powerful method of copper loss reduction.

> **The performance of coherent windings becomes limited more by the skin effect than the proximity loss, allowing for much thicker conductors without detrimental effects**

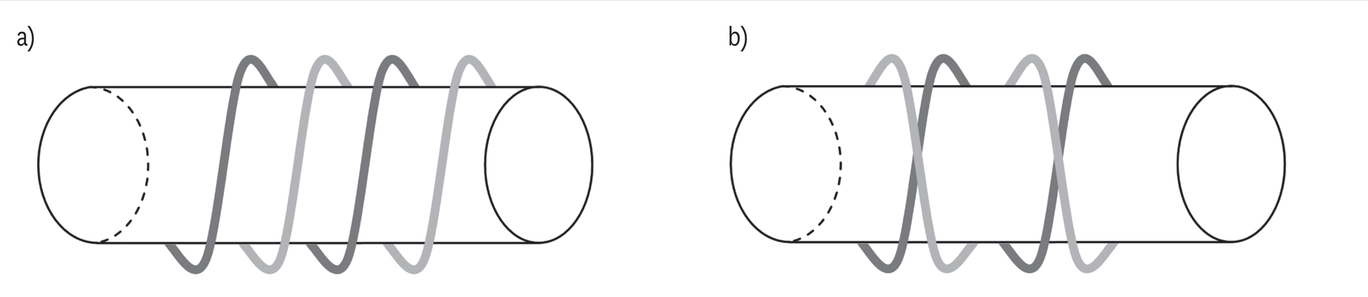


Figure 12. Schematic illustration of coherent (a) and non-coherent windings with wire crossings (b) [12, 13]

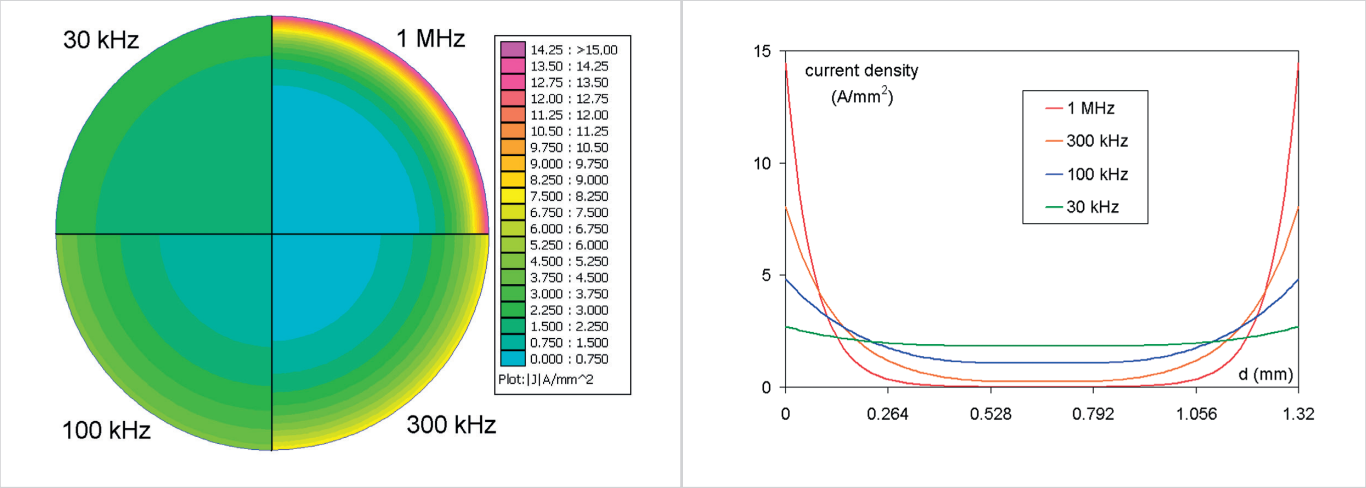


Fig. 14. Skin effect in 1.32 mm wire for various frequencies for peak current of 3.87 A (equivalent of 1.41 A/mm² for DC)

The penalty for coherent windings is that placing all the turns on a single layer requires proportionally “longer” core to fit all the turns of both primary and secondary coils within just one layer. Such winding will definitely not fit in the available window area, requiring a much larger core, with the penalty of increased core loss (due to larger core volume). However, the reduction of the proximity loss might be beneficial so that a longer core is acceptable. More details on the implications are given below.

Fig. 15 shows comparison for all calculated configurations. The figure contains many curves, but this is done on purpose so as to show a better comparison between all the variants. Some curves were already presented in the figures above, but they are also included for completeness.

Attention of the reader should be brought to the curve “wire 0.42 mm, coherent” in Fig. 15 (blue ovals). The improvement is not only significantly better than the 1-2 interleaving of the 0.42 mm tape, but also even better than the 1-2 interleaving of the 0.13 mm tape! For some transformer designs this could be an enough of an incentive to compromise the construction with appropriately elongated core.

The curve “wire 1.32 mm (0.42 mm), coherent” represents a configuration with a wire 1.32 mm used instead of 0.42 mm, but wound with as many turns as it would be for a normal 0.42 mm winding. The applied current is therefore the same as for 0.42 mm wire, so the current density is proportionally lower due to much greater cross-section area of the wire. The resulting DC resistance is an order of magnitude lower, and therefore the AC resistance and the high-frequency loss are also reduced by the same factor. Remarkably, the copper loss at 1 MHz is the smallest for 1.32 mm wire even though the wire is 20 times thicker than the skin depth (see also Fig. 14). This is not possible with any other winding style.

However, it should be noted that the coherent winding requires proportionally longer core. For the cases shown in Fig. 15, the coherent windings with wire 1.32 mm, 0.42 mm and 1.32 mm instead of 0.42 mm would require E cores whose central leg is longer by a factor of 3, 9 and 27, respectively. Therefore, Fig. 15 shows comparison of *only* the copper loss due to proximity and skin effects, whereas the core losses could be significantly different for each configuration. Nonetheless, the coherent configuration could be used in

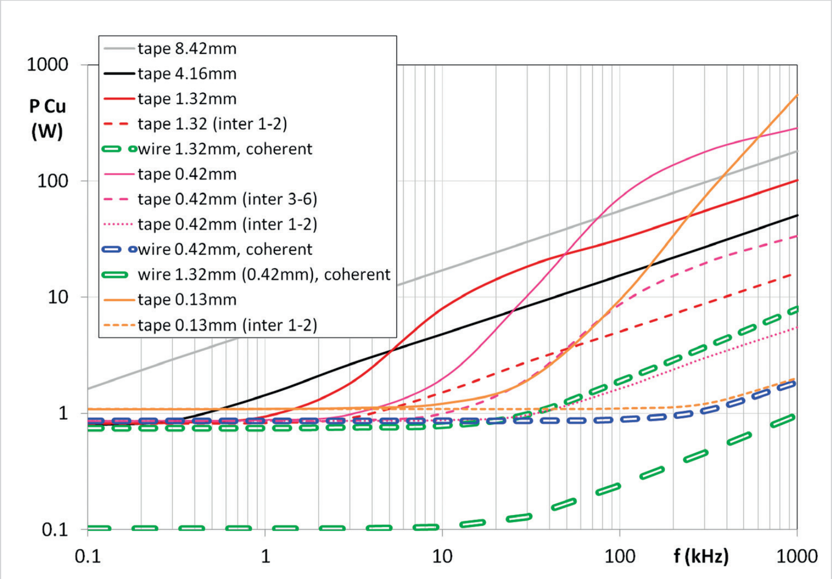


Figure 15. A comparison of all calculated configurations; it should be noted that the “coherent” configurations require proportionally larger cores, as described in the text

> **The penalty for coherent windings is that placing all the turns on a single layer requires proportionally “longer” core to fit all the turns of both primary and secondary coils within just one layer**

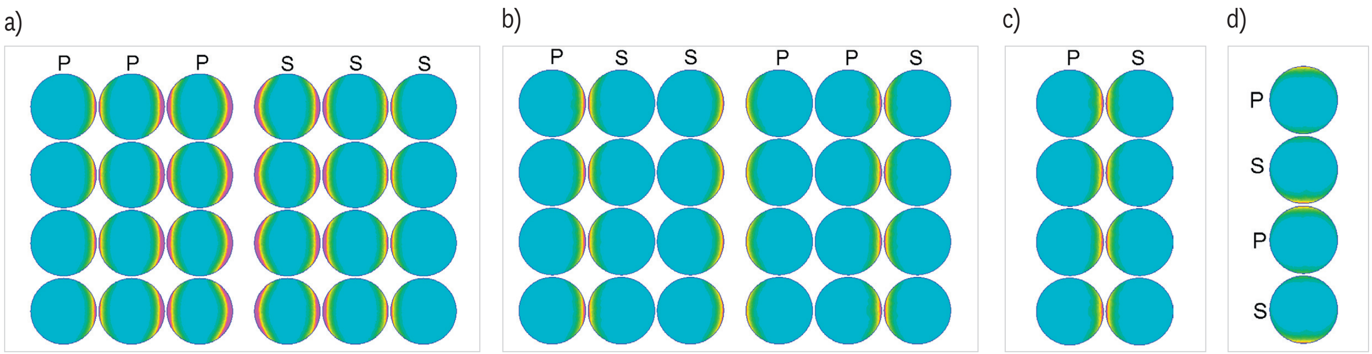


Figure 16. Eddy currents due to proximity loss for 1.32 mm windings at 1 MHz: a) non-interleaved; b) interleaved 1-2; c) single-layer primary and secondary; and d) interleaved on a single layer (coherent); (only a small part of the whole winding is shown for better clarity)

> **A thicker wire can be used even at 1 MHz, so that there is no need to strive for skin-depth-thin wires**

practice with the 1.32 mm, as explained in the next section.

The “coherent” curves were not calculated for even thinner wires, because it is very computationally expensive to represent every single wire. However, it can already be seen from Fig. 15 that a thicker wire can be used even at 1 MHz, so that there is no need to strive for skin-depth-thin wires.

The comparison of eddy currents is shown in Fig. 16. The per-wire current is the same for each configuration, but the lowest surface currents are generated for the configuration in Fig. 16d.

The single-layer interleaving allows a further decrease of the apparent number of layers. For instance, the 1-2 interleaving produces an equivalent of one layer. But the single-layer interleaving for the same wire diameter reduces this to 0.5 layer.

The situation changes if a thinner wire is used, because it is more difficult to produce the 1-2 interleaving for many layers of windings. But it is not as difficult to make “the same lay, the same pitch” coherent winding because this can be achieved even with the help of a bifilar wire.

The proximity effect is produced by the elevated level of magnetic field between the wires, which also penetrates the volume of the wires. But for thinner wires the main current in the wires has lower amplitude, as it must be scaled proportionally for maintaining the allowable current density. Therefore, purely from the viewpoint of the intensity of magnetic field, the structure behaves as if there were even fewer layers. For instance, let us assume that the configuration from Fig. 16d is equivalent to 0.5 layer. Then changing over to a wire which is three times thinner makes the magnetic field three times smaller between the wires. Thus, the resulting structure becomes equivalent to 0.5/3 = 0.167 layer. Further decrease of wire thickness by three times will drive this value even lower, to 0.056 layer. As seen from the Dowell’s curves in Fig. 4, such low number of effective layers would indeed make the proximity effect negligibly small, even for very large Q values (i.e. thick wires). This explains why even the 1.32 mm wire could be used at 1 MHz, as shown in Fig. 15 by the curve “wire 1.32 mm (0.42 mm), coherent”, although the wire diameter is significantly greater than the skin depth at such frequency (as shown Fig. 14).

5. Long core configurations

Let us stress here that as far as proximity loss is concerned the 1.32 mm wire is similar to the 1.32 mm tape (Fig. 6a, b). It would be sufficient to have the core only three times “longer” to achieve the much improved winding of Fig. 13a. This is impractical for an EE core, and it would disproportionately increase the core volume. But the same effect can be accomplished in a different way.

It can be observed from Fig. 7 that the outer limbs are not used by the windings. Their length is therefore “wasted” from this viewpoint. If the core was made as a “frame” core, like UU or UI configuration, then practically all its length could be used for housing the winding. A natural progression would be to use a toroidal core, or better still a torus, which would allow the best possible use of the winding length as well as reducing the wire length at the same time. Such toroidal cores are already widely used in practice, and are readily available as off-the-shelf components.

For the ETD49 core the useful winding length is 32.7 mm, but the outer core dimensions are 49 x 49 mm. So in order to produce 3 x 32.7 mm = 98.1 mm winding length a suitable torus would have to have inner diameter of 31.2 mm and outer diameter 64.6 mm, which is still smaller than the diagonal dimension of the ETD49 core (69.3 mm), as shown in Fig. 17.

The volume of such torus core would only be 32 % larger than ETD49. However, due to the larger core volume such transformer would also have a reduced thermal resistance [20], even more so since by definition of a coherent winding there would be only a single layer of wires. Therefore, the overall losses would be comparable – without the need to resort to costly very-thin-strand Litz wire. In order to avoid proximity effect for three layers the Q factor would have to be around 0.25, so the strand diameter for 1 MHz would have to be 0.016 mm. Such thin wires are prone to mechanical damage and difficult to use in practice.

There are other structures which can be used for the purpose of making “long”

> **Coherent windings require longer cores, making EE cores impractical, but UU or UI configuration could be used**

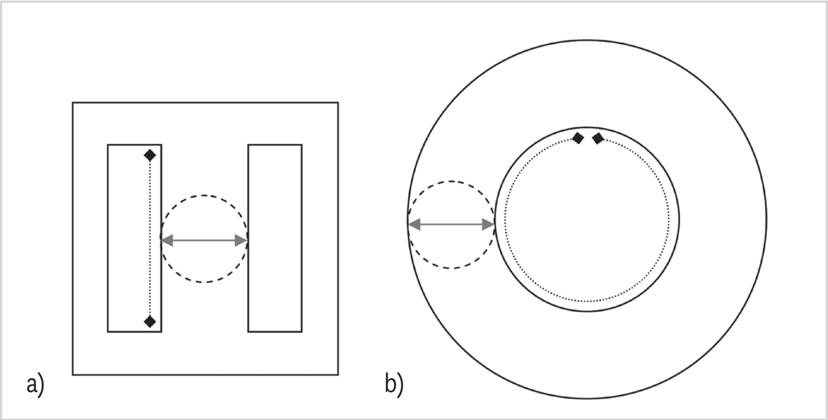


Figure 17. Comparison of ETD49 (a) and a corresponding torus with three times larger winding length (b)

cores, as proposed by Newton Ball [18]. Some examples are shown in Fig. 18. They are easily constructible from parts of torus and round rods. The multiple sub-parts lend themselves well to distribution of air gap, which is another important component generating additional copper losses through the flux fringing effect [11].

For instance, the winding for the curve "wire 1.32 mm (0.42 mm), coherent" in Fig. 15 would require nine times the length of the corresponding EE core. But the copper loss can be kept to a very small value even at 1 MHz for a very thick wire. Such a "long" core could be built as that shown in Fig. 18b. On the other hand, if the small footprint was critical then this could be achieved with a more "vertical" configuration, as in Fig. 18c. It should be noted though that construction of complete transformers based on such "long" cores would have to be verified in order to quantify the core loss, cooling conditions, required footprint and volume, manufacturability, etc.

The validity of the "coherent" method was verified experimentally on prototypes and indeed, the wire significantly thicker than the skin depth could be safely used at very high frequencies, without the penalty of the proximity effect. Fuller experimental study is being carried out and the results will be shown in the next paper.

There is one final improvement which can result in further reduction of the proximity losses. Namely, the windings would have to be made so that they are coaxial. For instance, the primary wire would be a tube in which the secondary wire is placed. Such configuration would, by definition, be coherent (the same lay, the same pitch, no wire crossings) and would make perfect equalisation of magnetic field everywhere around each primary-secondary pair.

Last but not least, this method lends itself well to application of insulation between the wires. But with the coherent technique the wires can be solid and thickness of insulation is not a critical parameter because the core length can be adjusted, for example by means of configurations shown in Fig. 18.

However, even with the ideal configuration the skin effect appears to be always present and must be taken into account. Nonetheless, if the proximity effect is not present or reduced to very small values then the skin effect can be compensated by using thicker conductors.

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> **Other structures can be used for the purpose of making "long" cores, and they can easily be constructed from parts of torus and round rods**

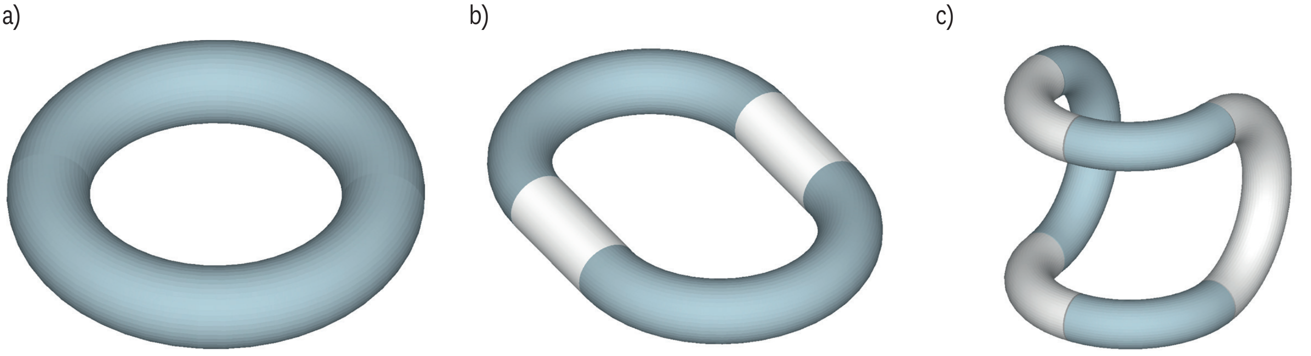

Figure 18. Examples of structures based on the torus approach: a) torus made from four quarters; b) oval core made from some torus halves and straight rods; c) 3D structure constructed from eight quarter-torus parts (allowing smaller footprint)

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Author

Stan Zurek completed a PhD in electrical engineering in 2005 and continued research in magnetic materials at Wolfson Centre for Magnetics, Cardiff University, UK. He joined Megger in 2008 and is Manager of Magnetic Development. He is the author and co-author of over 65 scientific publications related to magnetics and magnetic materials. Dr. Stan Zurek is a Senior Member of IEEE Magnetics Society.