

Winding loss (copper loss) in FEMM

Stan Zurek, 2022-01-07

Introduction

Finite Elements Method Magnetics (FEMM) is a software package [1] capable of performing 2D electromagnetic simulations (as well as electrostatic, heat transfer and current flow). The software is available under a Aladdin Free Public License, permitting free use, within the limitations of the license.

In FEMM, electromagnetic simulations can be run as magnetostatic or dynamic. **Magnetostatic** simulations are excited by DC currents. They can handle non-linearity of magnetic materials in a more direct way, by using a look-up table of the B-H curve of a given material.

Dynamic simulations (also referred to as “time harmonics” [1]) can be excited with AC currents (all at the same frequency for multiple coils). The solutions are linearised locally and certain simplifications are introduced in order to be able to solve a non-linear magnetic problem. This can lead to seemingly non-physical values of flux density (especially when operating near saturation), because the solution is provided for the fundamental harmonic [1].

In FEMM, a winding can be defined in two main ways: as a set of **explicit wires** (each turn is drawn in the geometry), or as a **bulk winding** with specified number of turns and wire diameter. A problem which often arises especially in the dynamic simulations is the interpretation of the power loss dissipated in the two types of windings. This article aims at clarifying some of the approaches, and the way the various values should be interpreted.

Explicit turns

With the explicit approach, each turn is represented as a separate wire (Fig. 1, green). Each turn is assigned the same current defined as “series”, and each turn has the number of turns set to “1” (or “-1” accordingly, for the other side of the winding). The material for each turn has to be specified as “solid conductor” (e.g. solid copper, see also Fig. 2) rather than some predefined wire such as 12 AWG. (Parallel currents are also possible, but they will not be discussed here, because the meaning of losses is similar.)

The main advantage of the explicitly modelled wires is that this can be used to visualise current distribution in each wire, which is important for example if the structure has excessive proximity loss [2] and needs to be optimised through modelling.

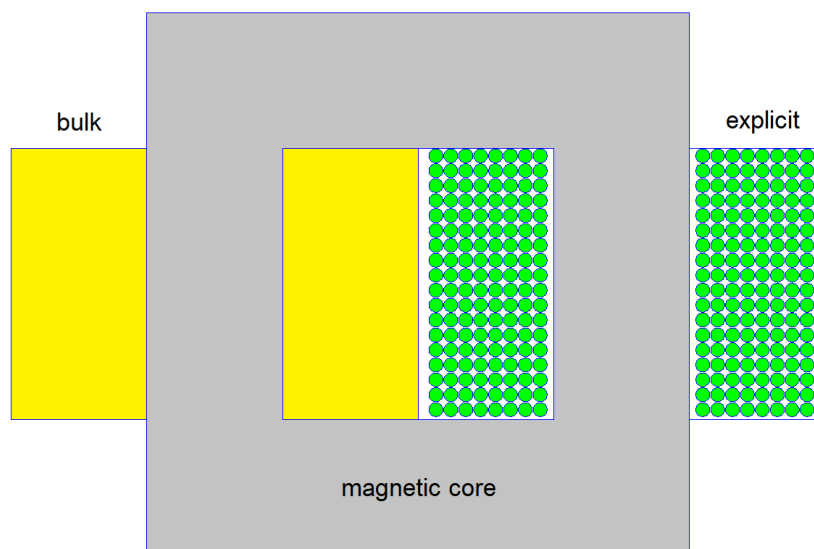


Fig. 1. Example of explicit and bulk windings as modelled in FEMM

The main drawback is that during drawing of the 180° arcs for the wires, the value of 1° step is suggested as default. This generates increased density of mesh around the arcs with so many nodes (Fig. 2) that the problem might become prohibitively too big to be held in the computer memory (FEMM will fail to mesh the problem). The simple solution is to increase the step of the arc to the maximum value of 10° which still preserves the shape of the circle, yet it significantly reduces the number of mesh nodes (Fig. 2). With the explicit round wires (with 10° arc steps) this model had 41k mesh nodes. (With the default 1° arc steps the mesh would have 732k nodes.) Further improvement can be achieved by lowering the value of “Min. Angle” in Problem Definition settings, from the default 30°, to some lower value.

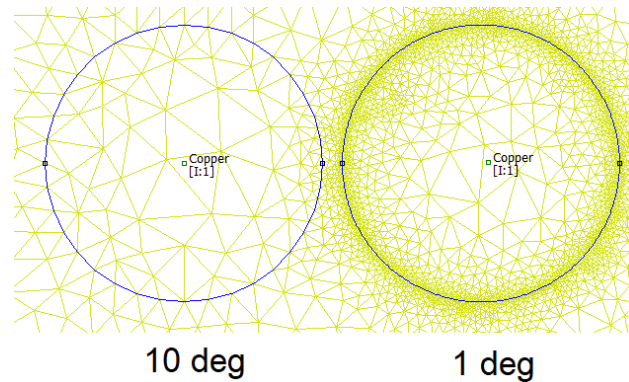
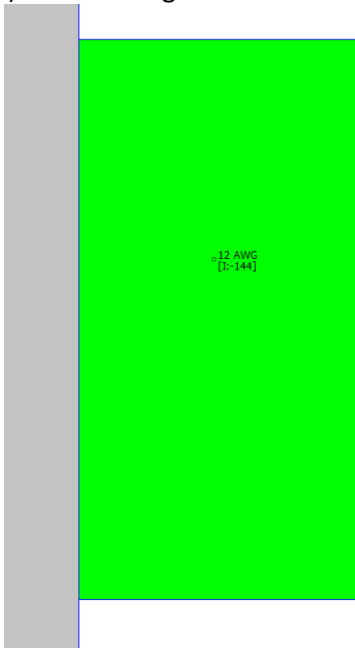


Fig. 2. Effect of “Max. segment, Degrees” setting for arcs on local density of mesh

Bulk winding

In the bulk winding, a large area (not necessarily rectangular) can be defined as the winding. Then just one “wire material” is assigned to such bulk area, e.g. wire “12 AWG” predefined in FEMM as “magnet wire” [3], with appropriate current source and number of turns representative for the winding.

a) bulk winding set to wire “12 AWG”



b) “Magnet wire” defined in FEMM

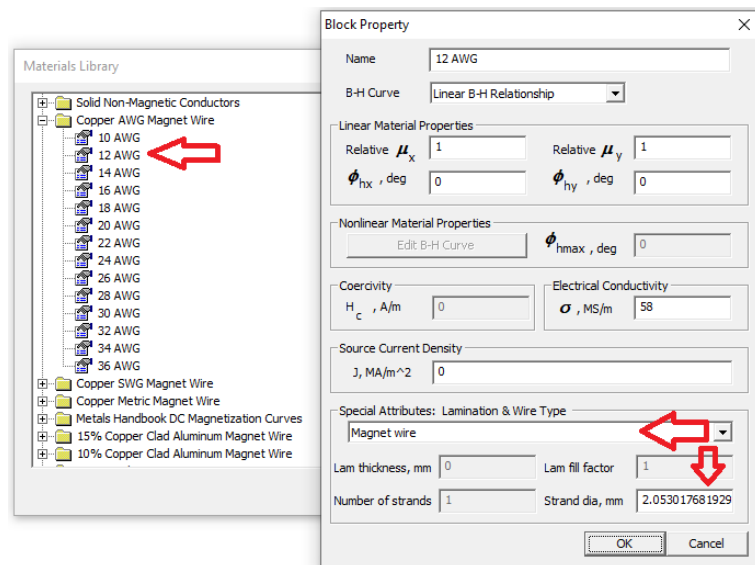


Fig. 3. Bulk winding as a single block, set to wire “12 AWG”, with current I, assigned to -144 turns

Dynamic simulation with an explicit winding

A simulation was set up with one active winding (driven with current). The geometry was based on 20 mm steps (including the depth), as shown in Fig. 4. The explicit winding was modelled with a round wire with diameter 2.053 mm (12 AWG). There were 8 layers of 18 turns = 144 turns in total, each with current of 1 A driven at 1000 Hz. The core was set to be linear (no saturation) with a permeability fixed to 1000, and conductivity of 0.001 MS/m (so some resistive losses will be present in the core, but no hysteresis).

The “secondary coil” was set up as passive, a solid resistive metal, conductivity 0.1 MS/m. There was no current assigned (no turns), because free conductors supposed to be shorted at infinity [1]. This configuration works effectively as a current transformer with a single shorted turn, with very small flux density in the core, less than 0.02 T.

However, the plot of current density in the windings is quite interesting (Fig. 4). In the round wires, the current density varies significantly (an order of magnitude between the highest and lowest) due to proximity effect [2]. In the “solid metal” the current is much more uniform, because it was set to much lower conductivity than copper, so the skin depth was much greater and could penetrate through the whole thickness of the block.

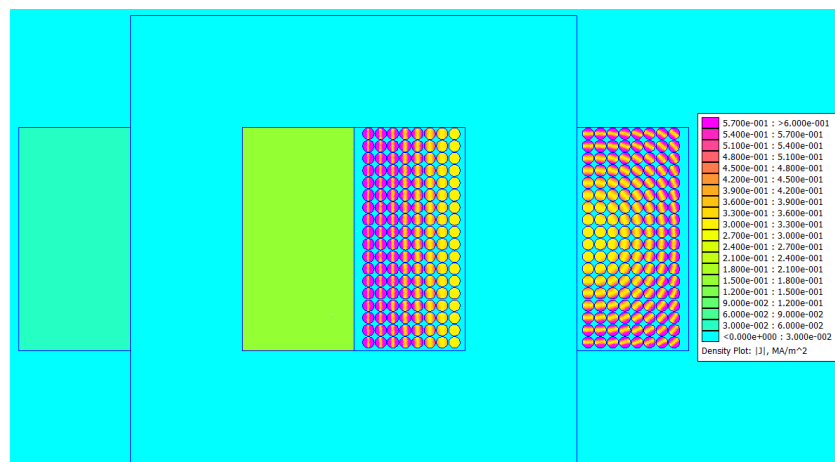
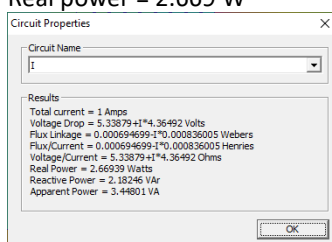


Fig. 4. Current density in the explicit model of wires (on the right), and with a shorted “secondary coil” modelled as a block of solid metal (on the left)

Various calculations of power and losses are performed in FEMM. The first is the one given in “Circuit Properties” (the “coil” icon in the post-processor). In this case, the Real Power for the explicit coil (energised) is returned as 2.669 W. However, as it is clear from the values in Fig. 5, this value comprised the actual losses dissipated in the active winding with current I, as well as the total loss dissipated in the “secondary coil”, because primary 0.0430 W + secondary 2.589 W + core 0.0371 = total 2.669 W \approx 2.669 of the Real Power as supplied by the current source.

Interestingly, the value of loss for the “Hysteresis, laminated eddy or proximity effect” integral comes as zero in all cases, even though the active winding certainly exhibits some significant proximity loss. It is because this loss mechanism (the type of integral) is reserved for calculations of proximity loss in the bulk winding, as shown in the next section.

Real power = 2.669 W



Integral (select all round wires, on both sides):

Resistive loss = 0.0430 W

Total loss = 0.0430 W

Hysteresis, laminated eddy or proximity effect = -3.0e-021 W

Integral over solid metal “secondary coil”:

Resistive loss = 2.589 W

Total loss = 2.589 W

Hysteresis, laminated eddy or proximity effect = 1.6e-020 W

Integral over magnetic core:

Resistive loss = 0.0371 W

Total loss = 0.0371 W

Hysteresis, laminated eddy or proximity effect = 4.4e-020 W

Fig. 5. Circuit properties, loss in explicit winding, loss in the passive “secondary coil”, and in the core

If the same geometry is simulated at a **quasi-static frequency of 0.001 Hz** (negligible eddy currents induced in the magnetic core or in the secondary winding) then the Real Power in Circuit Properties is 0.0151 W, which is the same as dissipated in the primary active winding (also 0.0151 W). The losses in the core and in the secondary passive are both at the level of $1e-10$ W.

It should be noted that the loss for the primary winding at quasi-static frequency is significantly lower (0.0151 W) than under high frequency (0.0430 W). The difference by a factor of x2.85 is caused by the proximity effect.

The correctness of proximity loss calculated in FEMM for explicitly modelled wires was verified experimentally elsewhere [4].

Bulk winding

If the active winding is defined as bulk (Fig. 6a) then this simplifies the creation of geometry. Also, the mesh size reduces considerably, to only 9k nodes, without any additional optimisation tricks.

As shown in Fig. 3, the bulk winding is defined as a single block, with wire “12 AWG” assigned to it (same diameter of 2.053 mm as for the explicit model), with a series current $I = 1$ A, assigned to 144 (and -144) turns.

The magnetic flux density B distribution is indistinguishable in both cases (Fig. 7). In the bulk winding, the plotted current density distribution is **uniform** (Fig. 6b), even though there should be a significant proximity effect, as already modelled in the explicit approach (Fig. 4).

This is the reason for the “Resistive loss” integral to return a much lower value of loss (Fig. 8) – because the “resistive loss” calculation takes into account directly the uniform current distributed over the whole bulk of the coil (scaled to the area of wire diameter and turns). The proximity loss is *not* accounted here so the value is lower, however, the proximity loss is added with an additional loss mechanism calculation in FEMM as can be concluded from Fig. 8 (see also [5]). Quoting FEMM manual:

For AC problems, the fill factor is taken into account, and AC proximity and skin effect losses are taken into account via effective complex permeability and conductivity that are automatically computed for the wound region.

Therefore the **total loss** in the winding correctly represents the total loss that should occur if the winding was made out of individual wires. A comparison is provided in Fig. 9.

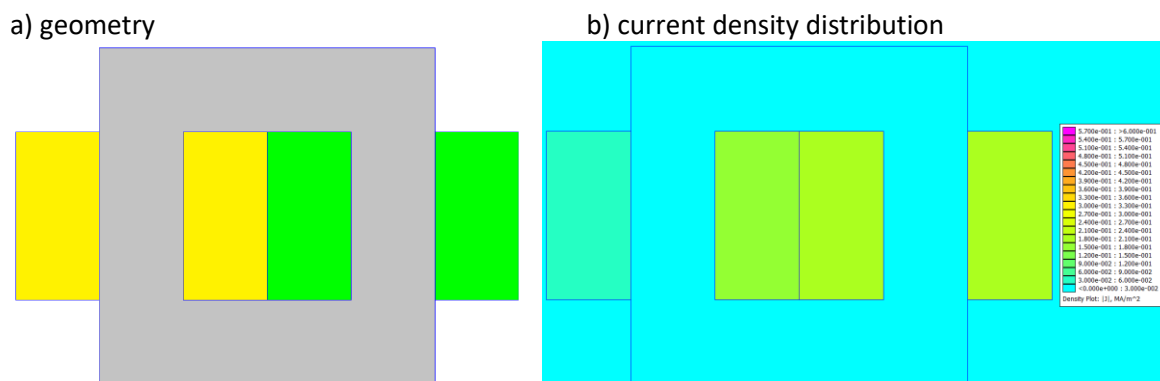


Fig. 6. Simulation with bulk windings

a) explicit wires

b) bulk winding

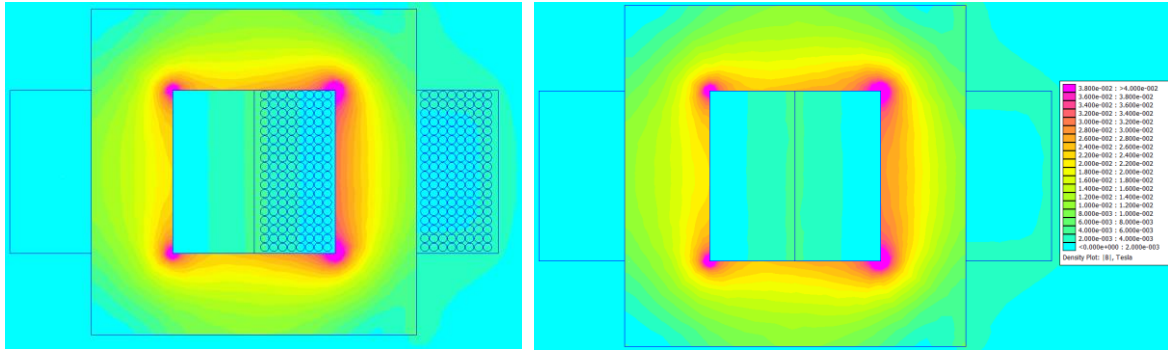


Fig. 7. Comparison of flux density distribution for both models

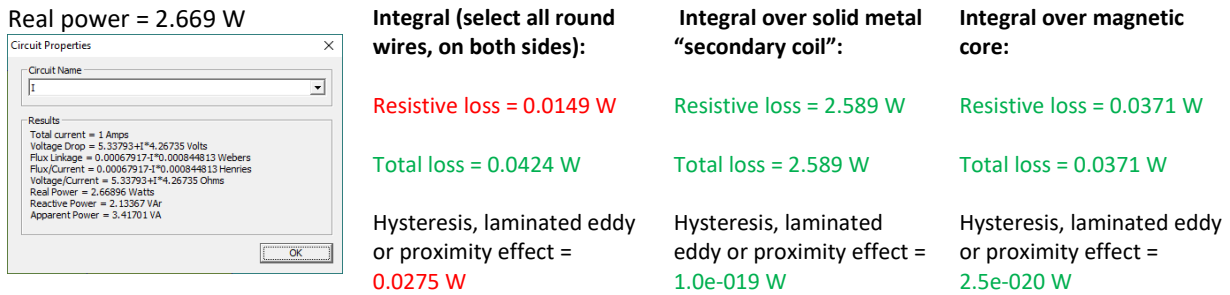


Fig. 8. Circuit properties, loss in explicit winding, loss in the passive "secondary coil", and in the core

The small difference of total losses in the primary winding in Fig. 9 could be caused by the differences in mesh between the two models, but this is beyond the scope of this paper.

Value	Explicit wires	Bulk winding	Difference
Circuit Properties, Real power	2.66939 W	2.66896 W	< 0.1 %
Total loss in active primary winding	0.0430	0.0424	1.4 %
Total loss in passive secondary coil	2.589	2.589	< 0.1 %
Total loss in the magnetic core	0.0371	0.0371	< 0.1 %
Sum (primary + secondary + core)	2.6691	2.6685	< 0.1 %

Fig. 9. Comparison of values for explicit and bulk winding

Effective cross-sectional are of a bulk winding

It should be noted that FEMM does not check if a given bulk winding will or will not fit into the provided space, and it is the responsibility of the user to ensure suitable space for the number of turns of the specified diameter.

By running the model from Fig. 6 at quasi-static frequency of 0.001 Hz only the DC loss should be present in the winding – and the outcome is as shown in Fig. 10. The Real Power value is calculated as 0.0150 W, compared to the 0.0151 W for the explicit winding, so the agreement is very good.

This indicates that it is the actual cross-sectional area of the modelled wires (in this case 144 wires of 12 AWG or 2.053 mm wire, calculated by FEMM as 948.5 mm² for both sides) that is used for resistive (and proximity) losses, and not the whole area of the block of the bulk winding (1600 mm²). Otherwise, a ratio of x1.7 of the two areas would produce almost 3-fold difference in losses between the two cases.

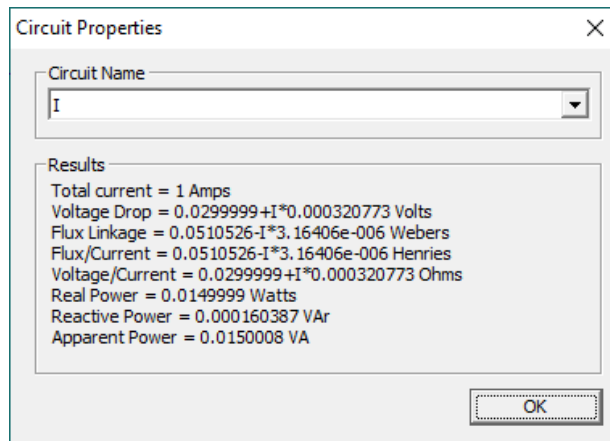


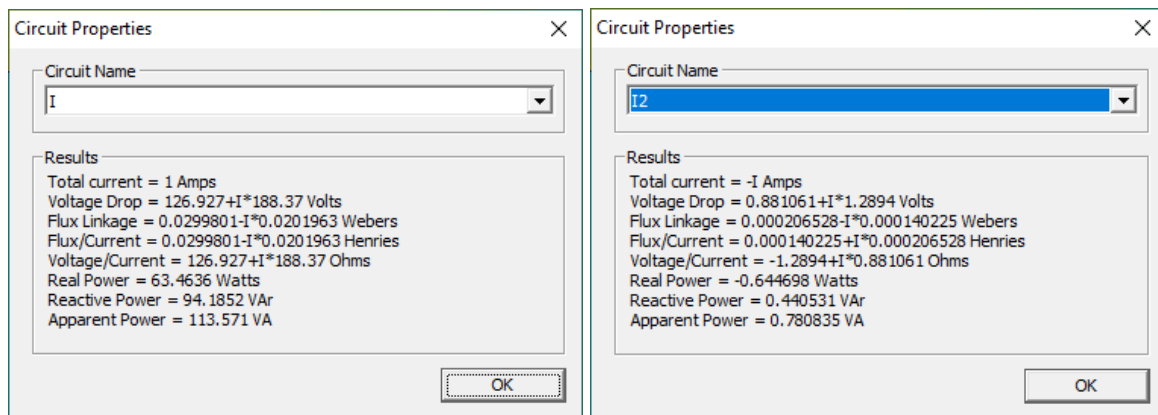
Fig. 10. Results for bulk winding at 0.001 Hz

Negative loss in circuit properties

For completeness, let us also consider what will happen if there are two energised windings, so that the power can be exchanged between them.

The bulk geometry from Fig. 6 was used, but the passive coil was set to have a current 90° out of phase (-1*I), into a single turn. Because the flux was no longer suppressed in the core, the flux density increased to large values, and the power loss associated with it, due to conductivity of the core.

In this case, the Circuit Properties for the secondary current I2 show *negative* Real Power, because the primary winding can overpower it, and thus deliver energy into it. However, summing all the losses shows that the values add up correctly, because: *primary loss + secondary loss + core loss* = 62.81883 W, which is the same as: *primary source + secondary source* = 62.818902 W, with the values agreeing pretty much to 5 significant digits.



Primary Real Power = 63.4636 W
Secondary Real Power = -0.644698 W
Primary winding Total loss = 0.0280 W
Secondary winding Total loss = 0.00413 W
Magnetic core Total loss = 62.7867 W

Fig. 11. Circuit properties for two active coils

Zero current condition

A current in a given winding can be forced to be zero (0 A). This will only force the total current through such winding as zero, and will therefore ensure that no energy is delivered in or out from the current source.

In such simulation (Fig. 12) the total current (i.e. the total sum of vectors representing current density) is indeed forced to be zero over a given area of a conductor. However, eddy currents are still allowed to be induced in the conductor, and their distribution will be driven by the distribution of leakage inductance, as can be seen from the shape of the flux lines penetrating the left coil in Fig. 12.

Therefore, resistive power loss will be still dissipated in such winding, even though the energy delivered to the winding through its terminals is zero. For the model in Fig. 12, the calculated power values are shown in Fig. 13. Note that 0.00389 Watts is comparable to the loss in the same winding when it was just passive (no current assigned to it at all), which was 0.00413 W (Fig. 11). So in this case this eddy current loss is certainly not negligible.

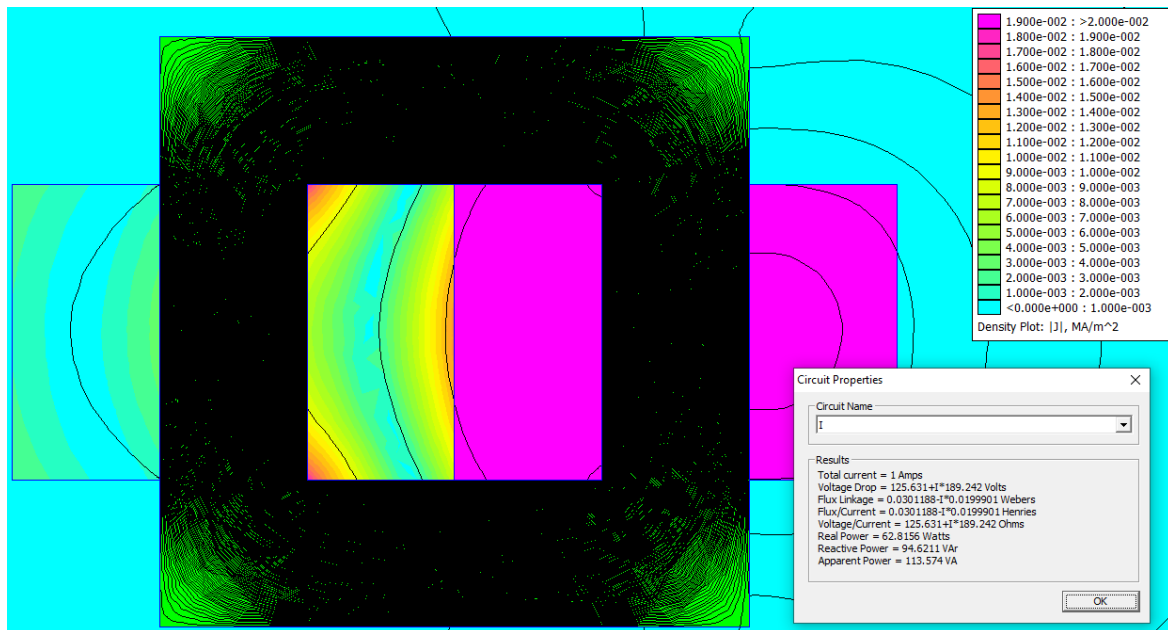
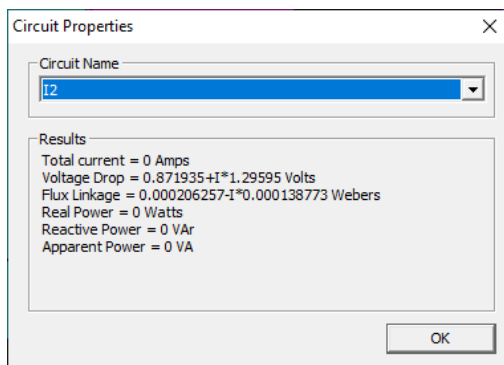


Fig. 12. The bulk winding on the left is set to have zero current



Integral: Total loss 0.00389 W

Fig. 13. Real Power delivered to the winding with I2 = 0 A current, and resistive loss due to eddy currents

Conclusions

- FEMM correctly models power losses in windings due to resistive, eddy currents and proximity effects [4].
- The windings can be represented as explicit wires, through the “brute force” approach. This allows investigating actual current density distribution in each wire. The modelled wires must be defined each as “solid conductor” rather than a “wire” as pre-defined in FEMM (e.g. “12 AWG”).

- The “explicit wire” can represent any shape of wire (e.g. rectangular).
- The windings can be also represented as bulk windings made from round wires with assigned number of turns. Bulk windings correctly represent all the loss for round wires. The values are equivalent to explicitly modelled round wires.
- FEMM does not check if the wires fit into the space provide by the bulk winding.
- Non-round wires cannot be represented in the bulk approach.
- Circuit Properties return a value of total energy delivered into (positive), or out of (negative) electrical terminals of each current source. Sum of Real Power values for the current sources is equal to all the losses dissipated in the circuit (in the windings, resistive, eddy currents, proximity, magnetic core loss).
- In the bulk winding the area of copper is correctly taken into account.
- Forced zero current does not stop power loss in the winding due to eddy currents.
- Negative “Real Power” of a current source means that energy is delivered to it from another winding.

References

- [1] D. C. Meeker, Finite Element Method Magnetics, Version 4.2, <http://www.femm.info>, accessed 2022-01-07
- [2] S. Zurek, Proximity effect, Encyclopedia Magnetica, https://E-Magnetica.pl/proximity_effect, accessed 2022-01-07
- [3] S. Zurek, Enamelled wire, Encyclopedia Magnetica, https://E-Magnetica.pl/enamelled_wire
- [4] S. Zurek, FEM modelling and experimental validation of proximity loss, Transformers Magazine, Vol. 4 (1), 2017, pp. 102-108, www.transformers-magazine.com/component/k2/3897-fem-modelling-and-experimental-validation-of-proximity-loss.html, accessed 2022-01-07
- [5] D.C. Meeker, "An improved continuum skin and proximity effect model for hexagonally packed wires," Journal of Computational and Applied Mathematics, 236(18):4635-4644, Dec. 2012. <http://dx.doi.org/10.1016/j.cam.2012.04.009>