Electromagnetic Analysis and Comparison of Conventional-Wound Cores and Octagonal-Wound Cores of Distribution Transformers

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Abstract. This paper presents comparative results of an electromagnetic study performed in two different wound core transformer configurations in order to know the best configuration that reduce excitation current and core losses. The results show that octagonal wound-core (OWC) reduces the excitation current and eddy-current losses with respect conventional-wound core (CWC). The results were obtained applying 2D and 3D FEM simulations, taking into account the non-linear properties of the core. In the last part of this paper, several grades of grain oriented electrical steels and the combination of them are analyzed to find the best mixing percentage to reduce eddy-current losses and excitation current.

Introduction

Conventional Wound Core (CWC) emerged with the necessity of reducing the size and weight in the distribution transformer, which leads to cost minimization. Other important advantages of wound core are [1], [2]:

a.   Improved distribution of the magnetic flux density than in the stacked core, since the rolling direction is not cut with air gaps in the corners. Wound cores are made of continuous strips so the complete path of the rolling direction is usable and the magnetic flux saturation is reduced.

b.   Because of the uniformity of the magnetic flux density along the lamination and the minimization of weight, the eddy current losses and excitation current are also reduced.

c.   Improved performance and increased efficiency, so they are a piece important in the electronic industry.

d.   A manufacturer who builds large quantities of identical designs will benefit from the automated processing of wound cores.

The manufacturing of the CWC consists of wounding the laminations in one circular mandrel, during this process the laminations are cut and the air gaps are formed (see Fig.1) This process and the formation of the core window damage the characteristics of the cores and their properties are restored through of an annealing process at a temperature between 780-820°C inside of an environment that protects the material (nitrogen mixed with nitrogen); the most interested readers can consult [3] for more details about annealing process. While the OWC is processed as follows: Each lamination is cut according to the required length and then every lamination is bent at each of

the four corners. The worker arranges the laminations, the most internal laminations first and the most external laminations at the end. There are some companies that anneal the OWC, but there are other companies that do not anneal depending on the level of transformer losses.

Now the OWC emerged from CWC with the purpose of reducing even more the size and the weight, preserving all the advantages of the CWC, additionally a reduction of the excitation current and the eddy losses is observed.

Fig. 2 shows the annealing process of CWC in a bach-type furnace. Batch-type furnaces have advantages where volume of electrical steel is small, production is intermittent or the sizes of the cores vary considerably.

The geometry and design parameters of CWC are shown in Fig.3a; where the window height is h, window width is w, lamination width is p, core width is q, overlap length is s, air gap length is g, lamination thickness is d, and interlamination space is u; in appendix A are the values of these parameters (Table 1). The design parameters of OWC are shown in Fig.3b; where the exterior frame height is h_2, interior frame height is h_1, exterior frame width is w_2, interior frame width is w_1, exterior corner length is hw_2, interior corner length is hw_1, core width is q_1, lamination width is p.

Fig.1. Manufacturing of CWC on circular mandrel.
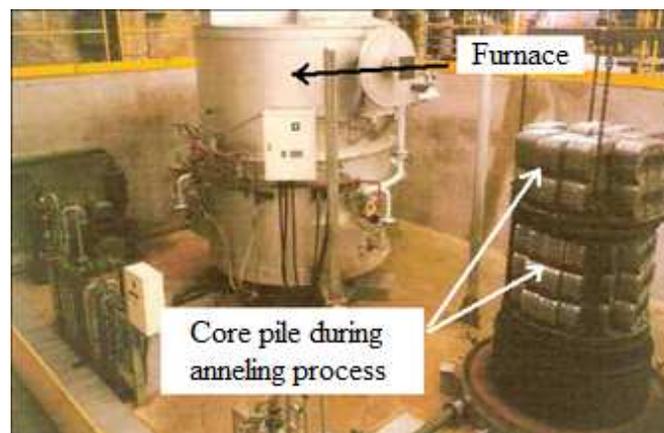
Fig.2.Annealing process in a batch-type furnace of CWC.

In the joint zone are the parameters such as: overlap length s, air gap length g, lamination thickness d, and interlamination space u; see Appendix A. The equations employed to determinate the core weight and the average core lengths are on Appendix B. Some equations used to design the core are on Appendix C. The cores that combine two degrees of laminations are manufactured using the process OWC. The process CWC is costlier and complicated to combine two degrees of

laminations. This paper validates the OWC by performing a rigorous electromagnetic comparison between OWC and CWC, launching with details the magnetic flux distribution, excitation current and eddy current losses. The numerical results were obtained from two-dimensional (2D) and three-dimensional (3D) FEM simulations taking into account the saturation and the anisotropy of the core.

Electromagnetic Analysis and Simulations

An electromagnetic analysis with FEM simulation was realized with the goal to determinate the magnetic flux distribution and compute eddy current losses in CWC and OWC. The studies were made using 2D and 3D simulations, taking into account the saturation and anisotropy, and several grade of grain oriented silicon steel M4 (0.28mm), M5 (0.3mm), M6 (0.35mm) and a super oriented grain electrical steel M5H2 (0.30mm). Fig. 4 shows the B-H curves for the different grades of grain oriented electrical steel employed. .

The magnetic flux density distribution and eddy current losses was determined by the solution of the vector potential formulation **A** in the frequency domain [4]:

$$\left(j\omega\sigma - \omega^2\varepsilon \right)\mathbf{A} + \nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A} \right) = 0 \tag{1}$$

where ε represents the permittivity, μ a tensor of the permeability of the different grain oriented silicon steel quality used and σ is its conductivity. An important parameter in eddy current calculation is the skin depth δ.

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \tag{2}$$

(a)

(b)
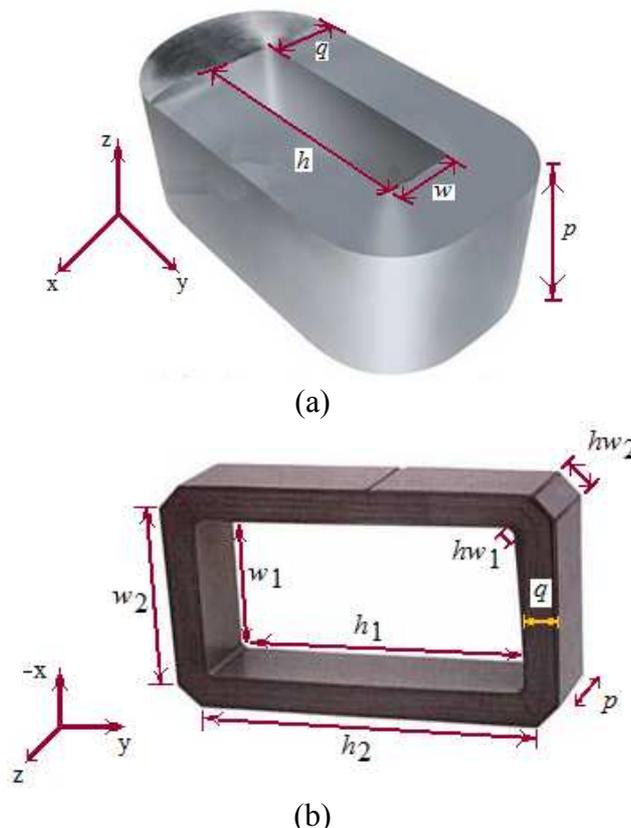
Fig.3.a) Conventional wound core (CWC) geometry with its design parameter. b) Octagonal wound core (OWC).
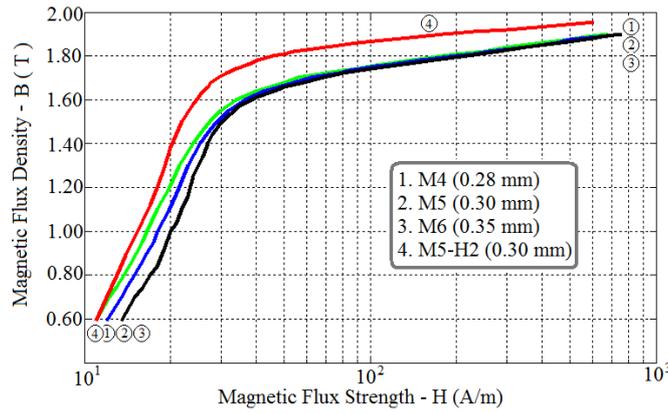
Fig.4. B-H curve for the different grades of grain oriented steels.

The distribution of the dissipated power, can be calculated from [5]:

$$P = \frac{1}{2}\mathrm{Re}\left[\sum_{i=1}^{n}\left(\rho_i Je_i^* \cdot Je_i\right)V_i\right] \tag{3}$$

where n represents the number of elements, ρ_i is a diagonal tensor of resistivity of the grain oriented silicon steel, Je_i is the eddy current density vector of the element i, and V_i is the volume element. The eddy current density is given by:

$$Je_i = -j\sigma\omega\mathbf{A}_i = -\sigma\frac{1}{n}\sum_{i=n}^{n}\mathbf{N}_A^T\mathbf{A}_i \tag{4}$$

where $\mathbf{N_A}$ represent the element shape functions for the vector potential $\mathbf{A}$.

A commercial finite-element software was used to perform the simulations shown in this paper. It is also important to mention that for the mesh volume we used the technique by extruding the meshed area and special care is taken in the laminations element size to be fine so as to capture the skin depth and obtain accurate calculation of the losses and excitation current.

Results and Discussion

Distribution of the magnetic flux density. The magnetic flux density B, in a CWC is shown in Fig. 5. For this simulation we used grain oriented silicon steel M5 (0.3mm). The excitation current was fixed to get an uniform B=1.70T in the core cross section. Fig. 5a shows that the magnetic flux density is smallest and useless on the corners of the CWC, from here emerged the designer's idea to trim the wound core and become it in a octagonal core. Fig.5b shows the magnetic flux lines distribution around the CWC and Fig. 5c illustrate the magnetic flux distribution in its joint zone, where it can be evident the magnetic flux distortion. This magnetic flux distribution on a CWC was compared with the results obtained from OWC, using the same steel grade material M5, and the same excitation current. Fig. 6a shows the magnetic flux density in an OWC. It is evident that magnetic flux density increases with respect to the CWC values. The same excitation current produces a B=1.710 T in the OWC, and B=1.705 T in CWC. This means that an octagonal core is able to produce greater magnetic flux density than the wound core using the same excitation current. Therefore is possible to get a reduction in the excitation current to obtain the same magnetic flux density. This reduction in the excitation current is due to the core length in an OWC is smallest than CWC and this produces the reluctance reduction of the core. An inconvenience in the OWC with respect to the CWC can be evident with these results; there is a bigger zone in the octagonal cores in the interior frame corner where the magnetic flux density raises saturation values in this example B=1.908T;

With goal of testing that magnetic flux follow the rolling direction and obtain a better calculation in eddy current losses both model cores were laminated also we took into account all the design parameter. The permeability in the rolling direction varies in accordance with the saturation curve and the perpendicular permeability to the rolling direction was given according with the manufacturer specifications [7]. In Fig.5c and Fig. 6c it can be observed that no exist a significant difference between the magnetic flux in the joint zone of both core configurations. We compared also the magnetic flux density along the lamination, for this we made a path along the lamination in the middle of a one random lamination. We denoted the rolling direction change by the numbers clearly specific in Fig.5b and Fig.6b.

The peak values of the magnetic flux density components in each lamination were calculated and compared for both core configurations. These components values were taken out from one random lamination along its perimeter.

The characteristic and comparison of the values components are show in Fig.7. The rolling direction changes happened in the frame corners and they were indentified with the consecutive number 1 to 4. Fig. 7a shown B_x and B_y components for both configurations, it can be observed that they have only a small difference on magnitude and in the octagonal core the magnetic flux density present a square shape, due to its geometry itself. The B_z was determinate, and we found that its magnitude was negligible in comparison with Bx and By components, this is logical due to this B_z component is perpendicular to the rolling direction.

The magnetic flux density norm of the three components was calculated and it is shown in Fig. 7b; it proves that the magnetic flux is uniform along the lamination except in its joint zone. There is magnetic flux drop in the cross sectional leg, this means that internal laminations have greater magnetic flux density values than external laminations. This reduction on the slope in both core configurations was analyzed and compared. For this we realized a cut in the opposite leg of the joint zone Fig.8a and realized integrations from the B values on the surface cut to obtain an average of the magnetic flux density on the leg. We excited the core until get a desire magnetic flux density, this case B=1.70 T in the cross sectional leg. Fig.8b, shows the slopes in both core using the same excitation current, and two different grades steel M5 (0.3mm) and M5-H2 (0.3mm) but this provides a super oriented electrical steel; it can be noticed that the magnetic flux density slope for octagonal core m_O is greater than wound core slope.
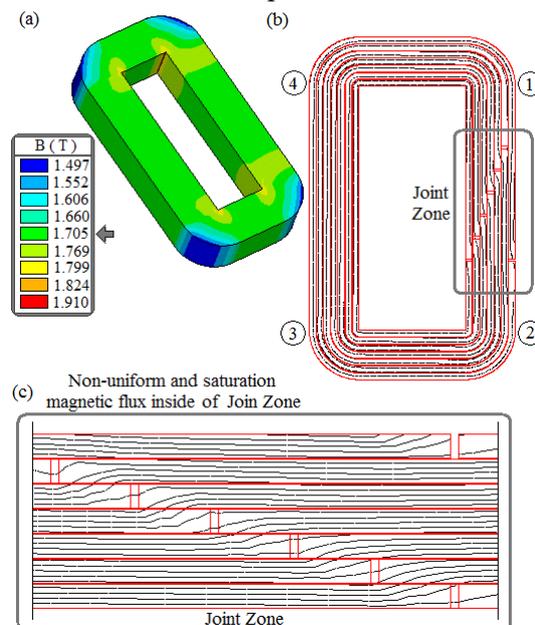
Fig. 5. a) Magnetic flux density distribution in a CWC, b) magnetic flux lines distribution around the CWC, c) magnetic flux distribution in the joint zone.
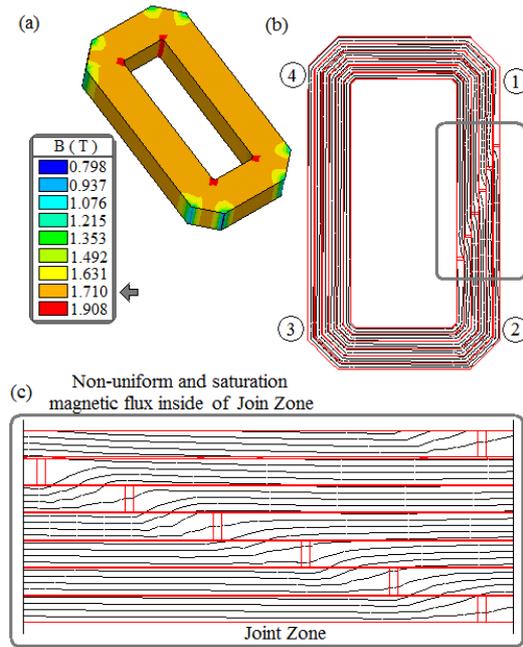
Fig.6. a) Magnetic flux density distribution in an OWC b) magnetic flux lines distribution in an OWC, c) magnetic flux distribution in the joint zone

This greater slope produce a reduction in the *B* values at the external laminations consequently a reduction eddy current losses. We simulated and compared the magnetic flux density distribution and the slopes in both cores for another grades of oriented electrical steel: M4 (0.28mm) and M6 (0.35mm).

Eddy current losses and excitation currents comparison in CWC and OWC. According to Fig.8b octagonal cores have a greater magnetic flux density slopes for the different grades and thicknesses of oriented electrical steel analyzed. Table 1 shows slopes values, eddy current losses and excitation currents in both core configurations. These values were obtained when the cross section in the leg has a magnetic flux density of 1.70T.

Table 1 also shows that the eddy current losses in octagonal cores were decreases until 17.68 % in an oriented silicon steel with smaller quality, this results show that even M6 has a smaller quality in the magnetic properties, using an OWC is possible to reduction the eddy current losses and the excitation currents. Using a material core with M5-H2 is possible to reduce the excitation current, it was about 12.0%

If besides the OWC uses a super grain oriented steel the eddy current losses is going to be reduced in about 25%. The M4 electrical steel also provides good results in eddy current losses decreases compare with the M5.

On the subject to excitation current the results show that OWC decreases this factor until 1.35 %. Use M6 instead of M5 increase the excitation current about 11%, this means that M6 has worse magnetic properties, on the other hand use M5-H2 for the core construction decrease the excitation current until 18% for CWC and almost 20% for OWC. With these results is evident that the manufacturing of OWC is favorable to reduce the current excitation and the eddy current losses.

Mixing the grade electrical steel in the cores. With the goal to reduce the excitation current and eddy current losses was applied the mixing of different grade laminations [6]. This simulation consisted to combine the high grain oriented electrical steels analyzed in this work, M4 an M5-H2 with the standard grain oriented M5. High grade steel was placed in the internal frame laminations where the magnetic flux density is greater, and the standard grade steel was placed in the external frame lamination. We applied a combination grade from 0% to 50 % of the total lamination in the core.
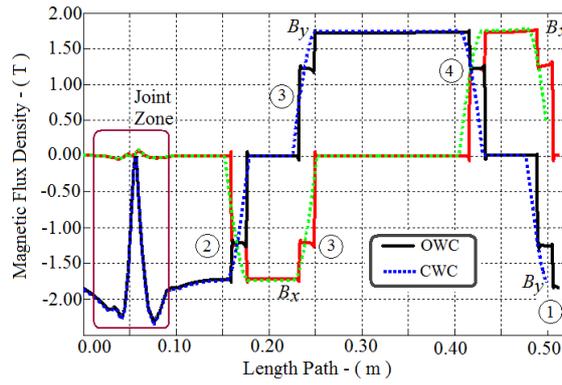
(b)
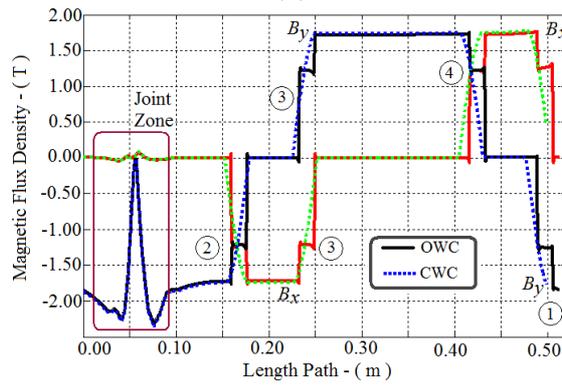
(c)

Fig.7. a) Magnetic flux density component B_x and B_y along the lamination, points 1 to 4 indicate change in the rolling direction. b) Magnetic flux density norm components along the lamination.
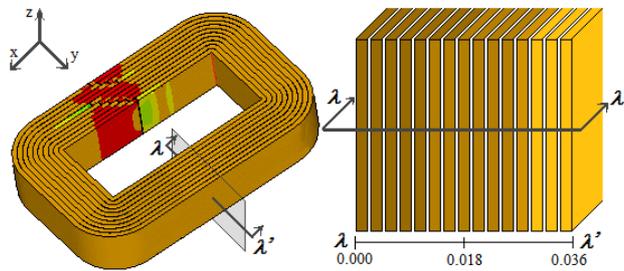
(a)
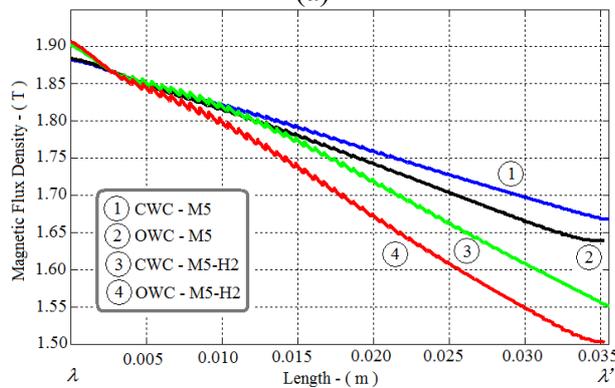
(b)

Fig.8. a) Cross section on the core leg to analyzed the magnetic flux density drop slope. b) Magnetic flux density drop slope on both core configurations.

Table 1
Comparison of Magnetic flux density Slopes, Excitation currents and Eddy current losses in CWC and OWC

GOES	Slope	%Δ Slope	Iexc	% Δ Iexc	Peddy	% Δ Peddy
CWC-M4	6.4948		0.9025		0.8694	
OWC-M4	7.5572	16.35	0.8941	0.93	0.7209	17.08
CWC-M5	5.7528		1.0000		1.0000	
OWC-M5	6.8453	18.99	0.9865	1.35	0.8318	16.82
CWC-M6	8.9736		1.1210		1.3717	
OWC-M6	10.7342	19.61	1.1106	0.92	1.1291	17.68
CWC-M5H2	9.7269		0.8158		0.8781	
OWC -M5H2	11.2982	16.15	0.8066	1.12	0.7319	16.64

All the values are given in p.u. The reference values are the excitation current and the eddy current losses for M5 electrical steel.

From the results in the mixing of different grade laminations in the core was evident that:
a. The excitation current was reduced in both cores depending of the mixed percentage.
b. The eddy current losses were reduced in both cores depending of the mixed percentage.

Conclusions

From the analysis and simulations results introduced in this paper are evident the advantages to manufacture the OWC. OWC requires an easier manufacturing process permitting the mixing of different grade electrical steel also it provides a decreases in eddy current losses and excitation currents. The results showed that OWC reduce the eddy currents about 16% and the excitation currents in 1.3%. To combine the high grain oriented electrical steels (in the internal laminations) with standard grain oriented reduce considerably eddy current losses. The reductions of eddy current losses and excitation currents depend of the proportions of the mix. In general, the results presented here are useful during the core manufacturing.

Appendix A – Constant Values Desidgn Parameters oft he Core

Table 2
Values of design parameters of the core

i	parameter	value	i	parameter	value
1	h	153.00	9	h_1	153.00
2	w	42.86	10	h_2	183.00
3	p	36.00	11	w_1	46.50
4	q	37.82	12	w_2	71.10
5	s	10.00	13	hw_1	2.60
6	g	1.00	14	hw_2	31.00
7	d	0.30	15	p_1	36.00
8	u	0.015	16	q_1	36.00

All the values are given in mm. Parameter d is the lamination thickness and it has values from: M5(0.3mm), M4(0.28mm), M6(0.35mm) and M5H2(0.30mm)

Appendix B – Weight and Mean Length Equations of Wound Cores

The following equations were obtained to determine the core weight and core average length for the analyzed core configurations. They were tested with CAD software tools and physical measurements.

CWC

Using the specific weight density for the silicon oriented electrical steel ρ_e [7]; the core weight could be determinate by:

$$P_{cwc} = fs \cdot \rho_e \cdot p \cdot q \left[2(h+w) + \pi \cdot q \right] \tag{1B}$$

The core length average for a CWC is given by:

$$\ell_{cwc} = 2(h+w) + \pi \cdot q \tag{2B}$$

OWC

The core weight:

$$P_{owc} = fs \cdot \rho_e \cdot p \cdot q_1 \left[h_1 + h_2 + w_1 + w_2 + 2(hw_1 + hw_2) \right] \tag{3B}$$

The core length average for a octagonal core is given by:

$$\ell_{owc} = 2(h+w+4 \cdot q_1 \cdot \sin\theta) \tag{4B}$$

The ratio between width cores;

$$q = q_1 + 0.5 \cdot hw_1 \cdot \sec\theta \tag{5B}$$

To being $\theta = \pi/8$.

Design equations of CWC and OWC

Dimensions of CWC core are obtained as follow: considering a frequency of 60 Hz, the net cross-section area (mm^2) of the core is given by [8]:

$$A_n = \frac{37513.18(V_{turn})}{B_m} \tag{1C}$$

where V_{turn} are the volts per turn, which are equals for the primary and secondary windings and B_m (kG) is the maximum magnetic flux density.

Since the steel laminations are covered by insulating coating, we define the effective area [9]-[11]:

$$A_e = \frac{A_n}{F_s} \tag{2C}$$

where A_e is effective area of the core (mm^2) and F_s is the stacking or lamination or space factor; typical values of this factor are 0.96-0.98.

A lamination width p, for the wound-core distribution-transformer family between 152.4 mm and 304.8 mm is recommended. The lamination width will be selected according to the transformer rating. Figure 3 shows the parameters of a typical CWC.

When the lamination width has been selected, we proceed to determine the core thickness q, using the equation:

$$q = \frac{A_e}{2p} \tag{3C}$$

The factor ½ appears in (3C) because the single-phase shell- type transformers require two cores and one winding to manufacture the transformer.

The frame dimensions of the core, h and *w* (width and height respectively) are determined by the winding thickness and winding height. The previous procedure is applicable for OWC.

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