

MODELING OF A THREE-PHASE APPLICATION OF A MAGNETIC AMPLIFIER

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Abstract

Applications of new soft magnetic materials, such as amorphous magnetic alloys, have enabled the use of magnetic amplifier (mag amp) technology in the design of competitive electric power regulators.

Magnetic amplifiers are used in the power supply of the Electronic Flight Control System in the Swedish "Gripen" fighter-aircraft. This technology is attractive in More Electric Aircraft (MEA) systems due to the possibility to achieve a compact, robust and a highly reliable design.

This paper describes a suggested approach to model a three-phase application of a magnetic amplifier. The model is based on a magnetic hysteresis MATLAB-model of the core material of amorphous magnetic alloys. The basic circuitry is based on a one-phase mag amp circuit extended to a three-phase circuit, analyzed in an engineering tool.

A key parameter in aircraft and automotive applications is power density [kW/kg]. Impact on weight and performance as a function of the magnetic material chosen and supplied frequency is presented

The demonstrated engineering tool offers a very quick method of analyzing if a mag amp design is possible for the application by analyzing power losses and efficiency as well as weight and volume.

1 Introduction

In the process of designing an electric power supply system for an aircraft, parameters like low weight and low losses are important. Reliability and robustness are other important factors. In the Saab Gripen aircraft the design of the primary power supply of the electric flight control system was updated by exchanging from a switching transistor regulator to a magnetic amplifier (mag amp). By introducing a mag amp design, weight was saved and we got a more reliable unit at a lower price.

An electric power supply system for an aircraft is basically specified by Mil-Std-704, which specifies a 28 VDC system as well as a three phase 115 VAC, 400 Hz system. By comparing the weight and size of the generators and transformers with units of comparable rating for the commercial systems 50/60 Hz, it can be noted that the aircraft units have a significantly lower due to the higher frequency. In the particular case with the power supply of the electric flight control system in the Saab Gripen fighter we could take advantage of a specific PM-generator supplying a variable voltage and a variable frequency varying between 2400 and 4000 Hz. The higher the frequency the better is the potential for lower weight. The weight is roughly proportional to the inverse of the frequency.

In the trend of More Electric Aircraft designs [1], with a power supply of 270VDC, we note that the generator used, most likely works with a

higher frequency than 400 Hz. Can we take advantage of a higher operating frequency?

A key parameter in designing magnetic amplifiers (mag amps) is low losses. New amorphous alloys are opening up new possibilities for the technique of designing magnetic amplifiers by offering extremely low losses. The core losses can be evaluated by studying the hysteresis loop, or by studying the equation or diagrams giving the power loss provided by manufacturers. Alternatively the core losses can be verified in tests evaluating the losses by electric or thermal methods.

2 The Magnetic Amplifier

The operation of a mag amp is based on alternating from unsaturated to saturated state. When the core is saturated the mag amp is conducting, the switch is on. During the following half cycle the mag amp can be reset to an unsaturated state.

2.1 The Ramey Magnetic Amplifier

In the Ramey amplifier, Fig. 1, the voltage time product for reset is given by $U_s - U_{reg}$ and the duration of the negative half cycle. The mag amp, M is off until the reset voltage time product is balanced and the switch is set on. The rectifying diode handles the positive half cycle from the power source U_s , which is filtered by the LC-filter and is supplied to the load R_L as DC-power. A typical application is in switched mode power supplies.

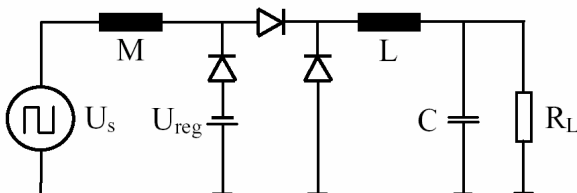


Fig. 1. The one-phase Ramey mag amp

The advantage of this design is the simplicity and the fast response.

2.2 The one-phase Magnetic Amplifier

With the self-saturating circuit in Fig. 2 a small control current I_C can be used to control the effective load voltage [2]. The functional elements are arranged such that a self-saturating circuit is achieved. In this design a control current I_C is required for the cores to go from saturated to non-saturated state.

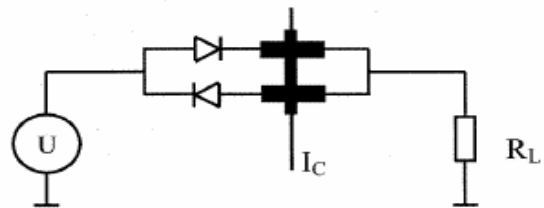


Fig. 2. The one-phase mag amp

The one-phase mag amp suffers from slow response time, due to the possibility of a circulating current in the power windings.

2.3 The Three-phase Magnetic Amplifier

The one phase self-saturating circuit can be extended to a full 6 pulse design. See Fig.3. The output from this mag amp design comprises the combination of the three phases and the six pulses to a rectified output.

The three-phase magnetic amplifier has a faster response time, compared to the one phase mag amp, since the circulating current will be limited by the load R_L .

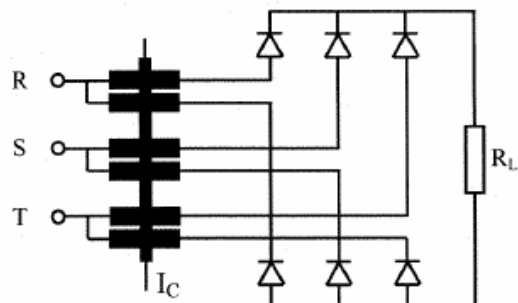


Fig. 3. The three-phase mag amp

The optimization of the mag amp can be slightly different depending on the load profile, i.e. whether the mag amp is mostly on or off. For a

general design it can be sufficient to look at the sum of the core and copper losses.

3 The Magnetic Amplifier Loss Model

The core losses can be divided into three different types of losses:

- static hysteresis losses
- eddy current losses
- anomalous losses (at higher frequencies)

- The hysteresis losses

The hysteresis losses can be explained as the frictional losses that occurs when the magnetic domains in the material moves in respect to each other. The hysteresis losses can be evaluated by studying the core characteristics. The area of the BH-loop represents the loss energy during one cycle and can be calculated according to:

$$W = \oint HdB \quad [\text{Ws/m}^3] \quad (1)$$

The power losses can then be expressed as:

$$P = \frac{f}{\rho} \int H \frac{dB}{dt} dt \quad [\text{W/kg}] \quad (2)$$

f is frequency [Hz]

ρ is weight per unit volume [kg/m³]

H magnetic field [A/m]

B is flux density [T]

- Eddy current losses

An AC magnetic field will always induce eddy current losses in conducting materials. The eddy current losses in the core can be expressed as a function of B, f and the thickness of the magnetic material. It can be expressed:

$$P_e = (2\pi f)^2 \hat{B}^2 \frac{d^2}{24\rho} \quad (3)$$

d is the thickness [m]

\hat{B} is the amplitude of the mean flux density

The anomalous losses are considered to be neglect able in the here studied applications.

- The total loss

At lower frequencies the total core losses are the sum of hysteresis and eddy current losses.

$$P_h \sim f$$

$$P_e \sim f^2$$

In an application the sum of P_h and P_e is rapidly dominated by P_e at increasing frequency. This implies that the losses are dominated by the factor with the highest exponent. The hysteresis model [3], is extended to include the frequency dependency [4]. The extension is performed by introduction of applicable data for permeability and the coercive force for the studied alloy at applicable frequencies. In Fig. 4 an example shows the hysteresis loops for 400 Hz and 5000 Hz.

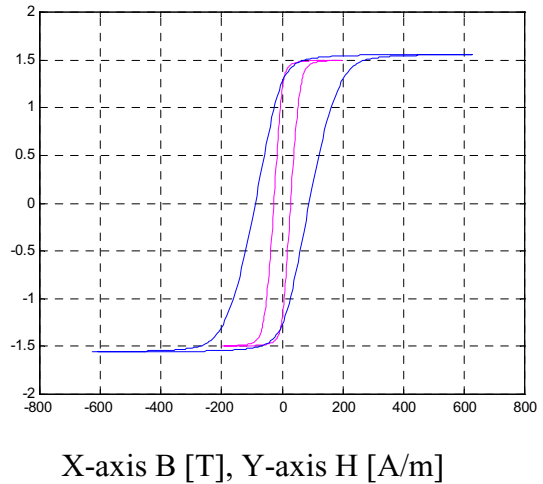


Fig.4. Hysteresis model for Metglas 2605 TCA

The power losses can be calculated for different frequencies. The core losses is in Fig 4 are verified for 400 Hz and 5000 Hz and is in compliance with the core loss curves provided by the vendor, see Fig. 5. The total core loss can be expressed as a function of f and B. The hysteresis losses can be expressed:

$$P = k_h \cdot f \cdot B_{\max}^n \quad (4)$$

where k_h is a constant depending on the material and n varies between 1,5 and 2,5, according to Charles Steimetz of General Electric company [5]. This can be compared with the equations for losses given by the vendor, Metglas for alloy 2714A [6]:

$$P = 9.93 \cdot 10^{-6} \cdot f^{1.57} \cdot B^{1.7} \quad [\text{W/kg}] \quad (5)$$

The studied amorphous alloys are of interest in design of magnetic amplifiers due to low losses and the square ness of the characteristics.

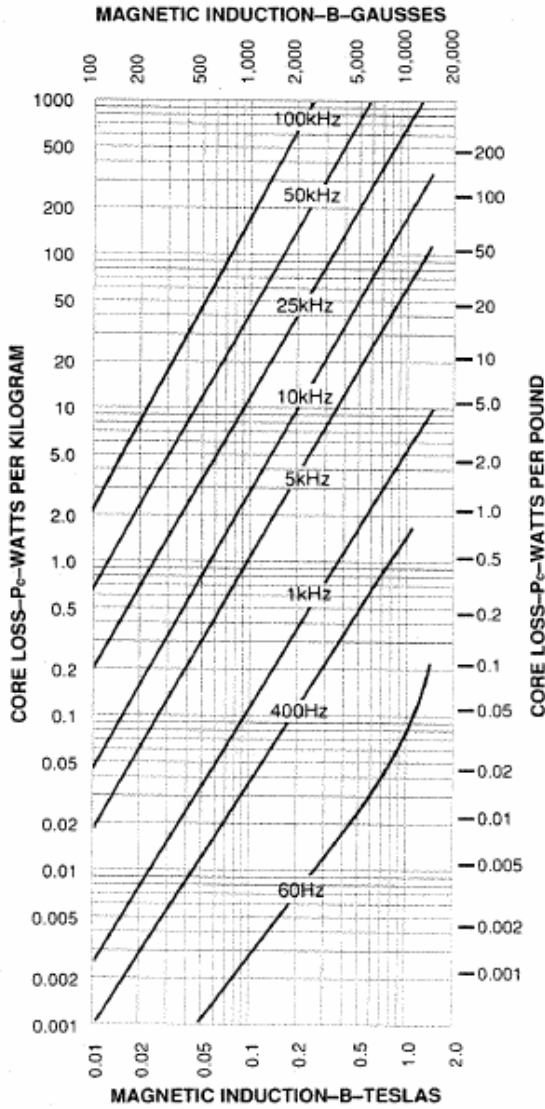


Fig. 5. Core losses for Metglas 2605 TCA

4 A Proposed Engineering Design Tool

The purpose of the proposed design tool is to from given input parameters calculate requested output parameters.

4.1 The Proposed Design Algorithms

Algorithms for the magnetic core and copper winding can be expressed as follows

Core Area

From a chosen material with maximum flux density, the needed core area A_{Fe} is calculated. The volt-second product $U \cdot t$ is calculated.

$$U \cdot t = 2 \cdot B \cdot A_{Fe} \cdot N \quad (6)$$

The flux density span is $2B$, because the flux can be used from over the whole span from negative to positive B . For a given number of N of turns the corresponding core area is:

$$A_{Fe} = \frac{U \cdot t}{N \cdot 2B} \quad (7)$$

Length of Copper Wire per Turn

The engineering tool assumes a squared core cross section, but is not limited to any standard selection. The average turn length will be calculated by as the sum of the length of the inner turn and the length of the outer turn divided by 2. The encapsulation of the core is estimated to add a total of 10 % of the inner turn length this gives a factor 0.4 for the 4 sides.

$$\text{The inner length} = \sqrt{A_{Fe}} \cdot (4 + 0.4)$$

4 is the number of sides.

0.4 represents the margin of encapsulation.

At a winding window utilization factor of 30% the inner diameter of the winding d_w can be calculated according to

$$(\pi/4)d_w^2 = (\pi/4)d_i^2 (1-0.3) \Rightarrow d_w = 0.8366 d_i$$

, where d_i is the core inner diameter without encapsulation, see Fig. 6.

$$\text{The outer length} = 4(\sqrt{A_{Fe}} + d_i(1-0.8366))$$

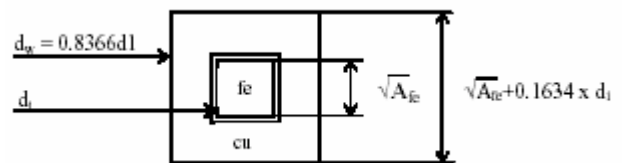


Fig.6. The copper winding, cross section.

The average turn length will be:

$$l_{Cu} = \frac{(\sqrt{A_{Fe}} \cdot (4 + 0.4) + 4 \cdot (\sqrt{A_{Fe}} + d_i(0.1634)))}{2}$$

$$l_{Cu} = \sqrt{A_{Fe}} \cdot 4.2 + d_i \cdot 0.1634 \cdot 2 \text{ [m]} \quad (8)$$

Iron Losses and Core Weight

The iron losses per kilo can be expressed by a function of frequency and the maximum flux. Such an equation is given by Metglas [4] for the amorphous material 2714A, in equation (5). For the material 2605TCA data from Fig. 5 data is extracted to give the equation:

$$P = 88 \cdot 10^{-6} \cdot f^{1.57} \cdot B^{1.7} \quad (9)$$

, which yields good compliance up to 10 000 Hz. The losses also are showed to be approximately 9 times bigger than in equation (5). Data complies with material from Arnold, Arnoglas 1, and fairly well with the Metglas, 2605SA1.

The weight of the core is:

$$m = l_{Fe} \cdot A_{Fe} \cdot \rho \quad (10)$$

, where l_{Fe} is the average iron core length

ρ is density for the different alloys:

2714A	$\rho=7590$	[kg/m ³]
2605TCA	$\rho=7180$	[kg/m ³]
2605SA1	$\rho=7190$	[kg/m ³]

The core losses can be calculated from the given input parameters and the equations (5) or (9). As an example, the core losses are shown for Metglas 2605TCA, defined by equation (9), as a function for different number N of turns. In Fig. 7 cases for N= 15, 25, 45, 75, 150 turns are presented with corresponding losses and core weights.

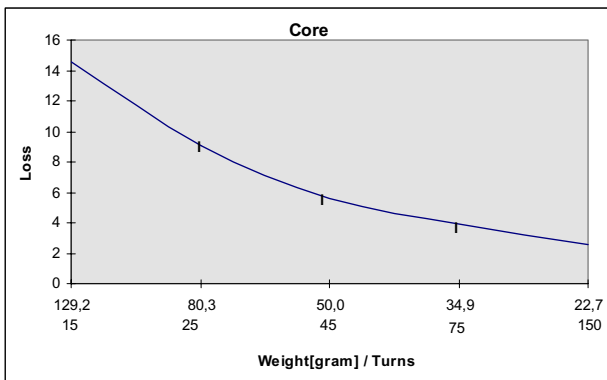


Fig.7. The core losses

Copper Losses

The copper losses are basically depending on the current, the turn length, number of turns and the copper area A_{Cu} . The wire length is calculated as an average length per turn, given in preceding paragraph giving the resistance:

$$R = \rho \cdot k \cdot l_{Cu} \frac{N}{A_{Cu}} \quad (11)$$

$\rho=2 \cdot 10^{-8}$ [ohmm] at 85 [°C]
 $k=$ skin factor >1 at high frequencies.

The skin effect is out of scope of this work, but it can be concluded that there is no impact (less than 10%) for a wire with a diameter less than 2 [mm] as long as the frequency is less then 10000 [Hz].

The copper loss is: $P_{Cu} = R \cdot I^2 / n \quad (12)$

, where n is the number of phases, except for the one phase application, where $n = 2$ due to the 50% duty cycle.

$n=2$ for a 1 phase mag amp
 $n=3$ for a 3 phase mag amp

Weight of Copper Wire

The weight of the copper wire is:

$$m = l \cdot N \cdot A_{Cu} \cdot \rho \quad (13)$$

, where $\rho = 8900$ [kg/m³]

As an example, the copper losses and corresponding copper weights are shown in Fig. 8 for the different cases with N=15, 25, 45, 75 and 150.

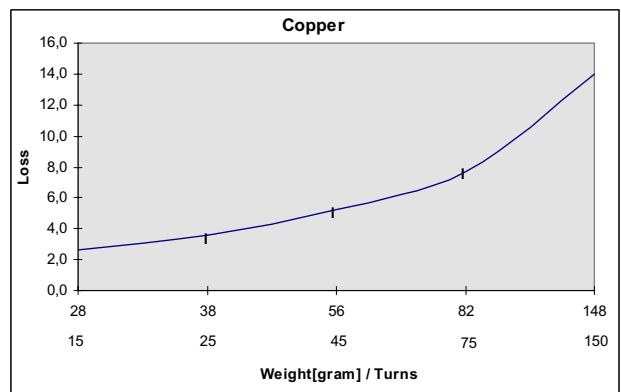


Fig.8. The copper losses

The Total Losses

Studying the core losses, it can be noted that the loss is decreasing for a higher number of turns, N , while the copper loss is increasing. One intention of this work is to find a way of minimizing the weight and losses. In the next step, the sum of core and copper losses $P_{\text{total}}=P_{\text{Fe}}+P_{\text{Cu}}$ are studied. The sum of the losses is shown as a function of the total weight for the different cases of N in Fig.9. It can be noted that the lowest weight coincides with the lowest losses in the presented example.

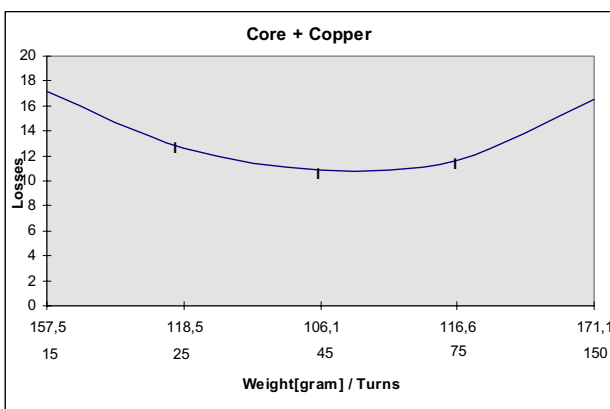


Fig.9. The core and copper losses

4.2 A Proposed Engineering Tool

The proposed engineering tool offers a quick method of analyzing whether a mag amp design is possible for a considered application. Weight and efficiency are parameters that are analyzed by the proposed tool. In aircraft design information such as frequency and weight, must be exchanged between system level [7] and component level, and this can be achieved from this engineering tool. So far the methodology of analyzing the losses is demonstrated by 1) analyzing the hysteresis loop 2) comparing the hysteresis loop losses with the power loss diagram, and now finally by using the equations analyzing the losses in the engineering model.

Feature

Based on the presented equations and input data, the tool calculates output data like weight, dimensions and losses. In similarity with a transistor circuit the mag amp must be designed to meet the requirements of current as well as

voltage. The difference is that the voltage capability in the mag amp design is volt during a period of time [Vs].

Usage

Numbers of turns are used as input parameters. Selections of different turns are used to evaluate weight end losses. The tool gives an opportunity to evaluate weight end losses for each N . The tool will support the design optimization process, by graphically showing where we can find the minimum weight and losses, e.g. see Fig 10. For some selected numbers of turns N the studied variables including the losses are graphically shown and the minima are easily found, if necessary by selecting additional N values.

Note that the design tool does not include any design margins with respect to e.g. tolerances in area and material as well as design margins normally considered due to variations in temperature and aging. The engineering tool also will not treat the losses in diodes or the control circuit.

Input Parameters

Typical input specification-data can be as in table 1. Core inner diameter d_i [mm] specifies the core without encapsulation. When choosing the wire area the current density [A/mm^2] must be considered with respect to cooling capability. In our examples $6.5 \text{ [A}/\text{mm}^2]$ is chosen, which requires cooling.

In the calculations a winding window utilization factor of 30 % of available area is used.

Table 1. Input parameters

Input Parameters	
Current [A]	37
Voltage [V]	270
Frequency [Hz]	5000
Phases p	3
Alloy	2605
Flux B [T]	1,5
Area A_{Cu} [mm^2]	3,3
Turns N	45
Core d_i [mm]	45
Winding window utilization factor %	30

From the given input parameters an Excel program can perform the calculations and present output parameters and graphs to support a design decision.

5 Calculation Examples

A feasible aircraft application can be a converter for 270 VDC, at a power level of 10 kW. A few cases (different input data) are studied. The output data can be studied in Table 2. The graphs for minimization of losses and weight can be studied in Fig. 10, 11, 12 and 13.

Output Parameters

A number of calculations have been performed with different input parameters, giving the outputs that can be seen in Table 2. The circuits studied in example 1 can be seen in Fig.1, and the circuit in examples 2-4 can be seen in Fig. 3.

Table 2. Examples of different calculations

Mag amp Example	1	2	3	4	5
Current [A]	74	37	37	37	37
Voltage [V]	270	270	270	270	270
Frequency [Hz]	5000	5000	10000	5000	60000
Phases p	1	3	3	3	3
Alloy	2605	2605	2605	2714	2714
Flux B [T]	1.5	1.5	1.5	0.5	0.5
Area A_{Cu} [mm ²]	8	3,3	3,3	3,3	3,3
Turns N	50	45	45	60	25
Core d_i [mm]	41	25	25	29	19
Outer d [mm]	58	35	33	40	25
Height [mm]	20	12	10	13	8.6
Volume [mm ³]	52690	11920	8330	16140	4170
Weight [g]		106	66	255	38.9
Total weight [g]	470	636	396	1530	234
Total power [W]	9990	9990	9990	9990	9990
Output/core [W]		1665	1665	1665	1665
Losses/core [W]		10.9	11.8	10.4	3.7
Total losses [W]	49	69.7	69.8	62.3	22.3
Losses %	0.5	0.65	0.71	0.62	0.23
Efficiency %	99.5	99.4	99.29	99.38	99.77

It is of special interest to study the total weight, the losses and the efficiency. In example 2 in Table 2, with 5000 Hz it can be noted that the weight and losses are minimized at the same number of turns (N=45), as can be seen in Fig. 10.

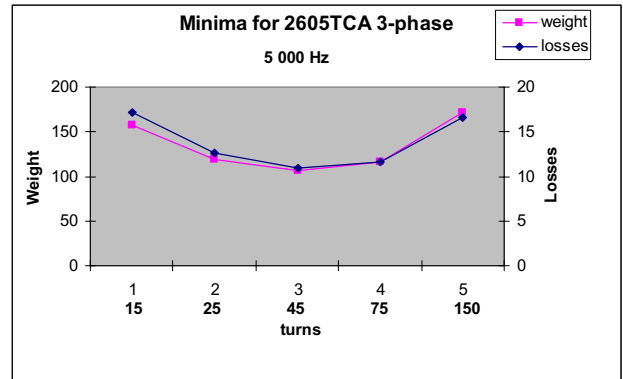


Fig.10. Examples of coinciding minima

When changing the frequency to 10000Hz, in example 3 in Table 2, it can be noted that the minima for weight and losses do not fully coincide, see Fig. 11.

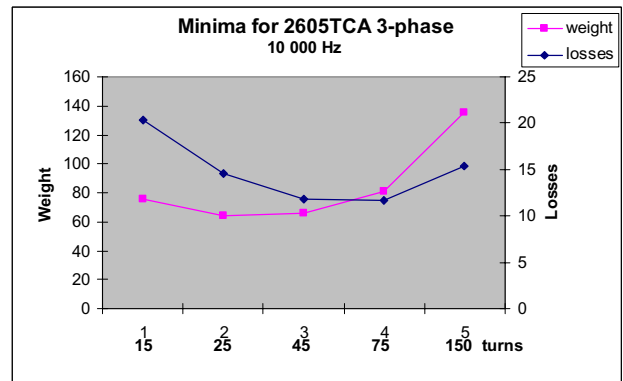


Fig.11. Examples of split minima

When changing the alloy to 2714A, in example 4 in Table 2, it also can be noted that the minima for weight and losses do not coincide, see Fig. 12.

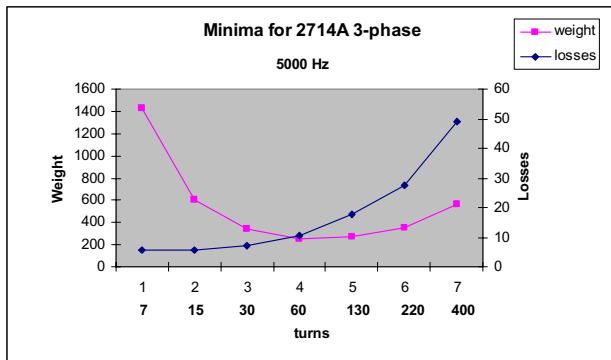


Fig.12. Examples of split minima

The presented data represent the weight minimum. The losses 62.3 [W] can be reduced to 22.3 [W], in example 5 in Table 2, at a weight decreased from 1530 [g] to a weight of 234 [g] in an application working with 60 kHz where the minima for weight and losses coincides. See Fig.13.

6 Conclusion

The conclusion is that in an optimized design the losses are minimized by minimizing the weight of the core.

The advantage with a design with 2605TCA at e.g. 5000 Hz, is that the lowest losses coincide with the lowest weight.

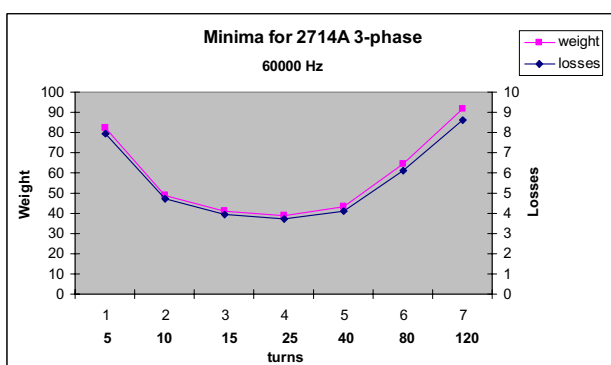


Fig.13. Examples of coinciding minima

When the losses coincide with the lowest weight the losses in the core are about equal to the losses in the copper wire.

In example 3 in Table 2, it can be noted that the doubled frequency (5 to 10 [kHz]) is giving a

weight of 396 [g], full advantage of the increased frequency, a weight of 318 [g] is achieved only when the current density is doubled. In our example the current density is kept at 6.5 [A/mm²].

It can be noted that the higher the flux density, the lower the weight can be.

The efficiency for the magnetic amplifiers are as high as 99.3 % and the power density can easily meet 15 [kW/kg] in the 5000 [Hz] application.

The conclusion is that a core in the 2605-family is the preferable alloy in audio frequencies, due to low losses and low weight. The 2714A alloy might be preferable in the 60 kHz range, with a potential of efficiency near 99.7 %. At this frequency however the skin effect must be considered.

The high reliability and robustness also represents a significant value adding to the attraction of magnetic amplifiers in aircraft applications.

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