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EUTRO À TERRA

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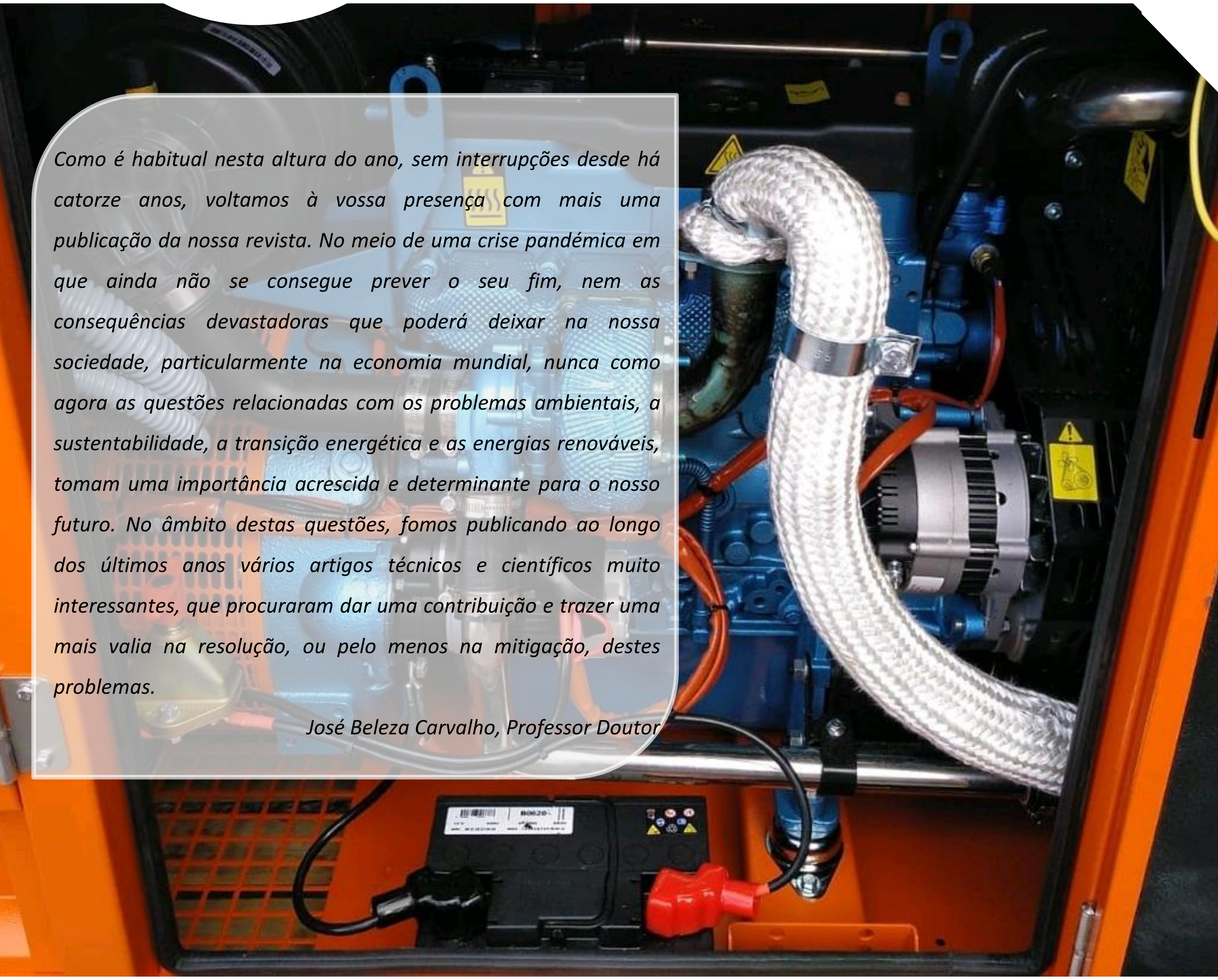

Como é habitual nesta altura do ano, sem interrupções desde há catorze anos, voltamos à vossa presença com mais uma publicação da nossa revista. No meio de uma crise pandémica em que ainda não se consegue prever o seu fim, nem as consequências devastadoras que poderá deixar na nossa sociedade, particularmente na economia mundial, nunca como agora as questões relacionadas com os problemas ambientais, a sustentabilidade, a transição energética e as energias renováveis, tomam uma importância acrescida e determinante para o nosso futuro. No âmbito destas questões, fomos publicando ao longo dos últimos anos vários artigos técnicos e científicos muito interessantes, que procuraram dar uma contribuição e trazer uma mais valia na resolução, ou pelo menos na mitigação, destes problemas.

José Beleza Carvalho, Professor Doutor

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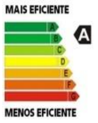

Gestão de Energia e Eficiência Energética

Automação, Gestão Técnica e Domótica

Instituto Superior de Engenharia do Porto – Engenharia Electrotécnica – Área de Máquinas e Instalações Eléctricas

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FICHA TÉCNICA

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Estimados leitores

Como é habitual nesta altura do ano, sem interrupções desde há catorze anos, voltamos à vossa presença com mais uma publicação da nossa revista. No meio de uma crise pandémica em que ainda não se consegue prever o seu fim, nem as consequências devastadoras que poderá deixar na nossa sociedade, particularmente na economia mundial, nunca como agora as questões relacionadas com os problemas ambientais, a sustentabilidade, a transição energética e as energias renováveis, tomam uma importância acrescida e determinante para o nosso futuro. No âmbito destas questões, fomos publicando ao longo dos últimos anos vários artigos técnicos e científicos muito interessantes, que procuraram dar uma contribuição e trazer uma mais valia na resolução, ou pelo menos na mitigação, destes problemas.

Nesta edição da revista merece particular destaque um artigo científico, que é publicado em Inglês, sobre a estimação das perdas no ferro para formas de onda sinusoidal e não sinusoidal da indução magnética. Este é atualmente um assunto fundamental na conceção e no modo de funcionamento das máquinas elétricas, sendo um contributo determinante na conceção de máquinas elétricas especiais mais eficientes. O artigo faz uma análise científica detalhada sobre este assunto.

Os assuntos relacionados com a mobilidade e os veículos elétricos estão na ordem do dia. Atualmente, existem opções desenvolvidas com o objetivo de potenciar a eficiência energética dos veículos, procurando simultaneamente reduzir as emissões dos gases nocivos para os seres humanos e dos gases que contribuem para o agravamento do efeito de estufa. Existem, atualmente, várias soluções e tecnologias, desde soluções totalmente elétricas, a combinações de motores elétricos e a combustão; de carregamento em movimento, a carregamentos ligados à rede elétrica. Todas as soluções contribuem para o objetivo de reduzir as emissões de gases nocivos. Nesta edição da revista, publicam-se alguns artigos sobre o assunto, que efetuam uma análise comparativa das caraterísticas e das várias soluções técnicas que existem atualmente disponíveis no mercado.

Outro assunto muito importante, também relacionado com a problemática da sustentabilidade ambiental, tem a ver com a remodelação e aumento da capacidade de transmissão das linhas de alta e muito alta tensão. Nesta edição, publica-se um interessante artigo sobre o aumento da capacidade de transporte de energia pelas infraestruturas existentes atualmente, contruídas nos anos 70. Estas instalações foram projetadas para um ciclo de vida económica e de engenharia de 50 anos. Agora requerem uma extensão do seu funcionamento, para conseguirem assegurar a devida qualidade do serviço. Atendendo a diversos constrangimentos para a construção de novas linhas aéreas, coloca-se a necessidade de otimização das instalações existentes torna-se uma prioridade antes de ponderar a construção de novas linhas aéreas. O artigo que é agora publicado procura definir uma metodologia na remodelação e aumento de capacidade das atuais Linhas Aéreas de Muita Alta Tensão.

Nesta edição publica-se um importante artigo técnico sobre as emissões de CO2 e a produção de resíduos radioativos pelas fontes energéticas em Portugal. No artigo são apresentados os resultados do cálculo das emissões específicas e totais de dióxido de carbono, e da produção específica dos resíduos radioativos de alta atividade, para diferentes comercializadores de energia em Portugal Continental e Regiões Autónomas. Os resultados são obtidos através dum simulador de cálculo de emissões, desenvolvido para o estudo que é apresentado. A metodologia adotada no estudo está em conformidade com a legislação em vigor, a Diretiva nº16/2018.

Nesta edição da revista “Neutro à Terra” pode-se ainda encontrar outros assuntos reconhecidamente importantes e atuais, como um artigo sobre os esquemas de ligação à terra e a proteção das pessoas contra contactos indiretos em instalações elétricas de baixa tensão, outro artigo sobre as instalações de climatização de uma unidade hospitalar, e outro sobre os graus de proteção assegurados pelos invólucros dos equipamentos utilizados nas instalações elétricas.

Fazendo votos que esta edição da revista “Neutro à Terra” satisfaça novamente as habituais expectativas dos nossos estimados leitores, apresento os meus cordiais cumprimentos.

Porto, 30 de junho de 2021
José António Beleza Carvalho

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Histórico de visualizações

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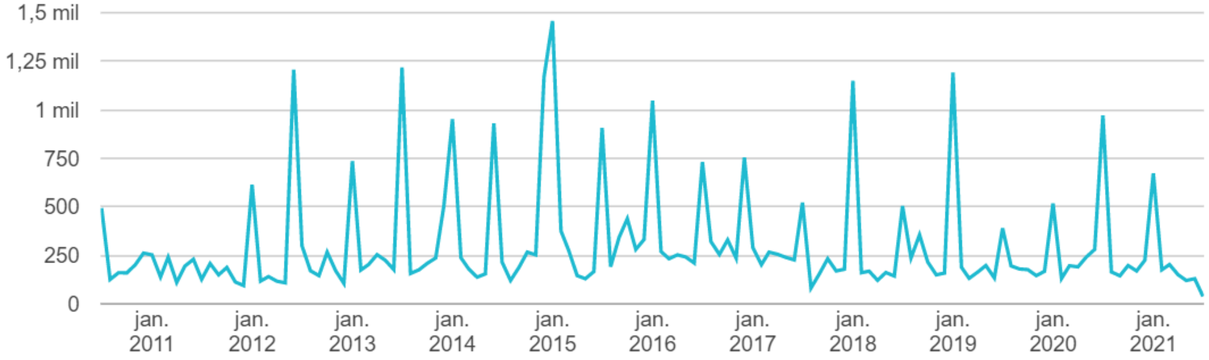

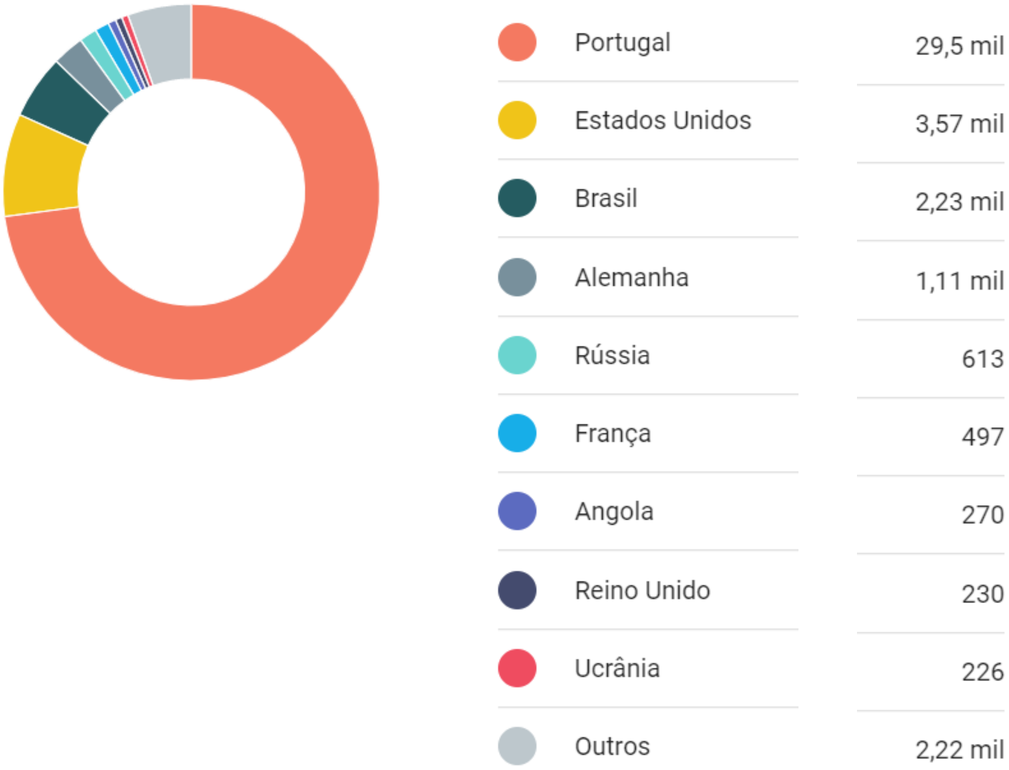

Portugal	29,5 mil
Estados Unidos	3,57 mil
Brasil	2,23 mil
Alemanha	1,11 mil
Rússia	613
França	497
Angola	270
Reino Unido	230
Ucrânia	226
Outros	2,22 mil

CORE LOSS ESTIMATION UNDER SINUSOIDAL AND NON-SINUSOIDAL FLUX DENSITY WAVEFORMS: OVERVIEW AND CHALLENGES

1. Introduction

Nowadays, electrical machines design and control developments are much attached to simulation models. Accurate loss estimation methods are fundamental for improving efficiency, but also to achieve the desired operation conditions [1].

The development of non-sinusoidal flux density machines and conventional machines fed by power converters (e.g., switched reluctance motors, brushless DC machines, permanent magnet synchronous motors and induction motors with PWM voltages), has motivated researcher´s efforts to reach a deeper characterization of magnetic losses under such excitation waveforms. This can be done either by measurement or estimation [2], [3]. New challenges arise, since sinusoidal-conventional methods are clearly insufficient. Moreover, different flux density waveforms are related to particular electric machines configurations, which suggests that specific approaches for characterizing core losses must be addressed, according to the machine type [3]. Usually, empirical models for core loss estimation are engineers first choice, due to its simplicity and faster processing. Parameter estimation is based on curve-fitting methods, validated by manufacturer iron sheet data, experimental results or through finite element modeling (FEM) [3], [4]. Accuracy is much sensitive to parameter values, so their estimation must be attached to specific conditions (e.g., flux density and frequency ranges). Moreover, the manufacturing process of the machine has also a deep impact on core losses, which is very difficult to address in the parameter estimation process [5], [6]. Cutting and punching operations have a relevant influence in the material properties, since they can create inhomogeneous stresses inside the lamination. This depends on the alloy composite, whereas the grain size seems to have the main impact [5].

Most often, lamination manufacturers provide core loss data under sinusoidal excitation in a limited frequency and flux density range, as depicted in Fig. 1.

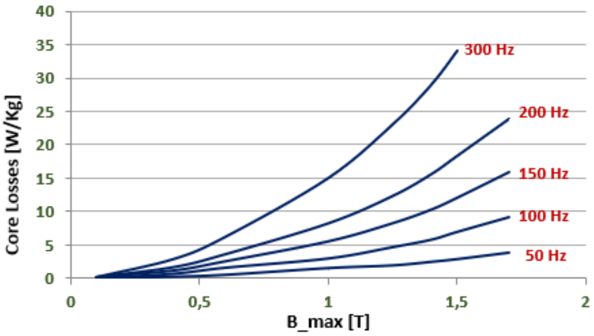

Fig. 1– Manufacturer core loss density (Lamination Steel: M35 (Fully Processed, thickness: 0,36 mm)) [7]

However, this might not be adequate for predicting losses in electrical machines with non-sinusoidal flux waveforms. Iron loss modelling is a very challenging task, since specific flux density waveforms may exist in different stator and rotor core sections. In addition, they depend on the motor design (e.g., geometry, number of stator and rotor poles, yoke size, number of phases), operating conditions and the type of control [8]. Core losses are more significant as speed increases, so for applications like hybrid and electric vehicles they must be carefully addressed.

This paper aims to give a general overview about magnetic lamination loss estimation methods (including some merits and demerits), which are the basis of most electrical machine´s cores. The paper is organized as follows: Section 2 addresses core losses under conventional sinusoidal magnetic flux, where engineer approaches for loss estimation are discussed. Section 3 deals with losses under non-sinusoidal flux densities, particularly the main challenges that still exist and need to be overcome. Finally, the conclusions are in Section 4.

2. Core Loss Estimation with Sinusoidal Flux Densities

In the following, an overview on iron loss estimation is addressed, from an engineering perspective. The evolution of the most relevant methods, as well as their merits and limitations, is discussed.

Electrical machines core losses can be addressed by three different approaches (in time or frequency domain): empirical equations, loss separation components and hysteresis models. Only the first two are discussed here.

2.1. Empirical Models Based on Steinmetz Equation

The Steinmetz coefficients depend on both frequency and flux density [9], so in a waveform with relevant harmonics it might be difficult to find their values. Based on the results of many tests, the classical Steinmetz equation was the first attempt to calculate core loss [10]:

$$P_{core} = C_m f^{\alpha} B_{max}^{\beta} \qquad (1)$$

Where Bmax is the peak value of the flux density at the lamination, f=1/T is the remagnetization frequency (T is the hysteretic cycle time interval), and coefficients Cm, α and β are estimated by fitting the loss model to the lamination manufacturer or measured data. It must be pointed that (1) assumes sinusoidal flux densities, with uniform distribution across the lamination thickness.. Over the years, several upgrades were performed, in order to account for non-sinusoidal waveforms.

The Modified Steinmetz Equation (MSE) is an improvement, aiming to calculate core loss under arbitrary B waveforms. The macroscopic remagnetization rate dM/dt (which is proportional to dB/dt) is directly related to the core losses, as a consequence of wall domain motion [11]. Eq. (1) is then replaced by:

$$P_{core} = (C_m f_{eq}^{\alpha-1} B_{max}^{\beta}\big) f \qquad (2)$$

With:

$$f_{eq} = \frac{2}{\Delta B^2 \pi^2} \int_0^T \left(\frac{dB}{dt}\right)^2 dt \qquad (3)$$

Where: $\Delta B = B_{max} - B_{min}$

The MSE has the advantage to highlight the physical origin of the losses, with the same parameters as in (1). A disadvantage of the MSE is that it underestimates losses for waveforms with a small fundamental frequency part. Another difficulty is the treatment of waveforms with multiple peaks, where peak-to-peak amplitude is not an enough description [11]. In fact, this reflects the increasing MSE limitations, as the flux density moves away from the pure sinusoidal waveform.

The Generalized Steinmetz Equation (GSE) in (4) was also developed from the original Steinmetz equation [11]. As with the previous one, losses are calculated in time domain. Here, the instantaneous iron loss is assumed to be a single-valued function of the rate dB/dt and B(t). The inclusion of B(t) allows to consider the DC-bias influence in the loss calculation, without additional measurements or curve-fitting functions.

$$P_{core} = \frac{1}{T} \int_0^T C_m \left|\frac{dB}{dt}\right|^{\alpha} |B(t)|^{\beta-\alpha} \, dt \qquad (4)$$

For different frequency ranges, different parameter values are necessary. Thus, in the presence of relevant harmonics, the accuracy decays. This is an important drawback, particularly in the presence of minor loops. To overcome this limitation, in [12] the flux density waveform is split into a major loop and minor loop(s), in order to consider the later effect over loss calculation. Nonetheless, DC-bias influence is no longer included. This approach was named improved GSE (iGSE). In [13] is reported a test for loss calculation in nanocrystalline materials, with non-sinusoidal excitation voltage. Harmonic decomposition was considered, including the phase displacements. According to this reference, iGSE gives better results than GSE.

Both MSE and GSE are applied in time domain. It must be pointed out that the time evolution (history) of the flux density waveform is neglected. This has an impact on the physical phenomena insight, where loss evaluation may be affected.

2.2. Loss Separation Method

For a general scenario, the hysteresis loss density related to one cycle, in a particular core part, can be calculated by the following expression:

$$P_h = \frac{f}{m_v} \oint_{B_{min}}^{B_{max}} H dB \tag{5}$$

Where B and H are, respectively, the magnetic flux density and the magnetic flux strength, f is the cycle frequency and m_v is the density of the ferromagnetic material[1]. The eddy current loss density is given by:

$$P_e = \frac{\sigma}{m_v} E^2 \tag{6}$$

Where E and σ are, respectively, the electric field and the material electric conductivity[2]. However, in many situations, these equations are unpractical, even with finite element analysis. The complex non-linear B(H) characteristic, which is also dependent on the lamination thickness, is the main reason [14]. So, empirical models for core losses evaluation are often considered. The most common is the Steinmetz equation [10]: the following expression for core losses density in a ferromagnetic material (formulated as the sum of hysteresis (P_h) and classic eddy current (P_e) losses) was first achieved:

$$P_{core} = P_h + P_e = k_h f B_{max}^{1,6} + k_e f^2 B_{max}^2 \tag{7}$$

Which is valid in the range of 0,1 T<B_{max}<1,5 T. Hysteresis and eddy current loss coefficients are, respectively, k_h and k_e, which can be extracted from measured data. They both depend on the core material; k_e also depends on the lamination thickness (d). In fact, k_e has an analytical formulation, which can be derived from Maxwell equations, assuming a uniform magnetic field distribution. Therefore, Eq. (6) can be expressed as:

$$P_e = \frac{\sigma \pi^2 d^2}{6 m_v} f^2 B_{max}^2 \tag{8}$$

An important remark is that (5) also assumes uniform flux density distribution across the lamination thickness. Over the years, the original Steinmetz expression was upgraded, which brought higher accuracy. Experimental data showed that the measured eddy current losses are higher than P_e. Based on statistical loss theory, Bertotti proposed an additional term to account for the excess losses (P_{ex}), which can be expressed as [15]:

$$P_{ex} = k_{ex} (f \cdot B_{max})^{\frac{3}{2}} \tag{9}$$

Where k_{ex} is dependent on the material micro-structure, the conductivity, and the cross-sectional area of the lamination. Different theories have been developed to explain excess losses, but this is still under discussion [14].

For the hysteresis term, the power of B_{max} was found later to be dependent on the material type, as well on B_{max}. Therefore, a more accurate expression was adopted for core loss estimation, with a modified hysteresis term (k_h, a and b are its parameters) and including the excess losses:

$$\begin{aligned} P_{core} = P_h + P_e + P_{ex} = k_h f B_{max}^{a+b \cdot B_{max}} \\ + k_e (f \cdot B_{max})^2 + k_{ex} (f \cdot B_{max})^{\frac{3}{2}} \end{aligned} \tag{10}$$

Further experiments, together with finite element analysis, revealed that it predicts core losses with very good accuracy for f ≤ 1500 Hz and B_{max} <1 T. For higher flux densities, it gives good results for frequencies up to 400 Hz [14].

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[1] For f [Hz] and m_v [kg/m^3], then P_h [W/kg]

[2] For E [V/m] and σ [S/m], then P_e [W/kg]

3. Core Loss Under Non-Sinusoidal Flux Densities

As stated before, (10) is suited for sinusoidal flux densities waveforms. Moreover, the hysteresis term is limited to symmetrically flux density variations about zero (i.e., -B_{max}< B <B_{max}) and, most important, without minor loops included in the main hysteresis loop [16]. Eq. (10) is then mostly suited for sinusoidal flux density waveforms, with uniform distributions in the core. Parameter estimation for empirical formulas under non-sinusoidal flux losses must be based on measured core loss values. Manufacturers data for sinusoidal flux may lead to large errors for non-sinusoidal core losses estimation. In order to consider non-sinusoidal waveforms, the product (f·B) is substituted by ($\frac{dB}{dt}$) in these two terms, leading to (11):

$$P_{core} = k_h f B_{max}^{a+b\cdot B_{max}} + k_e \int_0^T \left(\frac{dB}{dt}\right)^2 dt + k_{ex} \int_0^T \left(\frac{dB}{dt}\right)^{\frac{3}{2}} dt \qquad (11)$$

Where T=1/f.

It is important to highlight that most loss models assume uniform magnetic field distribution across the core lamination. However, the influence of skin effect and saturation over eddy current and hysteresis losses cannot be disregarded, in particular for high frequency operation. This leads to non-uniform field densities, which brings additional challenges for core loss modelling.

3.1. Eddy current, Hysteresis and Rotational Flux Losses

In this subsection, a brief discussion about the impact of non-uniform field density over eddy current and hysteresis losses is addressed. In addition, a short reference to rotational flux losses is included.

3.1.1. Eddy Current Loss

The skin effect in the magnetic core is due to the field created by eddy currents: for high frequencies, particularly for thick lamination core, eddy current density at the lamination surface is higher than 1n the center, as shown in Fig. 2.

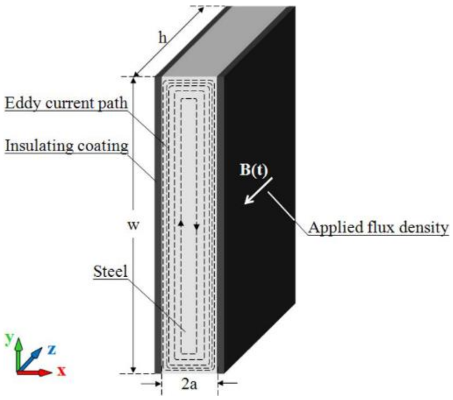

Fig. 2– Eddy current distribution in a magnetic lamination of thickness d=2a, due to skin effect [17]

The skin-depth penetration is the distance from the lamination surface where eddy current density has decreased by a factor of 1/e, and it is approximately given by:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (12)$$

Where f is the excitation frequency, μ the magnetic permeability and σ is the material electric conductivity.

Flux penetration in the lamination depends on the skin-depth penetration (δ) and the lamination thickness (d). For high frequencies, particularly if δ << d, the magnetic density field has a non-uniform distribution and it is mainly concentrated on the lamination surface (Fig. 3).

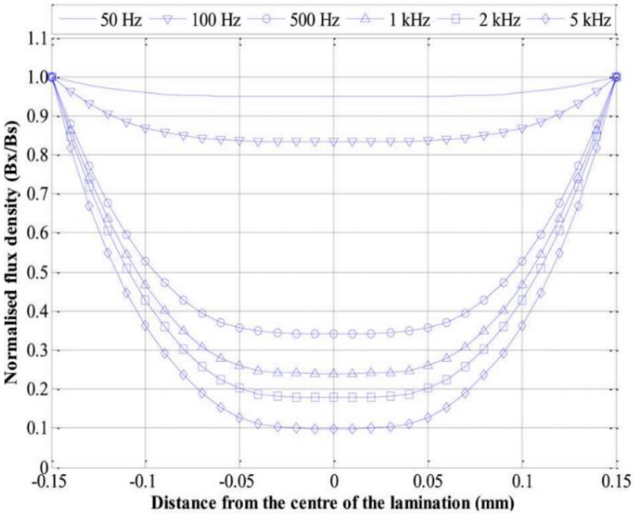

Fig. 3– Normalized magnetic flux density penetration into the magnetic laminationof thickness d=0.3 mm [17]

Moreover, their center and surface waveforms are also displaced [3], [14] Eddy current paths have now a higher resistance, meaning that its value and the correspondent losses are smaller, when compared to uniform field densities scenarios. Naturally, this is not foreseen by the previous expressions, which give excessive values. Several models to calculate eddy current loss in electrical machine laminations for non-uniform field density have been proposed [14]. A common approach for a periodic non-sinusoidal flux density waveform is to consider its Fourier series decomposition. The contribution of each harmonic component is calculated based on its frequency and magnitude, through Steinmetz expression. Frequency is particularly relevant, since it determines the skin effect magnitude of the individual harmonics. However, one must not forget that such an approach is based on the superposition principle. This way, its effectiveness must be always confronted with experimental loss values.

3.1.2. Hysteresis Loss

Depending on the machine geometry and operating conditions (in particular, high frequencies, local saturation and skin effect), the peak flux density may be very different in several parts of the lamination [3]. This causes local hysteresis loops, i.e., minor loops, in addition to the major loop (Fig. 4).

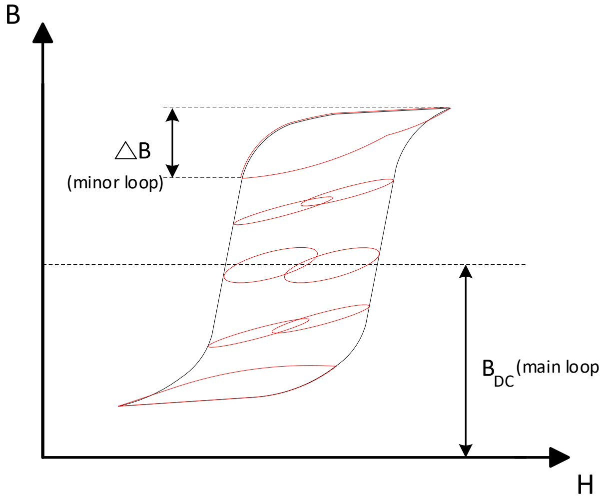

Fig. 4– Hysteresis loops (major in black, minors in red)

As a consequence, several points inside the lamination have different local hysteresis losses [3], [16], which may lead to core hot-spots. It should be noted that a relevant harmonic content in the flux density waveform reflects a significant number of minor loops. Moreover, these additional losses may represent an important proportion of the total hysteresis loss, which highlights the importance of modelling them [18].

A most relevant conclusion in this reference is that minor loop positions inside the main cycle (i.e., the DC flux density value associated to the minor loop) have a significant influence in the hysteresis losses. It should be noted that none of this is considered in the first term of (11).

Based on experimental studies, minor loop hysteresis loss evaluation has been frequently addressed through empirical formulas [3], [4] (in [4] is considered the Fourier series harmonic decomposition). However, one must be aware that the effectiveness of this approach is attached to certain simplifications and/or to specific flux waveforms.

This highlights the fact that for every kind of electrical machine, under specific operation conditions, a particular formula should be addressed. This suggests that a lot of work still has to be done, in order to get accurate methods to estimate hysteresis minor loop losses [3].

3.1.3. Rotational Flux Loss

Rotational flux densities (due to changes in the flux density vector direction, relatively to a given reference frame) may have important contributions for the total core losses in electrical machines.

Taking a Switched Reluctance Machine (SRM) as an example (Fig. 5), such rotational flux density variations are well pronounced around the stator and rotor tooth, due to changes in their relative position.

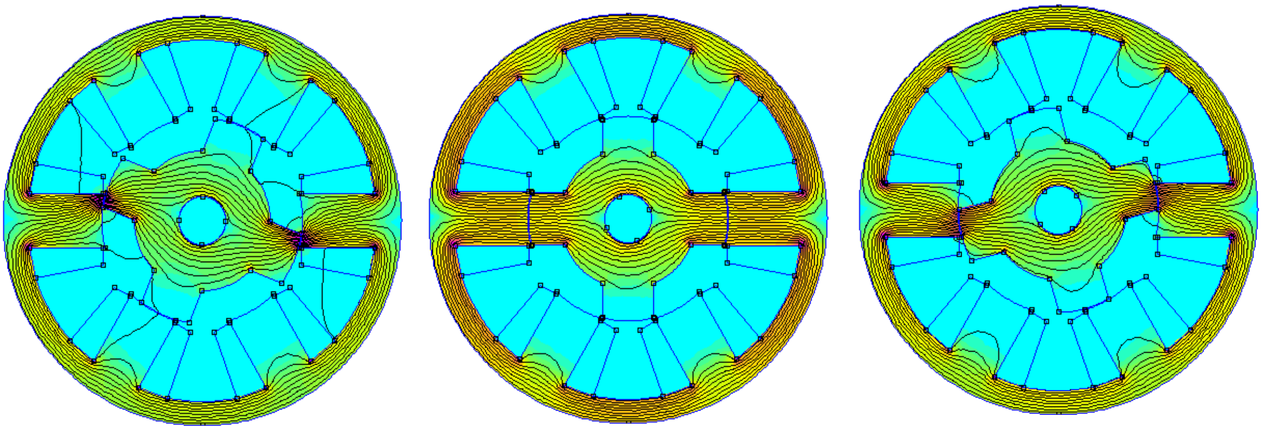

Fig. 5– SRM (6-4 pole) magnetic field distribution, for three rotor positions

Predicting rotational flux losses is much more complex than alternating flux, where the magnetic axis is fixed in space. Moreover, measuring them is quite complex, since precisely controlled rotational flux density waveforms are difficult to induce in test samples [16].

Some models have been proposed for estimating iron loss under rotational conditions but are based on sinusoidal flux densities. Usually, the flux density vector is decoupled into two orthogonal components, for a given machine region. For each component, losses are independently calculated and then added [19].

Once again, this approach relies on the superposition principle. Due to hysteresis high non-linearity, it seems reasonable to question the effectiveness of such approach.

4. Conclusions

Currently, electrical machines (EM) design and control developments are much dependent on simulation models, where FEM has a fundamental role. New losses estimation methods, in particular for core loss, are crucial to develop EM models with higher accuracy.

Traditionally, EM core loss estimation has been supported by empirical models for sinusoidal waveforms. However, this is not suitable for non-sinusoidal flux density machines and conventional machines fed by power converters, since flux density waveforms are no longer sinusoidal. Moreover, complex magnetic phenomena must be addressed, which are not considered in most empirical models.

In the last decades, considerable efforts have been addressing these issues. Nonetheless, further improvements are needed for a precise determination of the flux waveforms and correct calculation of iron loss at non-sinusoidal excitation and non-uniform flux distribution, which is a hard task.

This paper discusses some of the main challenges that must be tackled. These are open research fields, there is still a lot of work to be done.

Final Remark: this paper is based on the published work in [20].

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Sinopse:

Esta obra pretende ser, acima de tudo, uma ferramenta didática de apoio aos alunos de cursos de engenharia eletrotécnica, bem como a técnicos responsáveis pelo projeto, execução e exploração de instalações elétricas.

Pretende ser ainda uma ferramenta prática de estudo e de trabalho, capaz de transmitir conhecimentos técnicos, normativos e regulamentares sobre o projeto, execução e exploração de postos de transformação e seccionamento aos diversos agentes eletrotécnicos, tornando-os capazes de, para cada instalação na qual sejam intervenientes, maximizar a segurança, a fiabilidade e a funcionalidade, assim como reduzir os custos de execução e exploração das instalações.

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DE MÉDIA TENSÃO
POSTOS DE TRANSFORMAÇÃO
E SECCIONAMENTO

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