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Power Loss Analysis in Thermal Design of Permanent Magnet Machines – A Review

R. Wrobel, P. H. Mellor, M. Popescu, D. A. Staton

***Abstract*—This paper reviews recent developments in power loss analysis applicable, but not limited to, the thermal design of permanent magnet (PM) machines. Accurate and computationally efficient loss prediction is an essential element in thermal analysis of electrical machines, and has become an increasingly important part of the machine design process.**

The continuous drive toward 'more electric' technologies has resulted in a need for a more comprehensive and detailed design approach, where various multi-physics and multi-disciplinary effects are accounted for. This 'design for application' methodology relies strongly on the advancements and evolution of the existing theoretical and experimental design techniques to satisfy the evermore-demanding machine design requirements. The thermal behaviour and efficiency of the power conversion are essential performance measures, in the 'design for application' approach.

An overview of the challenges and limitations regarding power loss analysis in the context of thermal design of electrical machines is provided in this paper. All of the major loss components associated with the active parts of a machine assembly are discussed.

***Index Terms*—Power loss analysis, thermal analysis, electrical machines, design methodology, multi-physics analysis.**

I. Introduction

Power loss analysis in the design of electrical machines has been investigated extensively by many authors over the decades of commercial development and use of electrical machines. The existing techniques of power loss derivation stem from the initial, observation-based empirical approach and later more advanced computational electromagnetics. Computational electromagnetics in particular has had a significant impact on our understanding of the complex physical phenomena occurring within a machine assembly during its operation. However, this high-fidelity approach has not completely replaced the existing empirically derived or simplified analytical methods and techniques, and in fact these two approaches coexist, being commonly used by design-development engineers. The main reason for sustained popularity of the simplified and experience based approach is its instantaneity in providing loss estimates and ease of use when compared with the more modern complex and time intensive computational methods. It is important to note however, that the simplified approach is frequently insufficient to accurately predict the power loss over an intended machine-operating regime. Consequently, this method is usually employed in the initial machine sizing or for the coarse machine design, later supplemented with more detailed analysis if necessary.

The high demand for 'more electric' technologies and applications has been continuously moving the boundaries of modern machine design. This includes developments in the machine materials, manufacturing and assembly techniques, and design methods. The design methods in particular have been increasingly converging to an approach, where various multi-physics and multi-disciplinary effects are accounted for simultaneously in a single design process. This drive towards a more comprehensive and detailed 'design for application' technique has its background in various economic and environmental regulations. In that context, shortening the design-development process and consequently reducing its cost is very desirable for the dynamically developing market of the 'more electric' and 'green' technologies and applications.

When reviewing recent literature on the subject of design methodologies of electrical machines, two prominent research themes have emerged. The first one is focused on complete design-optimization methods, where both the electromagnetic, thermal and other design issues are considered simultaneously [1]-[11]. This approach however, is usually simplified with various power loss components being neglected, and therefore provides design solutions that have not been fully informed and consequently might suffer from various unforeseen effects, e.g. excessive power loss and/or heat generation. The second theme looks in detail into various power loss components and effects on an individual basis [12]-[115]. This approach does not provide a complete design-optimization methodology, but offers building blocks

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for the 'design for application' approach. Numerous loss components have been investigated here, resulting in the development of computationally efficient and accurate techniques allowing for a machine's complete operating envelope to be considered at the design stage. Details of these developments are discussed in the following sections of this paper.

II. Power Loss Components in Thermal Analysis of Electrical Machines

The level of detail of the power loss data required in the thermal design of electrical machines depends strongly on the fidelity of the thermal modelling approach used. However, the choice of an appropriate thermal model stems from an initial identification of the dominant power loss mechanisms within the machine assembly. The common approach adopted in thermal design of electrical machines is to account for all key loss sources associated with the active materials of the machine assembly. These electromagnetic loss components are usually supplemented with mechanical loss data, where appropriate.

The power loss is usually averaged over the machine regions or subassemblies, e.g. stator core pack, winding assembly, rotor core pack, permanent magnet array, bearing assembly and others. Such a coarse loss separation is frequently inadequate to yield a detailed and accurate temperature prediction, and a more comprehensive approach is required, in particular when considering high-power-density, compact and cost effective machine designs. This results from numerous multi-physics phenomena, e.g. inhomogeneous power loss distribution across various regions of the machine assembly or complex loss variation during the machine's operating-regime and operating-conditions.

A. Electromagnetic Loss Components

The electromagnetic loss components are associated mainly with the active regions of the machine assembly, as it has been outlined earlier. However, various other machine regions, e.g. the rotor mechanical retaining/sleeving [12]-[16], the elements of the rotor and stator mechanical support [17]-[18] and the heat extraction components [19] also contribute to the overall power loss generation. These loss components, usually have a secondary effect on the overall machine performance and are typically considered at a later stage of the design-development process.

1) Winding Power Loss

The winding power loss is usually the major heat source within the machine assembly. A good understating of the winding loss mechanisms is therefore a prerequisite of the accurate and computationally efficient thermal design-analsyis. The common approach used in thermal analysis of electrical machines is to assume an equivalent dc winding power loss for a single point representing the most demanding operating scenario or alternatively the entire torque-speed envelope, where appropriate. The temperature dependence of the winding power loss for such a modelling approach is usually updated according to the change in the electrical resistivity of the conductor material used in the construction of the winding assembly:

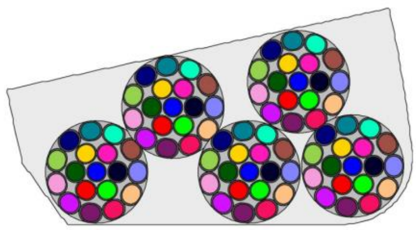
$$\rho = \rho_0\left(1 + \alpha(T - T_0)\right) \quad (1),$$

where, ρ_0 is the electrical resistivity of the conductor material at reference temperature T_0 = 20^{0}C, and α is the temperature coefficient of the electrical resistivity, e.g. $\rho_0 = 1.7\times10^{-8}\Omega$m, $\alpha = 3.93\times10^{-3}$K^{-1}for copper conductors.

This approach however, is appropriate only for machine designs, where the winding power loss from ac effects is negligible, e.g. the machine designs operating at low-speed and/or low-frequency or machine designs where a low-ac-loss winding construction is implemented.

The ac winding loss is associated with the skin and proximity effects and the rotor reaction effect [20]-[35]. The eddy-current related ac effects are resistance-limited meaning that the power loss generated by them reduces with an increase of the electrical resistivity of the winding conductor material [21], [22]. The inductance-limited ac winding effect results from the inductance imbalance between parallel strands of the winding/coil turns and consequently uneven per strand current share [33].

a)



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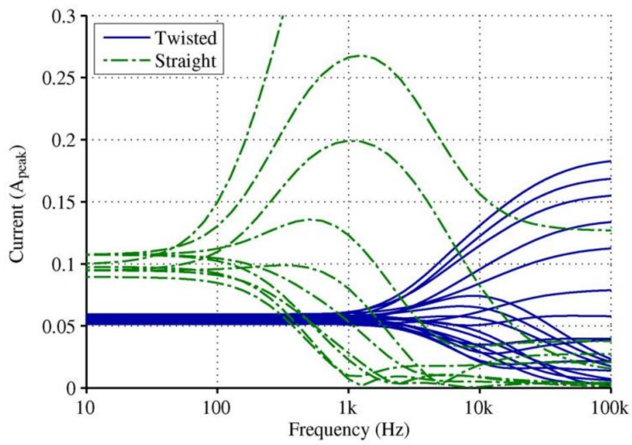

Fig. 1. An example from analysis of the uneven per strand current share [33]; a) multi-stranded winding construction with 18 strands per bundle; b) variation of peak current per strand versus excitation frequency for parallel (straight) and twisted (Litz) bundle construction.

Fig. 1 presents an example from the analysis of the current imbalance for multi-stranded winding constructions [33]. The effect of uneven per strand current share is particularly prominent for the winding arrangements with low number of turns per slot as shown in Fig. 1a. A comparison of per strand peak current for the multi-stranded bundle with parallel (straight) and twisted (Litz) conductor lay, Fig. 1b, demonstrates the effectiveness of the conductor transposition method in mitigating this undesirable winding power loss effect. A coarse conductor's transposition in the end-winding region has also been shown effective for the winding constructions with rectangular profiled conductors [116].
All the winding power loss effects are of particular importance in the context of the evermore popular and demanding high-speed and/or high-frequency machine designs.

A simplified expression for the winding power loss at ac operation includes three main components:

$$P_{ac}(I,f,T) = P_{dc}(I,T) + P_{ac\,effE}(I,f,T) + P_{ac\,effR}(f,T) \quad (2),$$

where P_{dc} is the dc winding power loss, $P_{ac\,effE}$ is the power loss from the ac effects resulting from the winding excitation and $P_{ac\,effR}$ is the winding power loss component generated by rotation of the rotor assembly, e.g. a machine construction with a permanent magnet (PM) rotor. The winding loss components related with the winding excitation depends on the current magnitude, I, and the winding temperature, T, and the excitation frequency, f, in the case of ac operation. The winding loss associated with the rotation of the rotor is assumed here to be independent of the winding excitation. It is important to note that the proposed winding loss separation is usually sufficient for accurate thermal design-analysis. In general however, there are many more factors affecting the winding loss at ac operation, some of which include the higher order PWM excitation effects, the excitation current angle or temperature of the PM array, among others [22], [26].

The temperature dependence of the loss components listed in (2) has significant implications on the accuracy of the thermal analysis of electrical machines. The power loss from dc excitation and ac effects varies with temperature in a different manner. The dc loss component changes with temperature according to (1), whereas thermal variation of the ac loss components is more complex and depends strongly on the severity of the ac effects. In [22], the authors have proposed an approach allowing for relatively simple and computationally efficient winding power loss adjustment with temperature at ac operation:

$$P_{ac}|_{T} = P_{dc}|_{T_0}\left(1+\alpha(T-T_0)\right) + P_{dc}|_{T_0}\frac{\left.\left(\frac{R_{ac}}{R_{dc}}\right)\right|_{T_0} - 1}{\left(1+\alpha(T-T_0)\right)^{\beta}} \quad (3),$$

where R_{ac}/R_{dc} is the ratio of equivalent ac to dc resistance commonly used in analysis of the ac loss effects [22] and β is the temperature coefficient for the ac loss component derived form a curve fit of (3) to the winding ac loss data derived from finite element analysis (FEA) or experiment at two reference temperatures, e.g. 20^0C and 200^0C, which correspond with minimum and maximum winding temperature intended for a particular machine design. The second term in (3) accounts for all the ac effects, outlined earlier, by means of an R_{ac}/R_{dc} ratio. It is important to note that a direct computation of the ac winding loss at a given temperature for consecutive iterations of thermal analysis typically proves to be computationally prohibitive.

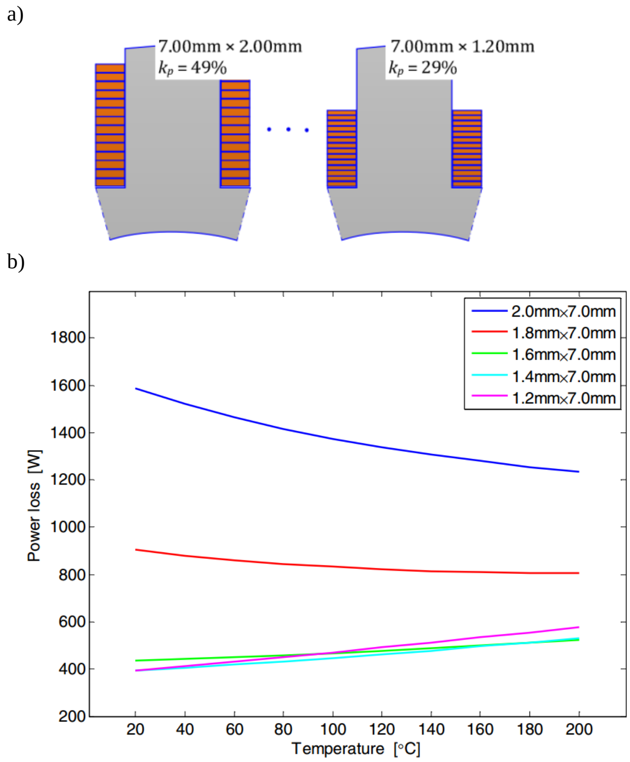

Fig. 2. An example from analysis of the ac winding power loss and its variation with temperature [21]; a) alternative winding constructions, where k_p is the conductor fill factor; b) winding power loss at ac operation versus winding temperature.

An example from the analysis of the ac winding power loss and its variation with temperature is shown in Fig. 2. A number of alternative winding constructions with different conductor height, and consequently different conductor fill factor, k_p, have been considered, Fig. 2b. It has been shown that for the winding designs, where the winding power loss component from the ac effects is dominant, e.g. winding construction with conductor height 2.0mm and 1.8mm, the overall winding loss decreases with temperature. This results from reduced electrical conductivity of the conductor material at elevated temperatures, for which the induced ac loss component is lower, Fig. 2b. In cases where the dc loss component is dominant, e.g. winding construction with conductor height 1.6mm and lower, the overall winding power loss increases with temperature.

The R_{ac}/R_{dc} ratio is derived using FEA, by experiment, or from various analytical formulae [20]-[34]. The analytical approach in particular allows for rapid estimation of the winding loss at ac operation. However, its use is limited to simplified problems and/or specific applications [20], [23], [28], [29], [34].

The next important issue associated with winding power loss at ac operation is the inhomogeneous loss distribution. It has been shown in the literature that the averaged winding loss approach might not yield sufficient resolution in the thermal analysis of electrical machines, where the ac loss effects are expected to be substantial [20], [21], [35]. An approach, where the winding assembly is subdivided into smaller regions with appropriate loss data provides a more accurate winding hot-spot identification and overall winding temperature predictions.

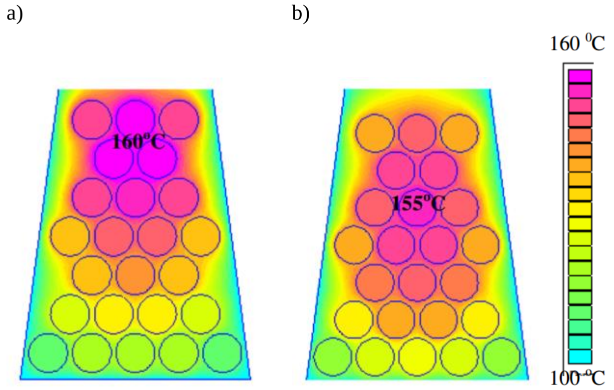

Fig. 3. An example from analysis of the inhomogeneous ac winding power loss distribution [20]; a) winding temperature distribution for the detailed loss model; b) winding temperature distribution for the averaged loss model.

Fig. 3 presents an example from the analysis of the localised ac winding power loss and the influence of accounting for detailed ac winding loss data on the winding temperature predictions. The detailed loss data, i.e. winding loss per conductor or winding layer provides more accurate temperature estimates, Fig. 3a, than more commonly used approaches, where the averaged ac winding loss per slot or winding body is considered only, Fig. 3b. The theoretical findings suggest that both the winding's absolute temperature and hot-spot location are affected by the level of detail of the ac winding loss data used to inform the thermal analysis.

These issues have been discussed predominantly in the context of the winding active length. The end-winding region has also had some attention particularly for the concentrated winding topologies, with a general conclusion being that the end-winding loss contribution from the ac effects is less prominent than that within the winding active length [20], [21], [24], [32]. An assumption of the dc loss end-winding contribution only is often a valid approximation if no means of evaluating the end-winding ac effects are available. However, further research is required to provide more comprehensive insight into the end-winding ac effects.

2) *Core Power Loss*

The core power loss is usually associated with both the stator and rotor core pack assemblies. The contribution of the core loss to the overall loss generated within the machine body depends strongly on the machine topology and the machine operating regime. The commonly used computational approach of deriving the core loss in design-analysis of electrical machines is based on the Steinmez and Bertotti methods or more comprehensive variations of these techniques [36]. Nowadays, these are usually implemented within the modern FE machine design-analysis software packages, where the overall core loss predictions are made for the individual elements of the FE discretisation mesh and averaged over a region or subassembly of interest.

A number of power loss coefficients informing the techniques are attributed with the core loss mechanisms, and are commonly derived from the specific loss data provided by the core-material manufacturer. In general, the core loss coefficients account for the hysteresis loss, Joule's (eddy-current) loss and the excess (anomalous) loss [36]-[53]. However, it has been reported in the literature that processes used in manufacture of the laminated core packs have a significant impact on the core loss generated, and the core loss coefficients derived from tests on representative material or core pack samples provide more accurate, and representative loss predictions [36]-[53]. Also, it has been shown that elevated temperature of the laminated core material has a moderate impact on the material magnetic properties and power loss generated [52], [53], and is usually neglected in thermal design-analysis of electrical machines.

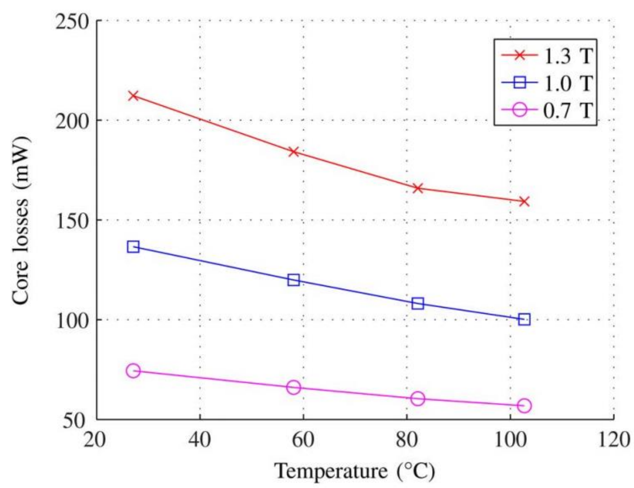

Fig. 4. An example from analysis of the core loss accounting for the core temperature [52]; (NiFe, 0.2mm laminated core pack); core power loss versus temperature.

An example from the analysis of the core loss variation with temperature is shown in Fig. 4. The core loss of a slotless laminated stator core pack (NiFe, 0.1mm and 0.2mm) has been investigated by employing an experimental approach [52]. The results suggest reduction of the core loss with increase of the core temperature. The rate of core loss reduction depends on the core material considered. It is important to note that in applications, where the core loss is the dominant loss component, accounting for thermal dependence of the core loss might be necessary for accurate thermal design-analysis.

The FE core loss prediction provides good accuracy if the analysis is informed with adequate loss coefficients. Also, the FE based approach assures a moderate solving time if a reduced number of machine operating points is considered. However, as the 'design for application' requires the machine performance to be evaluated over a complete torque-speed envelope or operating cycle, the direct use of the FE core loss prediction for the individual operating points is frequently computationally prohibitive.

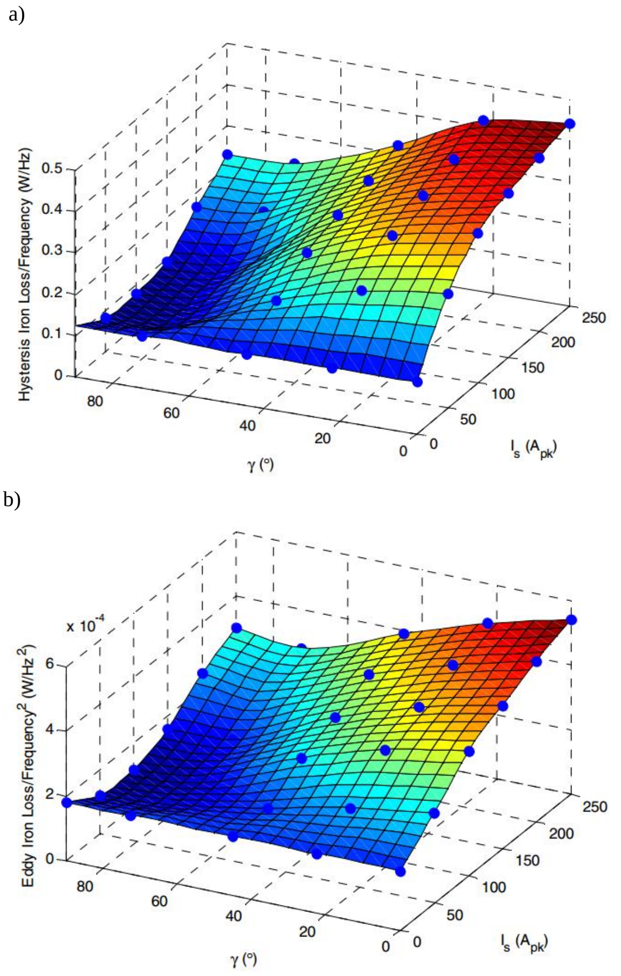

Fig. 5. An example of the coarse and interpolated iron loss functions used to derive the core loss for a given torque-speed envelope and/or operating cycle [56]; a) hysteresis core loss coefficient; b) eddy current loss coefficient versus current angle and current magnitude.

There are two recent developments reported in the literature allowing for the core loss to be derived in a computationally efficient manner [54]-[57]. Both the techniques stem from the concept of a reduced number of FEAs to fully inform the core loss data for the machine's entire torque-speed envelope. The first method is based on a coarse FE mapping of the core loss for various excitation and operating modes. The complete core loss is then derived from interpolation between coarse loss data points according to (4).

$$P_{Fe} = f C_h(I_s, \gamma) + f^2 C_e(I_s, \gamma) \quad (4),$$

where I_s is the peak phase current, γ is the current angle, C_h and C_e are the hysteresis and eddy-current core loss functions, which are used to preform surface interpolation between coarsely mapped loss data.

This approach allows for both the stator and rotor core loss for any machine topology to be analysed.

Fig. 5 presents an example of the loss functions (4) from analysis of an interior permanent magnet (IPM) traction machine. The coarse data points for the loss functions (see the points indicated in blue) have been superimposed with the interpolated surfaces for the loss functions, Fig. 5.

The second method makes use of the functional core loss representation, where the core loss is defined by a set of functions accounting for the maximum torque per Ampere and field weakened operation. The technique is rooted in the direct-quadrature (*d*-*q*) axes model of ac PM machines and the modified Steinmez/Bertotti approach of predicting the core loss [54]:

$$g_1(V_m) = \frac{a_h}{\lambda} V_m + \frac{a_J}{\lambda^2} V_m^2 + \frac{a_{ex}}{\lambda^{1.5}} V_m^2 \quad (5),$$

$$g_2(V_d^*) = \frac{b_h}{\lambda} V_d^* + \frac{b_J}{\lambda^2} V_d^{*2} + \frac{b_{ex}}{\lambda^{1.5}} V_d^{*1.5} \quad (6).$$

Where V_m and V_d^* are the equivalent magnetising and demagnetising voltages derived from d-q axes diagram:

$$\lambda = \frac{E_{phrms}}{f}, I_q = \frac{T}{k_T}, V_d^* = \lambda f \frac{I_d}{I_{sc}}$$
$$V_m = \lambda f \sqrt{\left(1 - \frac{I_d}{I_{sc}}\right)^2 + \left(\frac{I_q}{I_{sc}}\right)^2} \quad (7).$$

Here: E_{phrms} is the phase rms open-circuit voltage, f is the operating frequency, T is the torque, I_d and I_q are the magnitudes of the demagnetizing direct axis and the quadrature axis components of the stator phase current, k_T is the motor torque constant; I_{sc} is the short circuit current calculated from FEA. The coefficients a_h, a_J, a_{ex} and b_h, b_J, b_{ex} for the hysteresis, Joule eddy-current, and excess losses are found from curve fitting (5) and (6) to the FE results across the operating frequency range for the open- and short-circuit operation respectively. At a given steady-state operating point, the total stator core loss can be estimated from the superposition of the two loss functions given in (5) and (6). This technique requires only two FEAs to inform the core loss data over the entire torque-speed envelope. However, its applicability is limited to ac PM machines, where the rotor core loss is negligible.

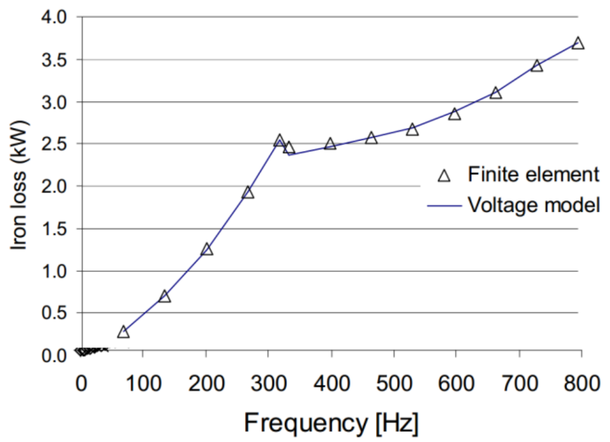

Fig. 6. An example from the core loss predictions using the direct FEAs and proposed voltage model approach [54]; core loss versus rotational speed for a given torque-speed envelope.

Fig. 6 presents an example from the analysis of the stator core loss for a PM traction machine over the entire torque-speed envelope [54]. The proposed voltage model shows good correlation with results from direct FEAs.

3) *Permanent Magnet Power Loss*

Sintered rare-earth permanent magnet (PM) materials are widely used in the construction of electric machines enabling high-energy-density and compact machine designs. However, these PM materials suffer from relatively high electrical conductivity (low electrical resistivity) resulting in the PM loss to be a non-negligible design factor. Accounting for the PM loss in thermal design-analysis of electrical machines is therefore essential, as excessive rotor temperature may result in premature machine failure. Also, elevated rotor temperature leads to a reduction in the torque output capability and in some severe cases irreversible demagnetisation of the rotor PM array. Since heat is not easily dissipated from the rotating PM assembly either the magnet loss has to be kept at a manageable level or enhanced means of rotor cooling is required. This is exacerbated by the difficulty of predicting the rotor temperature, as the rotary assembly does not allow for simple and reliable temperature monitoring and protection.

There is a wide variety of analytical and numerical techniques for PM loss prediction [58]-[89]. The analytical techniques are based on simplified assumptions regarding the magnetic field distribution within the machine assembly, and their use is usually limited to the selected machine topologies and operating regimes. Moreover, the existing analytical methods are also limited in terms of the PM loss mechanism which they account for, i.e. the slotting effect [61]-[67], or the armature reaction [68]-[78], [81]-[83] are considered only. These PM loss components are attributed mainly to the eddy-currents effects (Joule losses). The hysteresis loss effects in the PM material have been found to be negligible [89].

The numerical approach in the PM loss analysis makes use of the time-step or frequency domain FEA, and is commonly used to calculate the induced eddy-currents in the PM segments from which corresponding Joule losses are determined. Two-dimensional (2D) FEA is used predominantly in the design-analysis of radial-flux machines. For other less common machine topologies, e.g. axial-flux and transverse-flux, and machines with the segmented PM array constructions, three-dimensional (3D) FEA is usually required. It is important to note that the direct FE PM loss derivation for a large number of machine operating points is unfeasible.

There has also been some research into hybrid techniques combining a simplified static FEA with analytical formulae to estimate the magnitude of the induced eddy-currents loss [31]. The hybrid approach benefits from both methods providing accurate PM loss prediction in a timely manner. However, a degree of proficiency in using FEA is required to fully gain from the hybrid approach.

Recently, an alternative approach accounting for all the major PM loss mechanisms and assuring low-solving time has been proposed [87]. The method uses a limited number of FEAs to determine the parameters of a functional representation of the PM loss variation with speed (frequency) and stator current. The polynomial form of the loss function has been established based on initial series of exploratory FEAs. The initial work has shown that the proposed approach provides an accurate mapping of the PM loss across the full working envelope including the field weekend operation.

$$P_{PM} = \left(aI_q^2 + bI_d^2 + cI_d + d\right)\left(\frac{n}{n_w}\right)^2 \qquad (7).$$

At this stage of the research the technique has been demonstrated to be applicable for the machine topologies with surface mounted PM array construction. In (7), a, b, c and d is a set of parameters derived from initial FEAs including the open-circuit operation, the rated current with I_q only operation, the rated current with I_d only and 10% I_d operation. The n_w is the reference rotational speed at which all the parameters are derived [87].

Fig. 7 shows and example from the analysis of the PM loss for the entire torque-speed envelope accounting for both the constant torque (maximum torque per Ampere operation) and constant power (field weakened operation) [87]. The PM loss predictions from the proposed PM loss mapping approach (7) show good correlation with results from the direct FEAs.

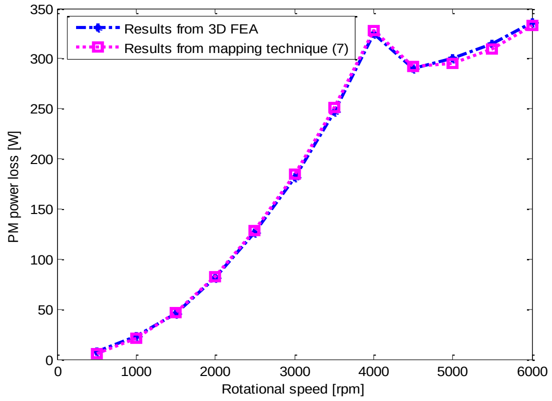

Fig. 7. An example from analysis of the PM loss comparing results from the direct 3D FEAs and proposed loss mapping technique [87]; PM power loss versus rotational speed for a given torque-speed envelope.

It is important noting that all the techniques for the PM loss derivation outlined earlier are based on several simplifying assumptions regarding physical properties of the PM materials. In general, the electrical resistivity of sintered rare-earth PM materials is anisotropic. However, isotropic PM material properties are commonly used in the PM loss analysis. The temperature variation of the PM electrical resistivity is also an important factor, which is frequently overlooked in the PM loss derivation. A linear temperature dependence for the sintered rare-earth PM materials has been shown to be an adequate approximation [88].

B. Mechanical Loss Components

The mechanical loss components have not been widely discussed in the literature in the context of thermal design-analysis of electrical machines. Frequently, these loss components are neglected or some experience based assumptions or approximations regarding their contribution to the overall loss are made. Such an approach stems from the complexity of these loss mechanisms and absence of reliable and computationally efficient techniques for the mechanical loss derivation. A common approach to provide an insight into the mechanical loss is based on hardware tests.

1) Bearing Loss

Bearing loss has received some attention in the context of testing techniques and related life span prediction [95]-[99]. There are various types of bearings used in the construction of electrical machines. These include the roll bearings, magnetic bearings, air bearings and others [95], [96]. In this review, the most commonly used in electrical machines, the roll bearings are discussed only. Existing methods of predicting the bearing loss are based on empirical formulae and do not account for the specifics of the applications in which they were used [95]-[99], [112]. In particular, design of the mechanical assembly accommodating bearings and/or operating conditions, e.g. elevated temperature have a significant impact on bearing performance and generated loss. These effects are difficult to account for at the design stage and tests on machine subassemblies might be required prior to the machine final assembly [96], [97], [127]. A common approach adopted in the thermal design-analysis of electrical machines is to assume the manufacturer provided bearing loss data at the bearings' nominal operating conditions [115].

2) Windage/Drag Loss

The mechanical loss components associated with the aerodynamic effects are difficult to analyse in a timely and generic manner. The existing research in the field is limited to selected aspects of these effects, which are usually considered at the later stages of the design process if found to be significant. The majority of work in the field is devoted to more demanding machine designs with forced air- or liquid- cooling of the rotor or rotor/stator assembly and/or high-speed applications [90]-[94], [100]-[105], [113], [114]. The importance of understanding the rotor windage/drag and associated heat transfer mechanisms has been acknowledged and investigated for various machine designs [90]-[94], [100]-[110], [113], [114].

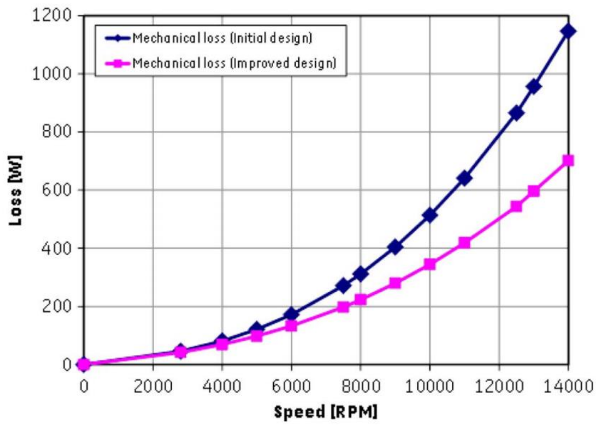

Fig. 8. An example from analysis of the mechanical loss accounting for both the bearing and windage loss components [17]; mechanical loss versus rotational speed.

Fig. 8 presents an example of measured mechanical loss from development of a low-cost high-performance traction IPM motor with continuous power output of 30kW and maximum rotational speed of 14000rpm [17]. The measured data from consecutive development iterations suggests considerable mechanical power loss contribution for the initial mechanical design of the machine and significant loss reduction for the later improved design. It has been shown that the mechanical loss can have a significant impact on the overall machine efficiency and careful considerations must be taken when designing the machine's mechanical assembly accommodating the bearing set and any features providing air/fluid flow within the machine's body.

The existing analytical approximations applicable in the design of electrical machines are based on accumulated experience and/or empirically adjusted formulae [106]:

$$P_{windage} = \pi C_d \rho R^4 \omega^3 L \quad (8),$$

An example here is the analytical solution for the windage loss of a smooth cylinder rotating within a concentric cylinder (8). Where: C_d is the skin friction coefficient, ρ is the air density, R is the rotor radius, ω is the angular speed and L is the active length of the stator-rotor assembly.

These simplified techniques are limited to specific machine topologies and operating conditions. A more widely applicable approach makes use of computational fluid dynamics (CFD) modelling techniques [90]-[100], [103].

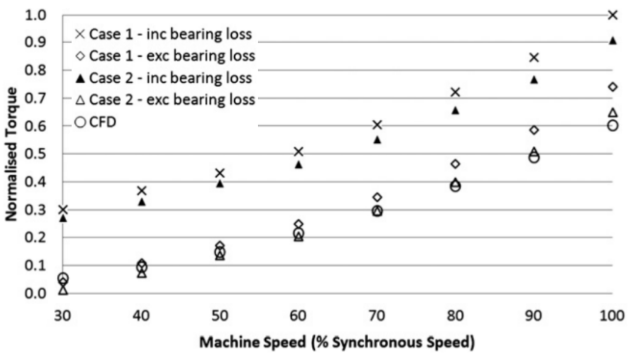

Fig. 9. An example from the CFD analysis of the windage loss [103]; normalised torque versus percentage of machine's synchronous speed.

An example from the CFD analysis of a synchronous salient pole wound-field generator with forced-air cooling is presented in Fig. 9. The machine's windage loss/torque, Fig. 9, has been investigated by the use of an experimental setup and CFD analysis. The experimental and theoretical data shows close agreement. The complete research outcomes presented in [103] provide a detailed insight into both the heat transfer and mechanical loss effects allowing for further improvements for the heat extraction, for the existing machine design.

III. Conclusions And Observations

There is a wide variety of techniques available for power loss analysis applicable to the design of electrical machines. High-fidelity computational methods like FEM or CFD provide a comprehensive and detailed insight into various loss mechanisms, but are computationally and time intensive. The high model-setup and model-solving time prevents these methods from direct use in multi-physics and multi-disciplinary design-analysis. The existing computationally efficient alternatives are based on numerous analytical solutions, which are limited to a particular class of problems, i.e. selected machine topologies, operating conditions and physical phenomena accounted for.

Recent developments in the field have resulted in several methods, which have been derived from exploratory theoretical analyses using high-fidelity techniques or hardware experiments. These new techniques provide accurate and computationally efficient power loss predictions. It is important to note that the advancements and evolution of techniques for the loss derivation have been reported mainly for the electromagnetic loss components. The mechanical losses have not had much attention in the context of the design-analysis of electrical machines. However, these effects become increasingly important when considering the evermore popular high-speed high-power-density and compact machine designs.

Also, it is important to mention that the experimental work into power loss mechanisms is a vital part of the research on loss derivation techniques. Findings from hardware tests are the driving factor in the development of more accurate computational methods for loss prediction. Despite the continuous research in the field and recent findings, further work is required to provide more definitive solutions.

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