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Review

Permanent-Magnet Eddy-Current Losses: A Global Revision of Calculation and Analysis

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Abstract: Eddy-current analysis is an important research field. This phenomenon occurs in multiple areas and has several applications: electromagnetic braking, repulsive effects, levitation, etc. Thereby, this paper is limited to eddy-current study in rotating electrical machines. In the design process, if the permanent-magnet (PM) loss calculation is very important, the overheating due to eddy-currents must be taken into account. The content of this paper includes sources, calculation methods, reduction techniques, and thermal analysis of PM eddy-current losses. This review aims to act as a guide for the reader to learn about the different aspects and points to consider in studying the eddy-current.

Keywords: analytical method; eddy-current; finite-element analysis; loss reduction; permanent-magnet losses; thermal analysis

1. Introduction

1.1. Context of this Paper

Eddy-currents are induced currents that originate, for example, in a moving conductor in a constant magnetic field or in a stationary conducting material subjected to a time-dependent magnetic field. According to [1], the term "eddy" originates from the fact that these induced currents create magnetic field vortices inside the conductors. Eddy-currents are used and exploited in many applications such as:

- Induction furnace: The rapid variation in the magnetic field generates very large eddy-currents, and the heat produced is sufficient to melt a metal;
- Electric brakes: The brakes expose the wheels (metal) to a magnetic field, which generates eddy-currents. The magnetic interaction between the applied field and the eddy-currents acts to slow the wheels down.
- Detection of flaws and cracks in materials.

In spite of eddy-currents' advantages, they can be undesirable. This is due to the fact that they generate thermal heat, which causes losses. This is very problematic in electrical machines.

A permanent-magnet synchronous machine (PMSM) is one of the most studied electrical machines. They are very attractive for different applications, thanks to their high efficiency, good torque density, lower maintenance costs, and easy manufacturing [2,3]. These interests have led designers to increase the frequency of electromechanical conversion, thus leading to a more detailed consideration of the various difficulties, PM loss being one of them [4,5]. Indeed, temperature issues can arise in high-speed applications due to eddy-currents [6]. In the ideal case, where the air-gap field contains only synchronized space harmonics (i.e., rotating in synchrony with the rotor), the magnetic eddy-current losses can be neglected (no losses). In real situations, the magnetic flux density in the air-gap has spatio-temporal variation: therefore, unsynchronized space harmonics are generated. For this reason, significant losses by eddy-currents are induced in the rotor [7]. In the PMSM design process, eddy-current losses' calculation and reduction have the primary objective to improve their performance. Several researchers have developed analytical and numerical models in order to better estimate these losses. In addition, techniques to reduce losses have been realized such as PM segmentation.

1.2. Objective of This Paper

The purpose of this work is to give a global revision of the calculation and analysis of PM eddy-current losses. Section 2 identifies the PM losses sources, then it explains their global causes in electrical machines. In Section 3, the methods of PM loss calculation are summarized, including 2D/3D analytical models, finite element analysis (FEA) methods, and hybrid models. PM loss reduction is analyzed in Section 4 in several categories, viz., PM segmentation, rotor shape, material type effect, and spatial filter. In Section 5, the methods of PM loss measurement are explained. Finally, Section 6 treats the thermal behavior of electrical machines generated by eddy-currents.

2. Sources of PM Losses

Before listing the methods of PM eddy-current losses' calculation, we will identify the different sources of these losses. Four major sources may be listed:

2.1. Slotting Effect

The harmonic content in the flux of PMSM due to the slotting of the stator was established in [8]. Eddy-currents in a solid rotor of a PMSM due to stator teeth were calculated in [9], by considering the magnetic saturation. It was shown that teeth harmonics decreased with saturation, and so, the losses were lower.

In [10], the no-load tooth-ripple due to the distortion of the fundamental flux density wave by the stator slotting was described. The permeance modulation that resulted from the teeth, in a tubular PM motor, was a major cause of the loss [11]. The calculation in the conducting regions of a rotor of PMSMs was presented in [12]. The determination of the PM eddy-current losses due to the slotting effect was investigated in [13–16] and in fractional-slot surface-mounted PMSMs in [17–19].

2.2. Winding Distribution

Space harmonics of the magnetomotive force (MMF) induce losses in the PM of electrical machines, due to the flux variation. In [10], the "on-load: term was used to denote the total harmonics losses occurring in the load condition. The non-uniform rotation of the armature MMFs induce eddy-current losses [20], referred to as commutation losses in [21,22]. The fundamental and lower order MMF harmonics can give rise to significant rotor eddy-currents [23,24]. According to [25], losses are almost double in concentric alternate teeth winding (single-layer winding) compared to concentric all teeth winding (two-layer winding). Eddy-currents are related to the asynchronous components of the MMF spatial harmonics [26], and the low order of unsynchronized spatial harmonics induces a large amount of eddy-current losses [27].

Based on the contents of space harmonics in the air-gap MMF distribution, a combination of slots and poles of a PMSM was done by [28–31] to get a topology with minimal PM losses. Combinations with a large number of poles and a small number of slots are characterized by large rotor losses [32]. For the same purpose, the impact of the number of phases is quantified to design lower eddy-current PM machines [33], and several windings were compared in [34]. Windings with different turns per coil side, in fractional-slot PMSMs, lead to reducing and/or canceling some space harmonics, resulting in lower rotor losses by the armature reaction field [35]. In [36,37], the interaction between the wavelengths of the space harmonics and PM pole dimension was studied. The analysis of MMF the harmonics of machines with a specific pole/slot ratio (ratio of 2/3) shows that second- and fourth-order space harmonics are dominant, which induces significant PM eddy-current losses [38].

2.3. Supply and Control

The stator currents cause asynchronous components in the air-gap field and induce rotor losses in electrical machines [39–41]. Control of PMSMS by pulse width modulation (PWM) can lead to PM losses due to the high frequency of stator magnetic field variations [42–48]. The eddy-current losses are mainly produced by the carrier harmonics of the PWM inverter [49]. A single-phase PM brushless DC motor supplied by a 180° square current waveform presents more eddy-current losses than when it is supplied with only the fundamental component of current [50]. In [51], by considering the carrier harmonics of PMW inverters, it was shown that the PM eddy-current losses in the concentrated winding motor were larger than the distributed winding motor. By comparing eddy-current losses per unit induced by PWM with sine wave supply, the authors of [52–54] deduced that PM losses were higher in the case of PWM supply. This was due to more harmonics content compared to the sine waveform. To calculate power loss in PMSMs in [55], two winding and rectifier topologies were considered (three-phase bridge rectifier and two three-phase bridges rectifiers connected in series). In [56], the harmonics caused by the PWM were incorporated into a series of steps to calculate the stator MMF. The eddy-current losses caused by the fundamental time harmonic of the winding have been calculated [57].

2.4. PM Hysteresis Losses

The behavior of PM hysteresis losses was experimentally investigated in [58]. The results showed that the hysteresis losses were larger than eddy-current losses when the AC field due to a slot ripple was of the order of several hundred hertz. The authors of [59] claimed that hysteresis losses in PM materials had no significant influence on rotating electrical machines' design. This conclusion was based on measurement results because the PM materials operated in the second quadrant of the $B(H)$ curve and mostly without crossing the J-axis.

A comparison study based on the hysteresis loss of different PMs (i.e., ferrite, samarium-cobalt, and neodymium PMs) has been established [60]. Rare-earth PMs exhibit less hysteresis losses than ferrite PMs, and the comparison, between samarium-cobalt and neodymium PMs, shows that samarium-cobalt PMs, at small field strength variation, have larger hysteresis losses. The investigation of the hysteresis behavior of the ferrite PMs in the second and first quadrants of the $B(H)$ curve confirms that hysteresis losses have a minor role in electrical machines' design [61].

3. Calculation of PM Losses

3.1. Two-Dimensional Analytical Models

Early in the 1970s, analytical models for calculating eddy-currents were developed. The variational methods were applied for thing purpose in thin conducting plates [62], and the surface impedance has been used to predict eddy-current fields in conductors [63]. To estimate PM eddy-current losses and retaining ring losses of a PMSM, the authors of [8] proposed a linear model, by taking as infinity the magnetic permeability of the rotor core and stator iron. The calculation was possible by representing PM by resistances in the equivalent circuits [64], where end effects were neglected, where the field was considered as one-dimensional, and by using the magnetic equivalent circuit (MEC) [65].

To predict eddy-current losses, a mathematical model based on a 2D electromagnetic field analysis in polar coordinates was developed in [41,43,44], while the stator and rotor cores were assumed to be infinitely permeable in [23,66], and an extended model considering time harmonics in the stator MMF distribution was proposed in [25]. To take into account the reaction field, an improved analytical model was proposed in [24,67]. A completely analytical solution of the losses generated by eddy-currents, in a cylindrical PM rotating inside a hollow conducting cylinder, was proposed by [68]. Based on the magneto-static flux density distribution in the air-gap, it is possible to calculate the eddy-current losses [69]. The excitation field may be replaced by a current sheet for a slotless structure [70]. To consider the slotting, the PM field is calculated in the slotless structure and then adapted to the structure with slots. The conformal mapping method allows the modulation function [14]. To take into account the 3D flow of eddy-current, a correction factor for the 2D analytical model was proposed in [71]:

$$F_{cn}(w_n) = 1 + \frac{2/(aL)}{\coth(\lambda L/2) + (a/\gamma)\coth(\lambda L/2) - 2a/Ly^2} \quad (1)$$

where L is the axial length of the PMs. a, λ, and γ for the n^{th} harmonic are given by:

$$a = np_s/R_s; \lambda = \sqrt{j\omega_n\mu_0\mu_r\sigma}; \gamma = \sqrt{a^2 + \frac{\lambda}{g\mu_i}}$$

where μ_r and σ are respectively the relative permeability of the coil and magnets. ω_n is the angular frequency of the n^{th} harmonic.

A nonlinear MEC applied to an interior PMSM was exposed in [72]; the method takes into account magnetic saturation and PM eddy-currents. In [73], an expanded analytical loss model was presented where the PM may be replaced by a retaining sleeve to study the behavior of the new rotor configuration. An analytical approach for the simultaneous calculation of stator and no-load field was performed. The finite PM dimensions was considered by introducing a correction factor for endless dimensions [15]. At low frequency, the skin effect did not influence the results of PM losses. Nevertheless, at higher frequencies, the flux density in the PM was non-homogenous, and other formulas must be applied [74]. A method for calculating eddy-current loss using MEC (or reluctance network analysis) was presented in [75], associated with an electric network model for a surface-mounted PMSM [76], and applied to an axial-flux PMSM [54,77].

The interaction between eddy-current harmonics having the same frequency, but different spatial order may not be neglected, otherwise the PM losses can be under- or over-estimated [78]. The authors of [79] proposed a simple analytic model based on Carter's and surface impedance theories to calculate the PM losses. By considering the finite permeability of the stator and rotor cores and accurate permeability of the PM, eddy-current losses were analytically calculated for a slotless PMSMs where the eddy-current reaction field was neglected and the induced eddy-currents were resistance limited [80]. The eddy-current reaction field in the slot was considered by solving Helmholtz's equation [81]. To take the stator teeth geometry into account regardless of the magnetic field of the slotless structure, the relative permeance function may be used [82]. A 2D subdomain method in polar coordinates was proposed in [83]. The method was applied for a slotless PMSM with surface-inset magnets by considering the eddy-current reaction field. In [84], an approach in Cartesian coordinates based on a harmonic method was used to calculate PM losses. The MMF was decomposed into Fourier series where the period was the PM width. The Cartesian coordinates were chosen in [85] for the PM loss calculation by using a simplified rectangular geometry for the analytical model.

An exact subdomain model was presented in [86], and it was applied to a slotted PMSM, considering that the diffusion effect and eddy-currents were not assumed resistance limited. In [87], an analytical method taking into account the effect of the reaction field was presented. To consider the diffusion phenomenon and the finite length of a magnet along the x-direction, the work in [16] solved a Fredholm integral equation for the computation of the no-load PM losses.

3.2. Three-Dimensional Analytical Models

PM loss calculation based on a quasi-3D analytical model was presented in [88]. The method was performed in Cartesian coordinates, which considered the reaction eddy-current. A 3D analytical model that took into account the end-effect was proposed in [89]. The reaction field and the end-effect of an interior PMSMs was well considered by [90]. The model was based on the Fourier transform of the armature reaction, the armature, and the PM slotting effect. The authors of [91] proposed an analytical model based on the generalized image theory. The model was established in 3D rectangular coordinates; the slotting effect was neglected; and the cores were assumed infinitely permeable. The method was applied for the PMs with rectangular shapes. The magnetic field distribution may be calculated from analytical or FEA, and then, a 3D Fourier series was performed without including the eddy-current reaction field, so the accuracy of the results was only visible at low frequency. A modified generalized image theory was proposed in [92] to predict 3D high frequency eddy-current losses for surface-mounted PMSMs and applied to an eight-pole/18-slot interior PMSM [93,94]. A 3D subdomain model was used to englobe the slotting effect [95,96], where the method of variable separation was used to get the 3D eddy-currents in PMs. The work in [18] used an analytical method in polar coordinates for any pole-slot combinations of a surface-mounted PMSM under any conditions of load.

3.3. Finite-Elements Analysis

FEA was used to study the eddy-currents due to slotting effect in PMSMs [9] and loss calculation in both magnetic and non-magnetic sleeves [97]. Eddy-current losses were investigated on a tubular PM motor by using FEA [11]. Often, magnets are divided to decrease the eddy-current losses. However, the 3D FEA calculation of eddy-current in PM with slits is more difficult, and the computer resources (computation time) increase. The $A - \phi$ method with double nodes at slits was used to overcome this problem and increase the accuracy of calculation [98,99]. The side-insulation between adjacent PMs causes a discontinuity of the eddy-current distribution. This case was modeled by 2D FEA for surface-mounted PMSM [100]. PM eddy-current loss calculation by considering the end-effect and by using 3D FEA takes vast amounts of time. Yamazaki et al. [101] proposed a method where firstly a 2D nonlinear time-domain analysis was applied with the PWM voltage waveform. Next, the 3D frequency domain analysis was used for each remarkable harmonic. The total PM eddy-current losses were calculated by summing the results of the two steps, as shown in Figure 1.

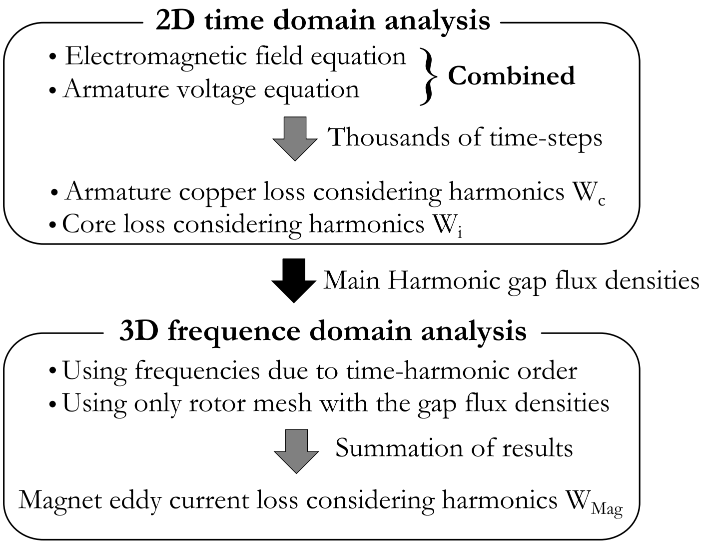

Figure 1. Outline of the proposed method [101].

Flux-switching PMSMs are characterized by a significant flux leakage. The latter induce significant eddy-currents that were investigated by FEA [102]. To take into account a motor's commutations ad time and space harmonics, FEA for surface-mounted PMSMs was used in [103]. Three different methods were explained in [104] to calculate eddy-current losses in PMSMs with concentrated windings:

1. FE magneto-static method with analytical post-processing:
   Loss was calculated analytically from the numerically-obtained flux density values. The inducing effect was neglected, as well as the eddy-current reaction field.
2. FE magneto-static method:
   FEA software was used to calculate directly the PMs losses without the need for additional post-processing. The reaction field was not considered.
3. FE magneto-dynamic method:
   The time-stepping method solved Maxwell's equation for a moving rotor and for any current waveform. It took into account the eddy-current reaction field, but it was very time consuming.

In [105], a combined 2D/3D method considering the harmonics and the magnetic saturation of the rotor was proposed to calculate eddy-current losses. The 2D time-domain analysis allowed the calculation of the flux density distribution. From this calculation, the differential permeability was determinate, which allowed the 3D linear frequency-domain analyses at each remarkable harmonic. The total rotor loss of the interior PMSM was obtained by the summation of the harmonic losses. According to the authors of this method, the calculation time of this method was less than 1/100 of the conventional 3D time-domain FEA.

End-effects are ignored in 2D FEA, causing large error in the results of eddy-current loss compared to 3D FEA. An adjustment was proposed in [106], where losses calculated trough 2D FEA were corrected by the factor F:

$$F = \frac{3}{4}\frac{L^2}{w^2 + L^2} \tag{2}$$

Fir the same purpose, to compensate the end-effect neglected in 2D FEA, another correction factor was proposed in [107]:

$$C_3 = \left(\frac{l_c}{l_c + \tau_m}\right)^2 \tag{3}$$

where l_c and τ_m are respectively the length and pitch of the magnet.

Eddy-current losses were analyzed for axial-flux PMSMs with concentrated windings using 3D FEA [108,109] and for two cases, when PMs were insulated or non-insulated [110]. To calculate eddy-current losses in interior PMSMs by FEA with less time calculation, a coupled 2D and 3D method was presented in [111]. The 3D eddy-current analysis only of the PM was calculated from the flux distribution obtained by 2D FEA. An extended coupled method applied to surface-mounted PMSM was presented in [112], where the uniform air-gap was replaced by a variable equivalent air-gap to consider the space variation of the air-gap width. The authors of [113,114] proposed a multilayer-2D-2D coupled model to estimate eddy-current losses in PMs of axial-flux PMSMs. Firstly, static 2D FEA for different rotor positions was used to calculate the 1D flux density data. The build up of this latter provided a 2D air-gap flux density distribution. These data were transformed into the frequency-domain and finally were used to calculate the eddy-current in PM by 2D time harmonic FEA.

In [115], eddy-current losses were calculated by a 2D magnetic vector potential solver ($2D - A - \phi - Solver$), which was coupled to a modified axial $2D - T - \Omega - Solver$ to include the influence of the PM axial length. The influence of the pole coverage (i.e., ratio of magnet width and pole pitch) on PM power losses was investigated for both cylindrical and linear arrangement [116]. It was shown that the influence of the pole coverage on power losses was visible only at lower harmonic waves. 3D FEA was used to investigate the influence of multi-phase and multi-layer windings of surface-mounted PMSMs on the PMs eddy-current losses [117]. Different windings layouts and layers numbers were compared.

3.4. Hybrid Models

A hybrid method to calculate eddy-current losses in PMs was presented in [118]. It consisted of a derived current sheet by 2D analytical method combined with a 3D FEA. The magnetic field at the stator inner diameter was calculated, and then, the 2D current sheet was determined. This latter was extended axially, and 3D FEA was performed. A nodal method was developed in [119], and it was based on network-field coupled time-stepping FEA (NF-TS-FEA). In [120], 2D FEA for a non-segmented magnet machine was done to measure the magnetic field. The data array containing the flux density on a path was obtained. These data were used to obtain the induced eddy-current density by solving analytically an equation derived from Maxwell's second equation. The work in [121] performed a frequency analysis of the data using FFT analysis. The eddy-current loss summation for each frequency gave the total eddy-current loss with consideration of the skin effect and the harmonics of the air-gap magnetic flux density. The computationally-efficient FEA (CE-FEA) developed by [122] calculated the eddy-current loss from the numerically-obtained flux density through a path. By applying Faraday's law and integrating over a path, the total losses of the PM were obtained. This method incorporated the 3D end-effects. The algorithm for mapping eddy-current loss within surface-mounted PMSM over a wide range of operating conditions was presented in [123,124]. The method required four FEA simulations for open-circuit at rated speed (n_R), at particular reference speed (n_w) in the field weakening region, rated current in the quadrature axis (I_q), rated current in the direct axis (I_d), and reduced current in the d-axis. Coefficients a, b, c, and d were calculated from those simulations and introduced in the following equation to calculate PM losses:

$$P_{PM} = \left(a \left(\frac{n_w}{n_R} \right)^2 I_q^2 + b I_d^2 + C I_d + d \left(\frac{n_w}{n_R} \right)^2 \right) \left(\frac{n}{n_w} \right)^2 \quad (4)$$

In [125], a 3D numerical hybrid method (NHM) of the PM eddy-current loss in axial-flux PMSM was described. The NHM is based on 3D FEA, where the PM magnetic flux density was determined in resistance-limited conditions. Then, the 3D PM eddy-current loss was calculated by the 3D finite-difference method. The semi-analytical model combined with 2D FEA was proposed in [126,127] to estimate the PM eddy-current losses. The flux density variation seen by the PMs was obtained from 2D FEA and then processed by an analytical model.

4. PM Loss Reduction

4.1. PM Segmentation

In [128–130], the effect of the number of PM segments per pole was investigated for conventional and modular PM brushless machines. It was shown that the circumferential segmentation allowed the reduction of the eddy-current losses in both machines. The use of a solid rotor core reduced the PMs eddy-current losses compared to a laminated one [131], and PMs' segmentation allowed the eddy-current loss reduction, but the losses in the rotor yoke increased. The segmentation was only useful for laminated rotors [45]. Losses caused by the slotting effect decreased with the number of PM segmentation for all motors. However, this was not the same case for losses caused by the inverter carrier. The carrier losses in the surface-mounted PM topology were more important compared to the interior and inset PMSM [132]. According to [133], in order to reach lowest eddy-current losses, the shortest PM side should be segmented. The concept of partial segmentation was introduced in [134], viz., single-sided partial PM segmentation (SS-PMS), double-sided partial PM segmentation (DS-PMS), and partial rotor yoke segmentation (PRYS). In the studied case, it was shown that the application of DS-PMS with four segments per PM and combined with PRYS with 128 segments gave a satisfactory loss reduction. In [135], it was proven that the eddy-current losses due to spatial the harmonics decreased by increasing the segmentation number, while those due temporal harmonics did not increase by decreasing the segmentation number. The non-uniform PM segmentation showed more reduction of PM eddy-current losses compared to the classical one; especially electrical machines with an integer number of slots per phase per pole [136].

Concentrated windings are characterized by higher orders of slot-harmonics and multi-loop eddy-currents distribution. In this case, the loss reduction effect by segmentation in surface-mounted PMSMs is smaller compared to interior PMSMs. The axial PM segmentation in the surface mounted

PMSM is more effective than the circumferential one, while both segmentations have an identical effect on the interior PM topology [137].

4.2. Rotor Shape

Loss reduction due to the grooving was studied in [138]. It was shown that the grooved rotor surface of PMSM had less ripple loss compared to the ungrooved one. This technique of grooving was applied in [139], where it was associated with a pulse width modulation (PWM) technique. To decrease the PM eddy-current losses for interior PMSMs with concentrated windings, the authors of [140,141] optimized the shapes of the stator teeth and rotor bridges. Reduction of slot opening had the effect of decreasing of PM eddy-current losses [142]. An optimal adjustment of the number of PM segmentation in the x- and z-direction was proposed in [143,144] to reach the optimized reduction of parasitic eddy-current losses. The authors of [145] realized cuts in the rotor yoke to increase the reluctance without modifying the PM flux path. Three types of cut have been realized to reach a maximum limitation of MMF subharmonic flux. Results showed that this modification of the rotor yoke geometry allowed a rotor loss reduction.

The authors of [146] proposed a special rotor shape to reduce PMs' eddy-current losses. They used flux barriers and slits on the rotor surface of multi-layer interior PMSMs. According to [147], the introduction of flux barriers into the rotor yoke along the d-axis led to lower eddy-current losses.

A tooth-coil open-slot axial-flux machine was designed in [148], to reduce PMs eddy-current losses. It was demonstrated via the prototype that steel laminations on top of the PMs allowed the PM flux linkage maximization and eddy-current loss minimization.

4.3. Material Type Effect

The materials of the retaining sleeves influence the rotor losses of PMSMs. The use of a carbon-fiber/epoxy sleeve gave 5.9-times lower rotor losses than the Inconel718 sleeve according to [149]. The PM losses decreased when a copper layer was put between a carbon fiber sleeve and PM ring [150].

4.4. Spatial Filter

A comparison based on MMF harmonics of SPM and IPM machines, with a pole/slot ratio of 2/3 and concentrated windings, was made in [38]. It was shown that the spatial filter effect of the rotor yoke in IPM machines allowed a significant reduction of PM losses. The increase of the PM depth is a viable solution to reduce PM losses.

In [151], optimized auxiliary slots were added to the structure. This technique allowed canceling partially the asynchronous harmonics produced by the armature field, which resulted in the PM loss reduction.

5. PM Loss Measurement

The major difficulty of measuring PM losses in electrical machines is to separate them from the total losses. Indeed, the measurement of the open- or short-circuit core loss generates the total losses in the machine [152]. By using the thermometric method, it is possible to measure PM eddy-current losses. Figure 2 shows a manipulation realized in [153]. The sintered PM was inserted into a solenoid coil, and its temperature was measured by thermocouples. The system was supplied by an alternating magnetic field, and the eddy-current losses were calculated following:

$$Q = CVD\frac{dT}{dt} \tag{5}$$

The same apparatus principle was used in [154] to study the PM segmentation effect experimentally.

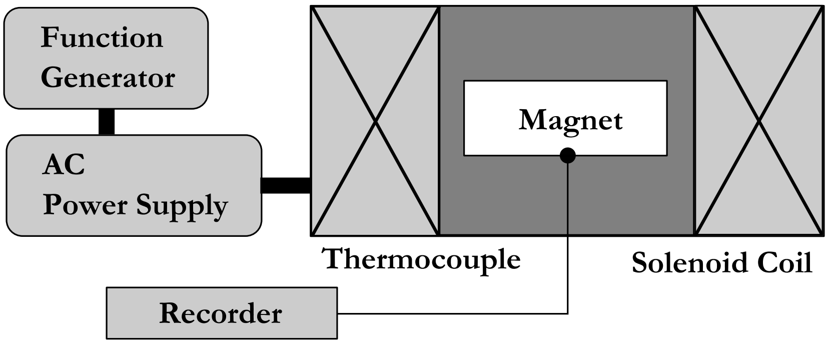

Figure 2. Schematic apparatus of eddy-current measurement [153].

To measure rotor losses of an axial-flux PMSMs due to slot-opening, the machine with magnetized PMs was driven without current. The impact of current/MMF harmonics frequency and the resultant losses was obtained when the machine was driven by AC/DC current with demagnetized PMs [145].

In [155], the rotor losses of an axial-flux PMSM were investigated by the measurement of different operating conditions. Static and rotary tests were done in [156] to measure rotor losses. However, the measurements were done for the total rotor losses, not for PM losses.

6. Thermal Analysis

The eddy-current losses in electrical machines are dissipated by radiation and natural convection. The temperature of the machine and of PM materials must be considered in electrical machines' design [157]. An analytical lumped-circuit method was used in [158], to analyze the thermal field of PM motor and generator. It was shown that the PWM duty ratio and the DC supply influenced directly the difference in temperature rises.

In [159], the influence of the axial cooling air in the air-gap on rotor air-friction losses was studied. A subminiature noncontact infrared thermometer was used to measure the rotor temperature.

7. Conclusions

This paper is a synthesis of the analysis and methods of eddy-current loss prediction in PMSMs. The different sources of these losses were outlined and divided into several categories. After the identification of the losses, their calculation was approached. The precision of the results and the time consumption are the compromises of the PMs eddy-current loss computation. Indeed, the 2D/3D analytical models allow a fast calculation, but a lower precision, considering the associated simplifying assumptions. On other hand, FEA allows more accuracy results, but with a greater time consumption. Hybrid models, as well as the introduction of correction coefficients are often proposed as a solution.

One of the consequences of eddy-currents in PMs is their demagnetization by a high temperature. Thereby, loss reduction by limiting these eddy-currents is necessary. This can be done with several methods, viz., PMs' segmentation, modifying the rotor shape, selecting the material type, and using a spatial filter.

The PM loss measurement is very difficult because the collective losses' separation is not easy. The most common methods to perform the measurement of losses are collective losses' separation and thermometric methods. This has been little discussed in the literature. Finally, the thermal analysis of PMs was discussed, and it must be taken into account in the design of PM electrical machines.

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