Doctoral Dissertation
Doctoral Program in Electrical Engineering (36^{th}cycle)

Advanced Modelling and Design Methodology for Electric Traction Motors

By

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Abstract

The current industrial and political momentum advocating for the electrification of the transportation sector underscores the imperative for an enhanced understanding of electric powertrains. While electric machines have been an invention since the 19th century, the research in this field has recently surged in popularity, especially over the last two decades. This thesis is situated within this context, with the objective of enhancing the modelling and design aspects of permanent magnet synchronous machines, namely the most widespread electric machine type in traction applications. The activities undertaken in this thesis are closely aligned with the current necessities of OEMs and Tier-1 companies; indeed, the primary goal is to provide solutions to some of the most intricate challenges faced in the field.

The initial outcome encompasses two innovative design procedures. The first procedure facilitates the initiation of a design from the ground up, integrating sizing equations with minimal reliance on Finite Element Analysis. In contrast, the second procedure is employed for designing a machine based on a reference pre-designed machine, employing scaling techniques.

The second segment of the thesis is dedicated to the estimation of iron, magnet, and copper losses. A significant scientific contribution lies in a novel procedure grounded in simple static simulations, enabling a comprehensive estimation of machine losses. Special emphasis is placed on intricate phenomena, notably the influence of PWM supply and magnet segmentation, which significantly affect losses. These loss estimation techniques culminate in an efficiency mapping procedure that adeptly considers profound phenomena while ensuring a manageable computational burden.

The offered procedures are validated through tests on 4 prototypes, corroborating their validity.

All the processes outlined in this thesis are openly shared through the open-source project SyR-e. This software platform serves as a valuable resource for the design and evaluation of electrical machines, as demonstrated by more than 8 thousand downloads worldwide. Over the last four years, I have been a developer of the tools.

Contents

Chapter 1

Introduction

1.1 Motivation and goals of the thesis

The current industrial and political momentum advocating for the electrification of the transportation sector underscores the imperative for an enhanced understanding of electric powertrains. While electric machines have been an invention since the 19^{th} century, research in this field has recently surged in popularity, especially over the last two decades. Concerning the future, numerous facets of electrical machine modelling, design, and manufacturing stand to gain significant improvements through collaborative efforts among experts in both industry and academia. This thesis is situated within this context, with the objective of enhancing the modelling and design aspects of permanent magnet synchronous machines (PMSMs), namely the most widespread electric machine type in traction applications. The activities undertaken in this thesis are closely aligned with the current necessities of OEMs and Tier-1 companies; indeed, the primary goal is to provide solutions to some of the most intricate challenges faced in the field.
Numerous design procedures are outlined in the literature, with a more comprehensive discussion available in Section 2.3. These approaches vary widely, ranging from effective and time-intensive techniques such as optimization algorithms to more agile yet less precise methods like analytical models. Nowadays, significant attention is dedicated to augmenting the computational power of modern workstations. Capitalizing on this technological trend, optimization procedures are anticipated to become increasingly competitive in the future. That said, the PhD research is grounded in

the present computational landscape. The objective is to deliver a design procedure that is both agile and precise, aligning with current computational capabilities. Regarding the performance estimation of PMSMs, one of the most critical contemporary challenges lies in accurately estimating losses. Inaccuracy in this quantity results in imprecise efficiency estimations, leading to incorrect autonomy predictions, as well as inaccurate estimates of machine thermal behaviour (continuous performance - S1). This thesis offers a comprehensive loss estimation framework capable of encompassing intricate phenomena through a simplified approach, specifically tailored to the automotive context.

1.2 List of published papers

In the following, it is reported the list of papers authored and co-authored by the candidate during the M.Sc. thesis [1] and the PhD research [2]–[11].
Conference papers:

1. **P. Ragazzo**, S. Ferrari, N. Rivière, M. Popescu and G. Pellegrino, "Efficient Multiphysics Design Workflow of Synchronous Reluctance Motors," *2020 International Conference on Electrical Machines (ICEM)*, Gothenburg, Sweden, 2020, pp. 2507-2513, doi: 10.1109/ICEM49940.2020.9270670.

2. S. Ferrari, **P. Ragazzo**, G. Dilevrano and G. Pellegrino, "Flux-Map Based FEA Evaluation of Synchronous Machine Efficiency Maps," *2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, Modena, Italy, 2021, pp. 76-81, doi: 10.1109/WEMDCD51469.2021.9425678.

3. S. Ferrari, **P. Ragazzo**, G. Dilevrano and G. Pellegrino, "Determination of the Symmetric Short-Circuit Currents of Synchronous Permanent Magnet Machines Using Magnetostatic Flux Maps," *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Vancouver, BC, Canada, 2021, pp. 3697-3704, doi: 10.1109/ECCE47101.2021.9595806.

4. S. Ferrari, G. Dilevrano, **P. Ragazzo** and G. Pellegrino, "The dq-theta Flux Map Model of Synchronous Machines," *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Vancouver, BC, Canada, 2021, pp. 3716-3723, doi: 10.1109/ECCE47101.2021.9595187.

5. **P. Ragazzo**, G. Dilevrano, S. Ferrari and G. Pellegrino, "Design of IPM Synchronous Machines Using Fast-FEA Corrected Design Equations," *2022 International Conference on Electrical Machines (ICEM)*, Valencia, Spain, 2022, pp. 1-7, doi: 10.1109/ICEM51905.2022.9910753.

6. G. Dilevrano, **P. Ragazzo**, S. Ferrari, G. Pellegrino and T. Burress, "Magnetic, Thermal and Structural Scaling of Synchronous Machines," *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2022, pp. 1-8, doi: 10.1109/ECCE50734.2022.9947472.

7. **P. Ragazzo**, S. Ferrari, G. Dilevrano, L. Beatrici, C. Girardi and G. Pellegrino, "Scaling of Ferrite-assisted Synchronous Reluctance Machines for Lifting Systems," *2023 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, Newcastle upon Tyne, United Kingdom, 2023, pp. 1-6, doi: 10.1109/WEMDCD55819.2023.10110927.

8. **P. Ragazzo**, S. Ferrari, G. Dilevrano, L. Beatrici, C. Girardi and G. Pellegrino, "Synchronous Reluctance Machines with and without Ferrite Assistance for Lifting Systems," *2023 IEEE International Electric Machines & Drives Conference (IEMDC)*, San Francisco, CA, USA, 2023, pp. 1-7, doi: 10.1109/IEMDC55163.2023.10239091.

9. G. Dilevrano, **P. Ragazzo**, S. Ferrari and G. Pellegrino, "Comparative Design of Ferrite- and NdFeB-PMSMs using the (x,b) Design Plane,"*2023 IEEE International Electric Machines & Drives Conference (IEMDC)*, San Francisco, CA, USA, 2023, pp. 1-7, doi: 10.1109/IEMDC55163.2023.10238969.

10. **P. Ragazzo**, G. Dilevrano, S. Ferrari, G. Pellegrino, "Magnet Loss Computation for PMSMs Under PWM Supply via Corrected Magnetostatic FEA", *2024 IEEE International Conference on Industrial Technology (ICIT)*, Bristol, UK, 2024.

11. **P. Ragazzo**, G. Dilevrano, S. Ferrari, G. Pellegrino, "Fast and Accurate Iron Loss Evaluation Using Static FEA for Traction PMSMs", *2024 IEEE International Conference on Industrial Technology (ICIT)*, Bristol, UK, 2024.

12. **P. Ragazzo**, G. Dilevrano, A. Bojoi, S. Ferrari, G. Pellegrino, "Fast efficiency mapping procedure for PMSM accounting for the PWM supply impact", *2024*

IEEE International Conference on Industrial Technology (ICIT), Bristol, UK, 2024.

Journal papers:

1. S. Ferrari, **P. Ragazzo**, G. Dilevrano and G. Pellegrino, "Flux and Loss Map Based Evaluation of the Efficiency Map of Synchronous Machines," *IEEE Transactions on Industry Applications*, vol. 59, no. 2, pp. 1500-1509, March-April 2023, doi: 10.1109/TIA.2022.3221381.

2. S. Ferrari, G. Dilevrano, **P. Ragazzo**, P. Pescetto and G. Pellegrino, "Fast Determination of Transient Short-Circuit Current of PM Synchronous Machines via Magnetostatic Flux Maps," *IEEE Transactions on Industry Applications*, vol. 59, no. 4, pp. 4000-4009, July-Aug. 2023, doi: 10.1109/TIA.2023.3265952.

Submitted journal paper:

3. S. Ferrari, G. Dilevrano, **P. Ragazzo**, G. Pellegrino and T. Burress, "Rapid Magnetic, Thermal and Structural Scaling of Synchronous Machines based on Flux and Loss Maps," *IEEE Transactions on Industry Applications*

1.3 Manuscript Organization

The thesis commences with a review of PMSMs for traction applications in Chapter 2. This chapter first unveils industrial trends and it continues by providing examples of PMSMs mounted in commercial vehicles. Subsequently, it delves into the most prevalent design techniques employed for EMs.
The novel design procedures are presented in Chapters 3 to 6. Specifically, Chapter 3 introduces a procedure for initiating a new PMSM design from the ground up. This is achieved through a graphical approach based on analytical models and Finite Element Analysis (FEA). Expanding on this approach, Chapter 4 addresses the safe turn-off mode, incorporating it into the preliminary design stage. The subsequent Chapter 5 elucidates the performance mapping of PMSMs, focusing on flux and efficiency maps. Also, experimental flux maps are included to validate the adopted motor modelling. These map-based models are then leveraged in Chapter 6 to introduce a novel scaling procedure. This procedure enables the design of a new PMSM starting

from a reference motor in seamless computational time with magnetic, thermal and structural perspectives.

Following the design procedure discussions, the subsequent chapters, from 7 to 9, delve into the estimation of machine losses, namely iron, magnet and copper losses. Each loss contribution is addressed in a dedicated chapter, which incorporates a review of existing models followed by novel models, grounded in static FEA. These are described and applied to case studies; they are also supported by experimental findings. The loss models culminate in an efficiency mapping procedure presented in Chapter 10 capable of contemplating the PWM supply effect.

Finally, the thesis concludes by summarizing key findings, drawing conclusions, and revealing potential paths for future research.